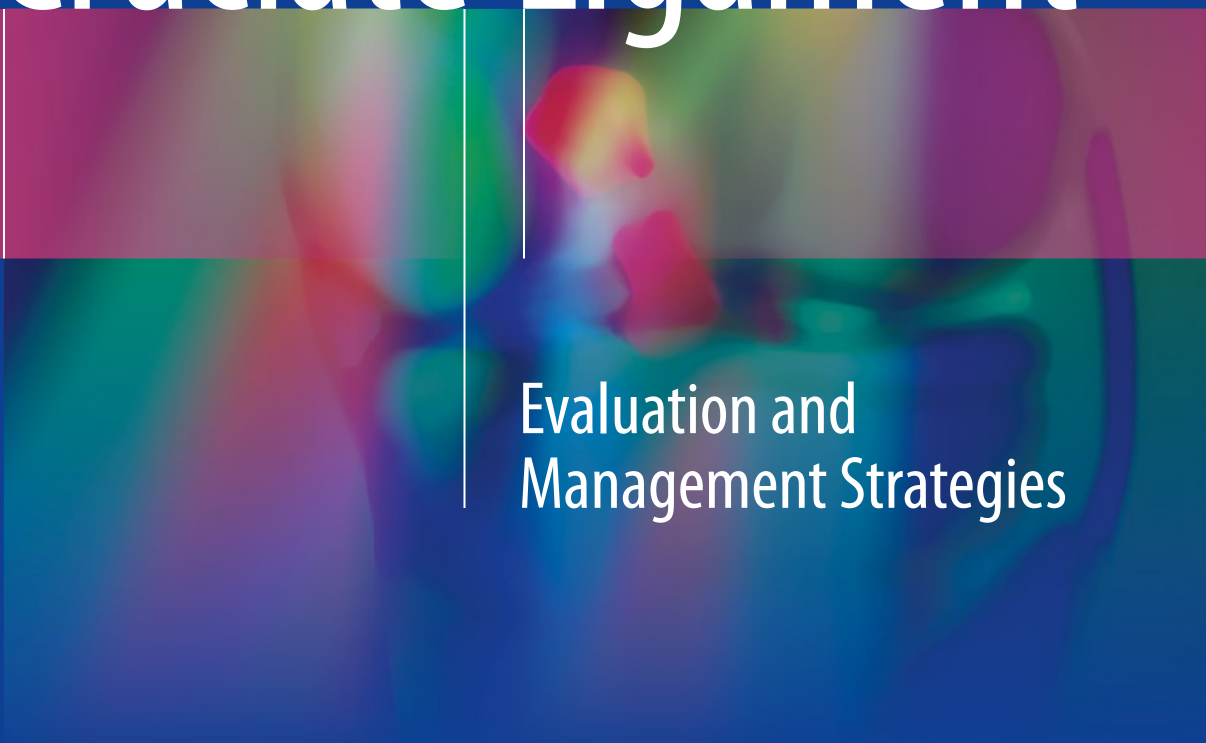
Shital N. Parikh
Editor

The Pediatric Anterior Cruciate Ligament



Evaluation and Management Strategies

Springer

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To my wife, Preeti, for her love, patience, and support and for sharing her unique and unconventional wisdom,

To my children, Ria and Rohan, for allowing me to miss their performances and to take precious time away from home,

To my parents, Kokila and Navnit, for their blessings and unconditional support through all my endeavors.

Shital N. Parikh, MD

Foreword I

I am very pleased to write a foreword to the "*The Pediatric Anterior Cruciate Ligament*" which has been compiled and edited by Dr. Shital Parikh. This topic has been one that has always been of great interest to me and many other pediatric orthopedic sports medicine practitioners. It has been and remains a controversial topic. This book goes a long way towards addressing a number of the issues related to the pediatric ACL including its injury, repair, and prognosis.

In the short span of approximately 40 years this topic has gone from one which was dismissed as being largely irrelevant to the care of the child to one which is now one of the most discussed and debated topics in the area of sports medicine.

To put this in historic perspective, Dr. George Lloyd-Roberts in his landmark textbook on pediatric orthopedics, *Orthopedics in Infancy and Childhood*, published by Appleton-Century-Crofts in 1971 states, "instability of the knee is a very unusual symptom in children. Torn menisci and anterior cruciate avulsions are seen very rarely." Several years later in "*Turek's Orthopaedics: Principles and Their Application*" it was stated, "in youth, the anterior cruciate is strong and, instead of rupturing at the anterior insertion, the bone is avulsed." This text was published in 1976. It is evident from the foregoing that the potential for an anterior crucial ligament midsubstance tear in this age group was considered to be rare or nonexistent.

With the growth of participation in children's organized sports in subsequent years, injury to the anterior cruciate ligament in this age group began to be recognized, and in many instances required specific treatment because of disability or subsequent injuries to the articular and meniscal cartilage of the knee. The increased recognition of this injury is due to the growth and availability of magnetic resonance imaging, the availability of appropriate arthroscopic tools to be used in this age group, and a refinement and attention to a careful physical examination of the knee looking for ligament instability in this age group including the systematic use of the Lachman Test to assess the extent of injury to the knee even in the young child.

At the present time, a number of studies have suggested that not only does anterior cruciate injury occur in this age group, but that the incident of this injury seems to be increasing. In association with this, the treatment of this injury in the child remains controversial, this controversy includes debate on whether the treatment in the growing child, particularly preadolescent child, should be operative or nonoperative, and in the event that operation is required, which operation should be performed in this age group. In particular, because of the presence of the physis and the potential for physeal cartilage injury, the debate has been focused on whether transphyseal or extraphyseal interventions are indicated.

The editor is to be congratulated on having gathered a roster of authors who are recognized scholars on this unique subject. In my opinion, this text will be recognized as a must read for anyone dealing with injuries to the young athlete. I am sure going forward it will serve as a foundation for further study and research in this important area of sports injury in the child.

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Foreword II

The treatment approaches and surgical techniques selected by an orthopedic surgeon dealing with pediatric patients are still evolving; however, there have been major advances in the past decade which are emphasized in this important publication. The authors of the chapters have been selected based on their unique expertise and patient derived outcome data to support their treatment recommendations. This book provides a comprehensive and detailed analysis of the inherent problems in treating ACL injuries in the pediatric patient.

As all surgeons know, these knee injuries are not just confined to the ACL disruption, but involve a total traumatic insult to the knee joint that is commonly associated with injury to other ligament structures and secondary restraints, a high rate of meniscus tears needing repair, and articular cartilage injuries. Paramount to treatment is the selection of an ACL surgical technique that does not risk a growth abnormality in this patient population. The various operative procedures to consider in ACL reconstruction are presented, with appropriate emphasis placed on newer primary repair techniques for select proximal one-third ACL ruptures to preserve the remaining ACL and its neurovascular innervation. Of equal importance is the monitoring of postoperative rehabilitation to avoid arthrofibrosis in younger patients who must be compliant with exercises to restore normal knee motion and lower extremity function. There is no doubt that the treatment of the pediatric patient, similar to the adult population, requires a team approach of experienced surgeons, physical therapists, athletic trainers and others that produces an atmosphere that is supportive, caring, and conductive to the healing and rehabilitation process.

A special emphasis is placed on the treatment of young patients with ACL injuries to preserve and repair associated meniscus tears, including red-white tears and complex tears that have disruption in more than one plane [1, 5, 9]. The emphasis on meniscus repairs in adult ACL surgery applies even more to a pediatric population, because the loss of meniscus function is a disaster for future joint function. The principle is to take as much time to repair a meniscus as it takes to perform an ACL reconstruction, which may require added personnel because the gold standard still remains an inside-out technique with multiple well-placed sutures to restore anatomic continuity. Granted, there have been advances in all-inside meniscus repair techniques that are adapted to select longitudinal, circumferential, and radial tears. However, more complex and extensive meniscus tears must be repaired with multiple well-placed superior and inferior sutures using the classical inside-out technique which has been shown in numerous studies to provide reasonable success rates in the long term. Unfortunately meniscus transplants, even though performed in pediatric patients that are symptomatic after meniscectomy, provide only a short-term benefit [2, 4, 6]. Accordingly, the first meniscus repair procedure needs to be as meticulous and skilled as possible.

A special emphasis is also placed in the rehabilitation chapters in this textbook that include return-to-play objective testing and an emphasis on neuromuscular training to reduce ACL reinjury or contralateral ACL ruptures. There are maturity-impeding factors that must be included in a well-structured neuromuscular training program (such as Sportsmetrics) to condition the athlete and overcome demonstrated neuromuscular control deficits [3, 7, 8]. Thus, the need to proceed cautiously for pediatric ACL patients on return to athletics and the requirement of objective testing to determine coordination, neuromuscular control, and muscle deficits. The reinjury rate after ACL reconstruction in female athletes has been shown to be markedly reduced by neuromuscular training and a recent publication showing an ACL reinjury rate (to either knee) of nearly 20–30% is unacceptable in modern orthopedic treatment paradigms [10]. The recommendations in this book require special emphasis, as it is necessary in the extended postoperative period to institute these advanced training concepts.

Shital N. Parikh, M.D., is an ideal person to be the editor of this publication and is currently a Professor of Orthopedic Surgery at the Cincinnati Children's Hospital Center, having completed his pediatric fellowship at that center under Alvin H. Crawford, M.D., from 2001 to 2002. I have a special professional relationship with Parikh as he completed a Sports Medicine and Arthroscopic Fellowship at Cincinnati SportsMedicine and Orthopedic Center in 2003–2004. His knowledge base from his prior pediatric fellowship was an obvious asset to our staff. As his Fellowship Director, along with our academic staff, we enjoyed his enthusiasm and acknowledged his warm and attentive care of our patients along with his advanced surgical skills. We all wish Parikh the very best as he pursues his academic carrier at the renowned Childrens Hospital, and this book is an example of his contribution to advancing the care of patients with orthopedic related injuries. This book sets a high standard and will undoubtedly be followed in time by a second edition as these treatment advances evolve for the future.

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Preface

The anterior cruciate ligament (ACL) enjoys the accolade of being the most studied and written about ligament in the human body. Its first description is attributed to Galen (circa 170 AD), the Greek physician of the Roman Empire, who cared for the gladiators, and recognized the crucial ligaments in open knee wounds in these soldiers. Hey Groves (1917) is credited for the first description of ACL reconstruction using iliotibial band detached from Gerdy's tubercle, routed through femoral and tibial tunnels and then sutured to the periosteum on the tibia; it formed the basis for modern-day intra-articular ACL reconstruction. The term "Anterior Cruciate Ligament" in pubmed search in early 2017 revealed 17,198 results related to it. Several textbooks have focused on ACL tears and its management, albeit in adults. Despite widespread literature devoted to adult ACL tears, the literature related to ACL tears in the skeletally immature is sparse. There is a paucity of knowledge related to ACL growth and development, age-specific ACL changes, risk factors for ACL tears, ideal interventions for management and prevention of ACL tears based on skeletal immaturity, and long-term outcomes. This book is meant to fill this void.

The field of pediatric sports medicine is still in its infancy and pediatric ACL insufficiency is an evolving and exciting area of interest. In the classic text on *Children's Fractures* by Rang (1974), it was reported that "Complete ligamentous disruption occurs ONLY after growth plate closure." What was once considered to be rare is now accepted to be somewhat common. Increased participation in sports at a younger age, more competitive sports participation, increased professional and public awareness, and improved magnetic resonance imaging diagnostics have led to an increased recognition of ACL tear in the skeletally immature.

When a patient with ACL tear and open growth plates around the knee presents to a sports medicine specialist, one of two scenarios commonly play out. On the conservative end, the patient is recommended to wait for ACL reconstruction till skeletal maturity and to "take it easy" till then. This approach could potentially risk irreversible damage to the meniscus and cartilage. John C. Kennedy voiced his concern in his 1979 book on *The Injured Adolescent Knee* stating that, "the adolescent knee is not immune to early degenerative changes once instability develops. Youthful enthusiasm, a tendency to minimize complaints and a natural reluctance by the surgeon to perform operative procedures on the adolescent should not stand in the way of sound surgical principles." On the other end of the spectrum, an adult-type

ACL reconstruction is recommended, which would entail drilling and fixation across the distal femoral and proximal tibial physis. These physes around the knee contribute the greatest length to the lower extremities and hence physeal violation could risk growth disturbances leading to angular deformity or limb length discrepancy. Thus both approaches can be fraught with undesirable outcomes. Though the ideal approach for these skeletally immature patients with ACL tear remains controversial, “physeal-respecting” ACL reconstruction techniques have advanced the field of pediatric sports medicine. The treating physician should be able to estimate skeletal immaturity and remaining skeletal growth and then decide on patient-specific treatment option based on a variety of factors. If ACL reconstruction is then chosen to be the best treatment option for the patient, the involved surgeon should be knowledgeable and skilled enough to execute appropriate “physeal-especting” ACL reconstructive techniques, based on the patient’s skeletal immaturity and remaining growth.

It is difficult for the busy orthopedic surgeon to formulate the best age-appropriate treatment plan for a child with ACL tear by analyzing the existing literature. Several treatment algorithms have been published to help in medical decision making. Most of the existing literature is, however, low level evidence, with small cohort of patients across varied skeletal ages, and have short- to intermediate-term outcomes. I, with the help of world-renowned and experienced pediatric sports surgeons and scientists, have attempted to synthesize the current knowledge related to ACL deficiency in the skeletally immature in 25 focused chapters in this book. I would like to thank and congratulate all authors for their valuable and timely contribution to this book. Each chapter would review the relevant literature and its practical applications and would discuss the authors’ preferred approach based on their vast experience and literature support. This book is meant to be a one-stop resource for pediatric orthopedic surgeons, orthopedic sports medicine surgeons, primary care sports medicine physicians, pediatricians, fellows and residents in training, physician assistants, nurse practitioners, athletic trainers, physical therapists, scientists, and anyone interested in the evolving field of pediatric sports medicine.

I would like to acknowledge my mentors Alvin Crawford, M.D., and Frank Noyes, M.D., for their dedication, guidance, and support throughout my career. Their commitment to our field of orthopedics has always inspired me to “do more.” I would also like to thank my colleagues, fellows, and residents at Cincinnati Children’s Hospital whose wisdom and constructive criticism has always been thought provoking. They keep me challenged, grounded, and inspire life-long learning. Most importantly, I would like to thank our patients and their families who have entrusted their loved ones to our care. Without them, we have no existence. Lastly, I would like to thank the staff at Springer for their continued help with this project. Their efforts have led to the timely completion of the book.

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Pediatric and Adolescent ACL Injury and Sports Medicine: The Early Years

1

Carl L. Stanitski

Surgeons have cared for athletes and teams for millennia. In the mid-1950s, orthopedic surgeons in large measure became team physicians for collegiate and professional teams, primarily in American football. Orthopedic surgeons were aware of the opinions of emerging leaders in the field and followed their dicta for resolving athlete's injuries. The ultimate metric of success then, as now, was the athlete's return to play at their pre-injury level.

In the United States, organized sports medicine emerged in earnest in the 1970s. Interest in the field became widespread to include experts in exercise physiology, nutrition, sports psychology, biomechanics, physical therapy, and athletic training. Courses in sports medicine were developed, societies were formed, journals were begun, and fellowships were started. A subspecialty was spawned.

Research provided a progressive understanding of the role of the ACL, PCL, menisci, and secondary restraining structures in the normal knee. An appreciation was generated for the premature arthrosis consequences of knee functional instability and concomitant intra-articular damage. Prior to this, a knee injury, even with the early attempts at repair and reconstruction of the damaged tissues, was looked on as a career-ending injury. "The knee was never the same after that injury" was a common lament. "Operative measures generally employed for repair of the anterior crucial ligament are so formidable and extensive that one hesitates to undertake them unless disability is extreme" [1].

The sports medicine field was revolutionized with the advent of the arthroscope, initially brought to North America by Dr. Bob Jackson in 1964. By the mid-1970s, appropriate-sized fiberoptic camera systems for arthroscopy were developed and marketed with commercial success. Additional development of instruments for diagnosis and, later, treatment with arthroscopic guidance were made available. Over the next three decades, the development of endoscopic techniques led to the concept of "if you can see it, you can fix it." Intra- and postoperative anesthetic techniques for pain control allowed for outpatient surgery. Minimally invasive methods provided rapid recoveries and functional return to activity.

Pediatric and adolescent sports care was initially ignored as it developed within the banner of "sports medicine" writ large. Prior attitudes regarding injuries to the scholastic-aged athlete were engrained. Notions that "children do not get significant injuries until they are mature" and "children heal any injury without difficulty" were the guidelines of the day. ACL tears in the prepubescent patient were looked upon as curiosities.

It always seemed to this author that the scholastic-aged athlete accounted for the largest number of sports participants. In 1972, there

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were 4 million senior school (grades 9–12) athletes participating in school- and community-sponsored programs. This number grew exponentially with the onset of Title IX which mandated equal opportunities for sports participation (and injury) for girls/women as those for boys/men. Within this athletic participation, children did get injuries, usually not serious and with resolution with minimal intervention. However, enough of these participants did have injuries, usually about the knee, that had potential long-term negative outcomes. This view was not incorporated into the general sports medicine practitioner's attitude that care of these youthful athletes was really not equivalent to "sports medicine," i.e., caring for upper-level collegiate and professional teams. On the other hand, it was looked upon by pediatric orthopedic surgeons as not being true pediatric orthopedics, i.e., care of clubfoot, scoliosis, and DDH.

A pioneering sports medicine clinic devoted to the scholastic athlete was begun in 1977 at Boston Children's Hospital, directed by Dr. Lyle Micheli, my mentor, colleague, and friend. This unit provided multidisciplinary care and incorporated clinical research with presentations and publications in this field. This approach served as a role model for development of such clinics around the world. Textbooks were written with a focus on pediatric and adolescent athletes [2, 3].

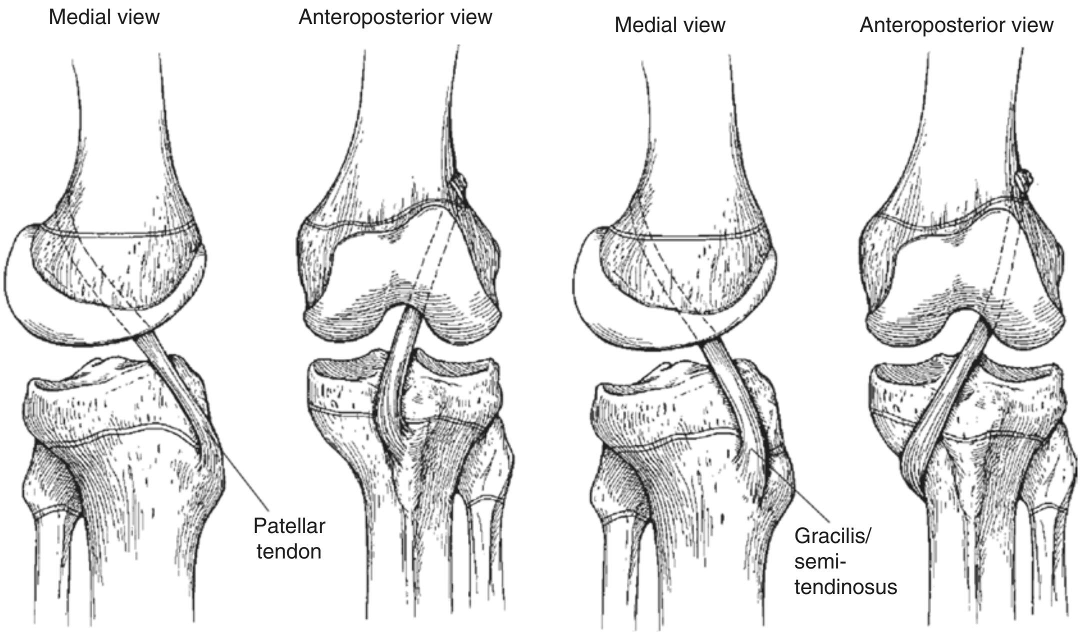
The clinical diagnosis of an ACL tear was improved with the understanding of Lachman and pivot-shift tests and the use of arthrometers to quantify anterior tibial translation. Development of imaging modalities, mainly CT and MRI, enhanced the orthopedist's diagnostic capability and, in addition to the clinical findings, led to treatment protocols. Data was presented regarding arthroscopically documented ACL injuries in prepubescent athletes which were highly associated with a hemarthrosis [4].

Differentiation between a mid-substance ACL tear and a tibial eminence fracture was emphasized that the latter was not the juvenile equivalent of an ACL tear. The former was due to a low load rapidly applied versus the latter that was associated with a high load applied slowly resulting in interstitial elongation of the ACL and no tear but rather a resultant chondro-epiphyseal avulsion fracture. The outcomes of the treated tibial eminence fracture were excellent in contrast to the nonhealing torn ACL sequelae.

Historically, the initial focus was on nonoperative treatment for an ACL injury in the skeletally immature patient due to concern for surgical damage to the distal femoral and/or proximal tibial physes, the sites of major growth in the lower extremity. This was especially true in the physiological "no man's land" of adolescence. Growth must be considered as a fourth dimension with its attendant variability of onset, rate, magnitude, and duration. During this rapidly changing physiologic background, variabilities in strength, coordination, and endurance are superimposed on growth evolution, and all these factors must be considered during diagnosis and treatment. Failures of nonoperative management were primarily due to patient's lack of compliance with the rehabilitation program with intra-articular injury at the time of the initial injury to the ACL or subsequent intra-articular damage due to continued functional instability, especially if the patient tried to return to high levels of sports activity requiring pivoting, acceleration, and deceleration. I refer to this combination of injuries as the "ACL plus" knee.

Early reports of ACL reconstruction procedures in this young-aged population had significant research design faults including absent or inappropriate assessments of physiologic maturity, lack of gender specificity, small number of patients, and short follow-up times. Despite the title of the papers regarding "pediatric and adolescent ACL tear," when the data was analyzed, most of the patients were quite skeletally and physiologically mature teenagers.

A classification of ACL surgical reconstruction procedures was presented which took into account the three "Ts"—tissues, tunnels, and techniques. The classification was based on the site and amount of physeal transgression and included physeal sparing, partial transphyseal, and complete transphyseal methods [5] (Figs. 1.1, 1.2, and 1.3). An extra-articular procedure has also been reported, initially used for patients with congenital absence of the ACL [6].



a b

Fig. 1.1 Non-transphyseal ACL reconstruction with (**a**) patellar tendon or (**b**) semitendinosus/gracilis autograft

Guzzanti and coworkers presented recommendations for ACL reconstruction based on evaluation of lower extremity growth remaining with patients being identified as high-risk (>7 cm), intermediate-risk (>5–7 cm), and low-risk (<5 cm) projected lower extremity growth [7, 8].

Postsurgical lower extremity deformities due to physeal injury are due to multiple factors. A survey of an elite group of orthopedic sports orthopedic surgeons regarding outcomes of ACL reconstructions in skeletally immature patients showed a significant number of unsatisfactory outcomes [9]. The poor outcomes were associated with a combination of poor judgment and/or technical errors in addition to lack of appropriate pre-op evaluation of growth remaining by assessing the patient's chronologic, not physiologic, age. There was lack of recognition of the ACL's anatomic origin's closeness to the femoral distal medial physis at the over-the-top position with surgical injury to the perichondral ring of LaCroix. Reported technical iatrogenic issues include too large transphyseal tunnels (>6–8 mm), high drill temperatures, excessive graft tension, graft size, and presence of transphyseal bone blocks and/or hardware. Consequential limb deformities included longitudinal (usually undergrowth,

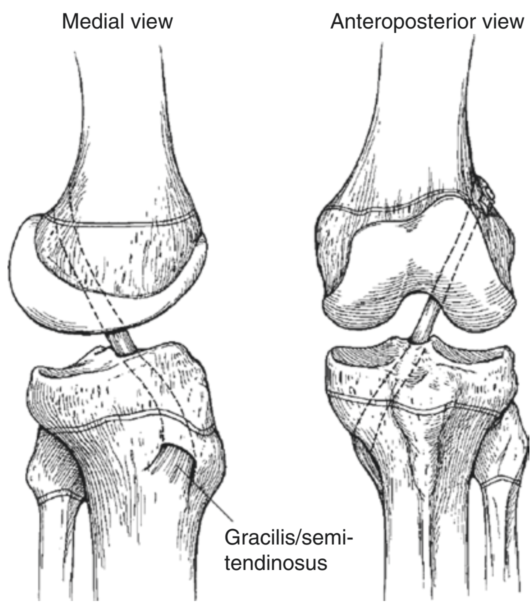


Fig. 1.2 Partial transphyseal ACL reconstruction with a tibial tunnel and central patellar or hamstring autografts with over-the-top femoral fixation

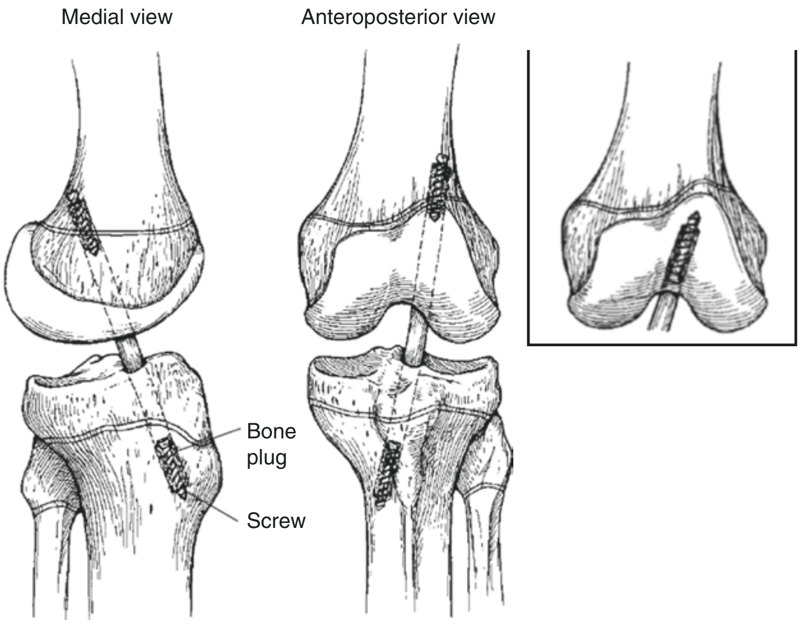


Fig. 1.3 Complete transphyseal ACL reconstruction using femoral and tibial transphyseal tunnels and a patellar tendon autograft with bone plug or hardware fixation including an alternative femoral fixation

possible overgrowth), angular (usually valgus), and recurvatum due to proximal anterior tibial physeal injury.

What Have We Learned About Pediatric and Adolescent ACL Injuries?

Hemarthrosis is a sign of a major intra-articular injury involving the ACL, peripheral meniscus, and/or an osteochondral fracture.

The overall incidence of lateral and medical meniscal tears associated with an ACL tear is about equal. Lateral meniscal tears predominate in the acute setting, and more medial tears are seen in the non-acute setting. Repairs are indicated for appropriate meniscal peripheral tear patterns. Attempts to salvage meniscal tissue should be done to restore the meniscal load-sharing function with articular cartilage.

Physeal transgression of a channel which is 5–6% of the physeal area with an in tunnel tendon graft appears to be safe regarding prevention of a physeal arrest.

Partial ACL tear outcomes are very patient dependent especially the posterolateral ACL bundle status and the secondary restraints' residual magnitude of tibial translation and pivot shift (Fig. 1.4). Activity-level stratification by sport demand has been proposed ranging from low to moderate to high demands [10]. Low-demand activities must be accepted by the athlete. Compliance is often difficult. Nonoperative treatment does not mean no treatment.

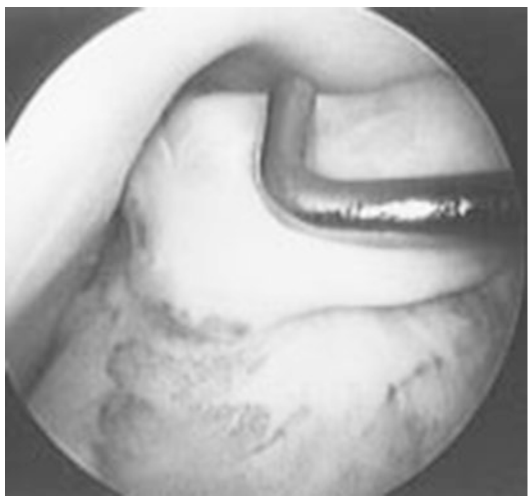


Fig. 1.4 Partial ACL tear with rupture of 90% of the posterolateral bundle

Preventive rehabilitation exercise programs are helpful for groups at risk including girls/women basketball, soccer, and volleyball athletes.

Children do require guided rehabilitation that must be incorporated in all post injury recovery.

Functional instability is detrimental to intra-articular structures, especially with attempts to return to high-level sports requiring pivoting and changes of speed. Physiologically age-appropriate ACL reconstructions and addressing any additional intra-articular injuries are recommended for patients with an ACL+injury.

The orthopedic surgeon needs to act as a "knee counselor" with discussion of treatment options and their particular pros, cons, and outcomes. Included in the discussions is information of the increased risk of re-tear of the ACL in the ipsilateral knee and also possible injury to the contralateral ACL during high-level practices and competitions.

What We Still Do Not Know

What is the true incidence/prevalence of ACL injury in the pre-skeletally mature athletic population? What is the risk stratification relative to growth remaining? There is a lack of significant outcome studies, ones not just to the patient's onset of skeletal maturity but later function for vocational and avocational activities [11].

Do the tendon grafts grow in concert with normal knee growth and are normal kinetics and kinematics obtained and sustained?

The attitude among some orthopedic surgeons suggests that the ACL tear and attendant injuries should be dealt with using any procedure that provides the most stability to prevent intra-articular injury and premature arthrosis. If physeal compromise occurs, any subsequent deformities can be addressed at a future date, but the knee will be spared early degenerate changes. Is this an appropriate approach?

Summary

ACL tears are high-profile injuries in elite, celebrity athletes with headline follow-up information regarding their return to play post reconstruction—or not. Scholastic-aged athletes (and their family, coaches, and peers) often expect (demand?) equivalent positive outcomes.

Over the past three decades, awareness has grown in the medical community about significant sports injuries in young athletes including ACL tears.

Year-round commitment to training and competition for a single sport has significant risk for injury in those participants who are becoming "premature professionals."

The decision for management of ACL injuries in a prepubescent athlete should be multifactorial and include the assessment of gender-related skeletal growth remaining. One must have respect for and not fear of the physis.

After these four plus decades, it is rewarding to see the progression to a true subspecialty of pediatric and adolescent sports medicine with multispecialty participation. A core of orthopedic surgeons who have taken fellowships in sports medicine and in pediatric orthopedics joined the older faculty and have emerged as leaders in this expanding and exciting field. The formation of PRISM (Pediatric Research in Sports Medicine), a multidisciplinary society, 3 years ago is a testimony of this growth and speaks well for the future of this field.

"There is a dead medical literature and there is a live one. The dead is not all ancient, and the live is not all modern"—Oliver Wendell Holmes.

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History of Ligament Injuries in Children

2

Shital N. Parikh

As Carl Stanitski quoted in the first chapter, "There is dead medical literature and there is live one. The dead is not all ancient, and the live is not all modern." A review of the literature would help to appreciate the efforts that have led to the steady advancement in the field of pediatric sports medicine, to learn from the mistakes made in the past, and to potentially prevent complications in the future. It is truly enlightening to read the experiences, success stories, frustrations, and motivation of great minds that have helped to shape the exciting field of pediatric sports medicine. On digging a little deep into the history, one would quickly learn that the medical literature is very much "alive." Some of the current techniques and "novel" ideas are, after all, not that novel. They are refinements of preexisting (and often abandoned or forgotten) ideas. One can call it "reinventing the wheel" but in a positive sense. The following chapter summarizes the history of ligament injuries in children prior to 1990, with focus on ACL tears. With increased recognition of true ligament injuries in children, knee arthroscopy gained increased popularity as a diagnostic tool. Currently, MRI is the standard diagnostic modality for suspected knee injuries; prior to 1990, there have been no reports on the use of MRI for evaluation of knee injuries in children.

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Ligament Injuries in Children

Professor Ivar Palmer (1897–1985) of Sweden was one of the greatest knee ligament surgeons to have lived [1]. In 1938, he published a book *On the Injuries to the Ligaments of the Knee Joint* which offered a glimpse of his in-depth knowledge related to ligament injuries around the knee [2]. The book provides detailed description of 57 patients with ligament injuries. Two of these were in children: a 13-year-old boy with femoral avulsion of posterior cruciate ligament and a 15-year-old boy with tibial avulsion of the anterior cruciate ligament (ACL). Compared to bony avulsion ligament injuries, mid-substance injuries or tears of the ligaments of the knee in children had been rarely reported prior to this. These ligament injuries are considered to be uncommon as the adjoining physis and bone were weaker than the ligaments and hence failed first [3]. With the increasing use of diagnostic arthroscopy in the 1970s (and with the advent of MRI later), ligament injuries in children became increasingly recognized [4, 5]. In 1979, Bradley et al. reported the first series of knee ligament injuries in six children less than 12 years of age; in the same year, Clanton et al. reported their series of nine children less than 14 years of age with knee ligament injuries [6, 7]. Clanton et al. reviewed 1749 cases of knee ligament injuries reported prior to 1979 and were able to find 9 cases of injuries in those less than 14 years of age [5, 7–14]. However, thorough review of the older literature

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related to knee ligament injuries revealed the following shortcomings:

1. The previous published reports on knee ligament injuries combined adults and children, without detailed description of cases. O'Donaghue reported on 82 patients who underwent surgical treatment for the "unhappy triad" of MCL, medial meniscus, and ACL injury, over a span of 15 years (1938–1953) [8]. The series included a 6-year-old girl, but no additional description of the case was provided. Since 85% of patients in the series had medial-sided injury (MCL or medial meniscus) and 75% of patients had ACL tears, one can only speculate the type of injury in the 6-year-old.
2. Several series of knee dislocation and knee fractures reported multiple ligamentous injuries in patients through a wide age range, without detailed description of pediatric patients or their injury patterns. Shields et al. reported on 24 patients with knee dislocation with their ages ranging from 11 to 60 years [9]. Shelton et al. reported on occult knee ligament ruptures associated with fractures in 34 patients, with the youngest patient being 12 years old [10]. The youngest patient in the series of 43 cases of knee dislocation reported by Taylor et al. was 8 years old [11]. These reports included cases of multiple ligamentous injuries in children, but lacked further details.
3. The earlier reports on knee ligament injuries include ligament avulsion fractures as well, making it difficult to delineate intra-substance ligament tears as a separate group. Abbott et al. reported on 26 patients with ligament injuries [15]. The youngest patient in their series (a 12-year-old boy) had sustained a tibial spine avulsion fracture. It had long been known that children sustain ligament avulsion fractures more commonly than ligament tears [16]. However, these avulsion injuries are frequently grouped and reported together with interstitial ligament injuries in the older literature.
4. Till the 1990s, ligament injury series in skeletally immature patients reported the chronologic age of the patients, rather than skeletal age or Tanner stage, which is more relevant [17, 18]. Bergstorm et al. reported on knee arthroscopic findings in 71 children less than 16 years of age [19]. Of these, majority (51 of 71 children) were 14 and 15 years old and likely skeletally mature. Thus, defining skeletal immaturity based on chronologic age and reporting it as pediatric injuries have diluted the older literature (and even recent ones) as to the true incidence of these injuries in patients with open physis.
5. Injuries in children have been thought to heal faster and more reliably than in adults. Surgery was rarely performed for ligamentous injuries in children. Most were treated conservatively. Since the diagnosis of a ligament tear could only be confirmed at the time of surgery (in absence of MRI), there was paucity of reports on injury patterns in children [6].

Mid-Substance ACL Tears in Children

The timeline of pediatric mid-substance ACL tears suffers from some of the same shortcomings as ligament injuries in children in general, as mentioned above. Several series of knee arthroscopy in children have been published; the ones without documented ACL tear have been excluded from this chapter.

In 1978, Youmans reported on 32 cases of isolated ACL tear with their ages ranging from 13 to 45 years [13]. Average age of the cohort was 21 years, eight patients were less than 16 years of age, but the number of skeletally immature patients was not reported. Of 32 cases, 21 had surgical treatment which included pes anserinus transfer with or without iliotibial band transfer, and 11 were treated nonsurgically. Twelve of 32 patients had poor results with increased instability or new meniscus tears.

Nakajima et al. reported on 118 cases of ACL tears, diagnosed by arthroscopy or arthrotomy between 1973 and 1978 [20]. Their ages ranged from 10 to 34 years, with most patients being athletes. Eighty-one percent of patients had associated meniscal tears. The authors describe the N (Nakajima) jolt test which is akin to the pivot shift test routinely used today for clinical diagnosis. Thirty-two cases were treated with iliotibial tract transfer, but specific details related to skeletal immaturity and treatment were lacking in their report.

In 1979, Bradley et al. reported on six children (6–11 years of age) with medial collateral ligament (MCL) tears who were surgically treated by primary repair [6]. Two patients had concomitant ACL tibial spine avulsion fractures, and a 13-year-old had a concomitant mid-substance ACL tear. The ACL tear was primarily repaired using sutures with a fair outcome; despite some rotatory instability on clinical examination, patient was able to hike and ski without much symptoms.

Clanton et al. (1979) reported on nine skeletally immature children less than 14 years of age with traumatic hemarthrosis of the knee [7]. One patient had ACL attenuation which was treated by ACL reefing. Five patients had tibial ACL avulsion fractures; all had ACL attenuation, and four of these five had concomitant collateral ligament injuries. Despite surgical repair, all nine patients demonstrated some degree of postoperative ligament instability; instability was more in those who had meniscectomy. However, none of the patients were symptomatic, and all had returned to the previous level of activities.

In 1980, McDaniel and Dameron reported on a 10-year follow-up study on 53 knees with surgically verified but untreated ACL tears [21]. Three patients (four knees) were less than 15 years of age. An 8-year-old with ACL tear underwent arthroscopy and lateral meniscectomy about a year after injury. At around 4-year follow-up, the patient continued to have discomfort, swelling, weakness, and giving-way episodes. The HSS score was 36 (best possible score 50) which was in the "fair" range, but there were no radiographic degenerative changes. A 14-year-old with bilateral ACL tears had an almost perfect HSS outcome score of 48 without any symptoms, but also had early radiographic changes of condylar flattening at 9-year follow-up. Overall, the authors found a high rate of anterior knee laxity, rotatory instability, and meniscal tears following untreated ACL tears.

Morrissy et al. reported one of the earliest series of knee arthroscopy in children [22]. In the preadolescent (<13 years of age) subgroup, 8 of 11 patients had an incorrect preoperative diagnosis. The challenges in clinical diagnosis in this age group has been later verified by other reports [23]. Two of 11 patients (a 12-year-old boy and a 7-year-old girl) had ACL tear that was diagnosed at arthroscopy.

DeLee and Curtis (1983) reported on three children aged 9, 11, and 12 years, who had sustained mid-substance isolated ACL tears [24]. The ACL tears were verified at arthroscopy and primary repair was performed for these patients. At an average 2-year follow-up, two patients continued to have giving-way episodes and positive pivot shift test. They were still able to return to their pre-injury level of activities.

In 1983, Bertin and Goble reported that 38% of knee physeal fractures were associated with simultaneous ACL injuries [25]. Six of 16 patients with distal femoral physeal fractures and 5 of 13 patients with proximal tibial physeal fractures had concomitant ACL tears. The diagnosis of ACL tear was made clinically, long after the fracture had healed. This was contrary to the previous belief that physeal injuries would preclude ligamentous tears [3].

Waldrop and Broussard (1984) reported on the youngest patient with a mid-substance ACL tear [26]. A 3-year-old girl fell while playing and sustained an ACL tear that was diagnosed by arthroscopy and was debrided. No outcome was reported.

Bergstorm et al. reported on 71 children less than 16 years of age who underwent knee arthroscopy [19].Of these, 30 children had acute hemarthrosis, and 13 of those 30 had ACL tears (age range, 7–15 years). None of the 41 children without hemarthrosis had ligamentous injury. Fifty-one of 71 children were 14 or 15 years old.

In 1986, Lipscomb and Anderson were the first to report on ACL reconstruction in 24 skeletally immature athletes (age range, 12–15 years) with open or partially open physis [27]. ACL reconstruction was performed using semitendinosus-gracilis autograft and a hybrid technique (transphyseal tibial tunnel and epiphyseal femoral tunnel). Twenty-one patients had extra-articular reconstruction as well. Twelve medial menisci and seven lateral menisci were removed at the time of surgery; the authors however recommended a more aggressive approach to save the meniscus. At an average follow-up of 35 months, there were 16 excellent, 7 good, and 1 fair result based on HSS subjective knee score. One patient had 2 cm limb shortening.

Kannus and Jarvinen (1988) reported on long-term (average 8 years) outcomes of conservative management of ligament injuries in 33 adolescents [28]. The age range was 10–18 years, but all patients were reported to have open knee physis. Twelve of 33 had ACL tears of which 8 were grade II (partial) and 4 were grade III (complete). Patients with grade II injuries had good to excellent functional scores despite clinical knee laxity. On the other hand, patients with grade III injuries had poor functional results, continuous symptoms, and early radiographic degenerative changes. These results were viewed to be unacceptable, and the authors recommended surgical treatment for these high-grade lesions.

In 1988, McCarroll et al. reported on 2-year outcomes of isolated ACL tear in 40 skeletally immature patients less than 14 years of age [29]. Of 24 patients who underwent either intra-articular ACL reconstruction (14 patients) or extra-articular ACL reconstruction using iliotibial band (10 patients), all patients were able to return to sports. Of 16 patients treated with rehabilitation, all continued to have instability symptoms, only 7 patients returned to sports, and 6 patients required arthroscopy to address meniscus tears. The authors recommended an aggressive approach towards early ACL reconstruction in these young patients.

Angel and Hall (1989) reported on the natural history of arthroscopy-diagnosed ACL tears in 27 patients less than 18 years of age [30]. Twelve of 27 patients were less than 14 years of age. At an average follow-up of 51 months, seven patients had or were recommended ACL surgery due to ongoing symptoms. Compared to 18 patients with partial tears, none of the 7 patients with complete mid-substance ACL tears were able to return to pre-injury level of sports participation. The authors summarized that with increasing follow-up, there was progressive deterioration of the knee joint and that the injury should not be considered benign.

In 1989, Harvell et al. reported on one of the largest series of diagnostic knee arthroscopy in 83 preadolescents (<13 years of age) and 202 adolescents (13–18 years of age) [23]. They reported on the difficulty of clinical examination in children; 55% and 70% of clinical diagnosis in preadolescents and adolescents, respectively, could be confirmed at arthroscopy, and 35% and 25%, respectively, had additional intraoperative diagnosis that were not suspected on clinical examination. Four preadolescents and 42 adolescents had an ACL tear; it was the commonest diagnosis in adolescent boys.

Summary

There is a lot to learn from the existing literature. As the use of arthroscopy increased during the 1970s and 1980s, the presence of ligament injuries, especially mid-substance ACL tears in skeletally immature patients, was increasingly recognized. The natural history revealed that this injury could lead to persistent instability, meniscus tears, and progressive deterioration of the joint. ACL repairs were attempted, often with persistent instability. ACL reconstruction techniques were developed including extra-articular techniques using iliotibial band and intra-articular techniques with close attention to the physis. The subsequent chapters in this book would focus on the current knowledge that has evolved over the years, including the recent resurgence of ACL repair.

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3 Developmental Anatomy of the ACL and Knee

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Applied Anatomy of the Knee

Embryology of the Knee

Morphological differentiation of the embryo occurs in the second gestational week [1]. During cellular proliferation, the lateral plate mesoderm is thickened and loses epithelial connections, which results in a mesenchymal mass. Mesenchymal cells rapidly proliferate to form a blastema. The central aspect of the blastema undergoes chondrification to form the matrix, which in turn, evolves into shapes resembling adult long bones [2]. The specific association of the mesenchyme and ectoderm controls internal differentiation and growth. Presumptive limb buds comprise the mesenchymal mass and will become specialized cells for the lower limbs during the fifth to sixth week of gestation [1, 3]. Four weeks after fertilization, the lower limbs of the embryo can be identified [3].

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As the mesenchymal cells enter the precartilage stage, they rapidly change into the cartilaginous anlage. The mesenchyme anlage then undergoes chondrification starting centrally and moving toward the periphery. During chondrification, the perichondrium differentiates and surrounds the anlage forming presumptive joints called interzones. At first the perichondrium establishes continuity with the interzones, but as development continues, the tissue becomes fibroblastic as it develops into ligaments and the joint capsule, resulting in a loss of continuity. The interzone contains two parallel chondrogenic layers and an intermediate layer. The intermediate layer is characterized as being less dense than the chondrogenic layers, and the peripheral regions of the intermediate layer form the synovial tissue. The joint capsule is penetrated by blood vessels to reach the blastemal synovium furthering the visualization of the menisci and cruciate ligaments in the intermediate mesenchyme. Minute spaces coalesce in the intermediate zone to form the joint cavity after the intra-articular structures and contours are defined. The blastemal cells no longer function as epiphyseal growth plate/physeal cartilage as they are now committed to becoming the articular surface [1].

ACL Embryology

The anterior cruciate ligament (ACL) originates from the vascular mesenchyme located within the

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embryological knee joint [4, 5]. At 44 to 45 days gestation, the mesenchyme tissue can first be seen between the distal ends of the femur and tibia with a crown-rump length (CRL) of 15 to 16 mm. Packed toward the periphery, the menisci specialized cells are observable with the cruciate ligaments during days 46–47. During gestation, the ACL and menisci have parallel development. The intercondylar notch is intertwined by the ventrally located ACL and remains extrasynovial throughout development. By 10 weeks the ACL is a separate structure from the posterior cruciate ligament (PCL) [6]. The ACL is close to its adult form by 20 weeks of development. Ferretti et al. [7] measured the ACL length as 3.7 ± 0.2 mm histologically in the sagittal view at 20 weeks gestation (Fig. 3.1). Initial formation of the ACL depends on genetics, while later function depends on kinetics [8]. A dissected 8-year-old male pediatric ACL is shown in Fig. 3.1.

Physis

The physis (growth plate) of the distal tibia and femoral physis maintain its planar structure throughout gestation [1]. The resting zone, the proliferative zone, and the hypertrophic zone are considered the three zones of the growth plate and are responsible for endochondral ossification at the growth plate [9]. The resting zone contains a high level of extracellular matrix with chondrocytes that are in a quiescent state neighboring the epiphyseal bone. Within the proliferative zone, chondrocytes are organized in cell columns, which are flat in appearance and undergo mitosis. In the hypertrophic zone, terminal cell differentiation occurs and chondrocyte division ends [10]. The femoral and tibial physes are discoid in shape, but as development progresses, the physes gradually decrease in width.

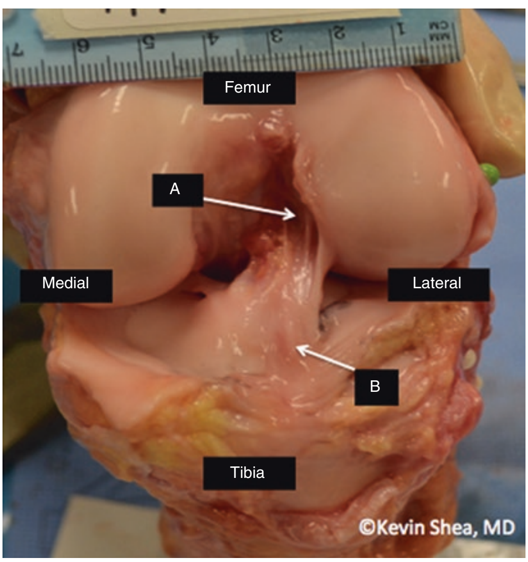

Fig. 3.1 Dissected 8-year-old male, left pediatric knee, showing an intact ACL with femoral origin (**a**) and tibial (**b**) insertion sites. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

Anderson et al. [11] published work about growth and characteristics of growth plate development. There were several limitations to this work, including the following: (1) they studied a small group of patients with half of the patients having polio in their contralateral knee, and (2) they assumed that there was a constant contribution of each physis during development [12]. Nonetheless, they suggested that the distal femoral physis contributed 70% to the overall femoral length and 40% to overall lower extremity length with the tibia physis contributing 55% and 27%, respectively. The maturation height was 175 cm in males and 162 cm for females. Modern American children maturation height increased slightly to 179 cm (males) and 167 cm (females) [12].

Pritchett [12] reported that the distal femur contributed to an average of 1.3 cm of femoral growth per year and slowed to 0.65 cm during the last 2 years of maturation. His work also showed that the distal femoral and proximal tibia make increasing contributions to growth as age increases. The proportion of femoral growth for girls at the distal femoral physis was 60% at age 7 and 90% at age 14. Boys showed a similar trend with the distal femur contributing 55% at age 7 and 90% at age 16, and activity slowing as they reach skeletal maturity.

Tibial Tuberosity

The tibial tuberosity does not become discrete until 12–15 fetal weeks [13]. The vasculature of the tuberosity differs from that of the metaphyseal and epiphyseal. Ogden and Southwick further characterized the several stages of development through a continuum model of the tibial tuberosity [13].

The tibial tuberosity physis is divided into three regions that are not easily recognizable. Proximally, the cytoarchitecture is analogous to the remainder of the proximal tibial growth plate and transitions into [14] the fibrocartilaginous zone, which is composed of hyaline cartilage [15], bone forming from membranous ossification, and [11] fibrocartilage. In the distal region, there is a transformation from hyaline cartilage to fibrous tissue, which further transforms into bone through membranous ossification. After the distal extension and growth of the secondary ossification center, the columnar region becomes more distally extended [13].

Stages I, II, and III comprise the prenatal phase. The physis is transversely oriented during stage I with no discrete tibial tuberosity. Stage II is defined by the anterior outgrowth of the tibial chondroepiphysis, and this development occurs simultaneously with the vascularization and fibrovascular ingrowth of the chondroepiphysis. During stage III there is continued fibromesenchymal-vascular ingrowth, which causes anatomical separation from the proximal tibial physis. Distal displacement of the tuberosity by longitudinal growth at the proximal tibial physis also occurs at stage III [13].

The postnatal phase includes four subsequent, distinct, developmental stages. Stage IV is characterized by development of an additional growth plate at the tibial tuberosity, which coalesces with the proximal tibial physis. During stage V, a secondary ossification center in the distal portion of the tuberosity develops. At stage VI, the proximal tibial epiphysis and tuberosity ossification centers coalesce (Fig. 3.2). The end of the postnatal phase is marked by the closure of the contiguous growth plates of the proximal tibia and tuberosity (stage VII) [13].

ACL Femoral Attachment

The ACL originates on the lateral femoral condyle (LFC) and inserts on the medial intercondylar spine of the tibia (Figs. 3.3, 3.4, and 3.5). At the lateral and medial insertion sites of the ACL, the area is three times larger than the ligament itself [6]. The femoral origin site has an oval-shaped appearance and is smaller than the tibial insertion site (Fig. 3.3) [16, 17]. As the knee is extended or flexed, the femoral origins change in orientation becoming vertical in extension and horizontal with flexion [7].

Ferretti and colleagues studied the femoral attachment landmarks for both fetal and adult patients [18]. They identified two ridges, the "lateral intercondylar ridge" and the "lateral bifurcate ridge," which together make up the ACL femoral origin. The lateral bifurcate ridge was present in 6 out of 7 fetuses. Of those six specimens, four had a distinct ridge that separated the two bundles. The lateral bifurcate ridge was better identified in all patients in the anterior aspect of the ACL origin and separated the AM bundle from the PL bundle. ACL insertion did not occur

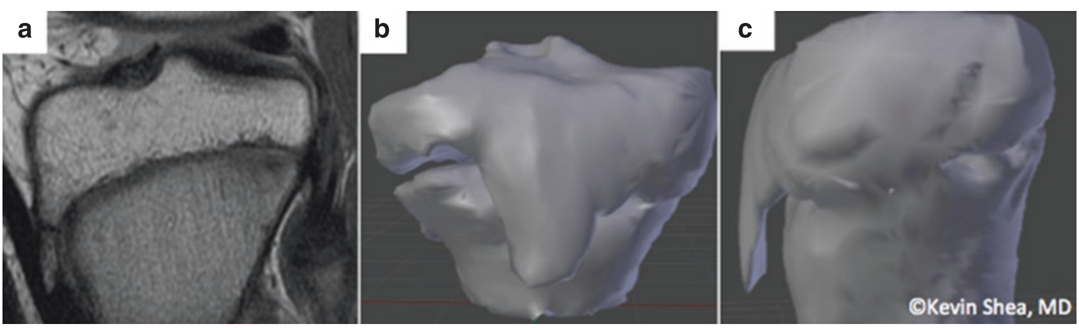

Fig. 3.2 Sagittal MRI (**a**) and frontal (**b**) and side view (**c**) of 3D models identifying the tibial tuberosity in a skeletally immature knee. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

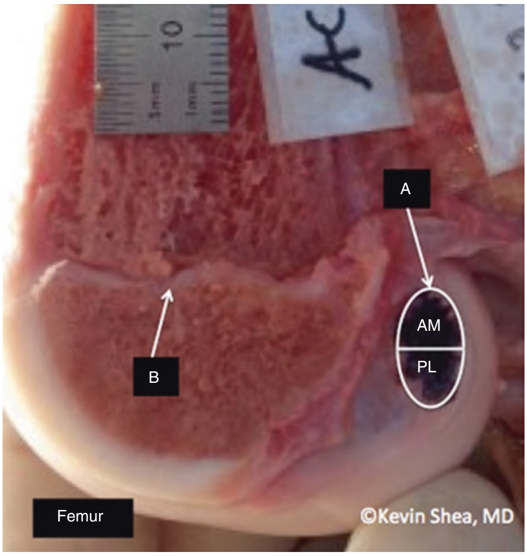

Fig. 3.3 Disarticulated cadaveric specimen. Femur cut in half showing the ACL origin defined with dark stain (**a**) and femoral physis (**b**). The ACL origin is divided into two regions, for the AM and PL bundle origins. Note the undulation of the femoral physis. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

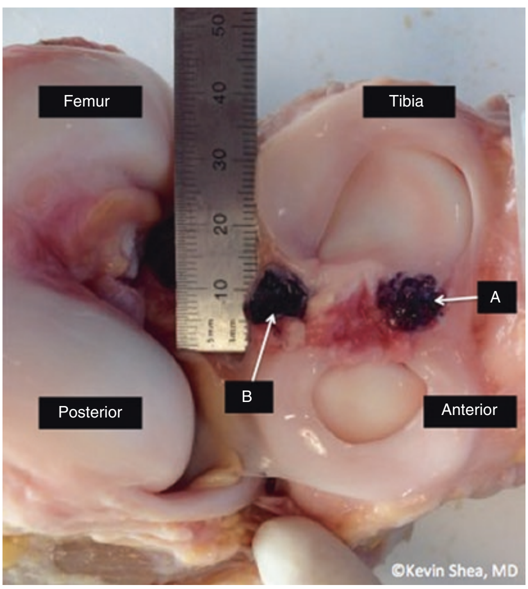

Fig. 3.4 Disarticulated left knee of a pediatric cadaver. *Black marks* represent ACL (**a**) and PCL (**b**) tibial insertion sites. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

anterior to the "resident's ridge" and was a mean 17.1 ± 1.2 mm in length and 9.9 ± 0.8 mm wide with a total area of 196.8 mm^2.

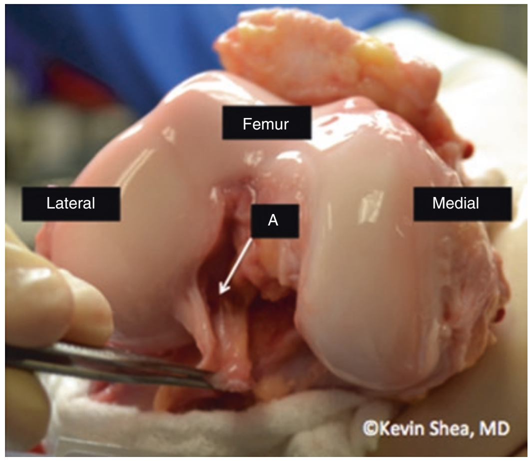

Fig. 3.5 An 8-year-old male, right knee, displaying the ACL femoral origin (**a**). Published with kind permission of © Kevin Shea 2017. All Rights Reserved

The origin/attachments of the anterior cruciate ligament are in close proximity to the physis, so ACL reconstruction risks iatrogenic physeal injury in the skeletally immature knee (Fig. 3.3). Studies by Shea and Behr have investigated the tibial and femoral origins of the anterior cruciate ligament in relation to the physis in the skeletally immature [4, 19].

Behr et al. [4] examined 12 fetal specimens ranging from 20 to 36 weeks gestation and 13 skeletally immature knees between the ages of 5 and 15. The ACL origin was located distal to the femoral physis in all specimens. Specimens younger than 24 weeks gestation showed a fetal ACL origin, which developed as a confluence of ligament fibers with periosteum. Vascular infiltration into the epiphysis is present at 24 weeks, and the ACL is completely epiphyseal by the age of 36 weeks gestation. The distance from the most superior aspect of the ACL origin to the distal femoral physis in fetal specimens was 2.66 mm and showed no significant change in preadolescent and adolescent specimens at 2.92 mm. In relation to the growth of the femur, there was no significant increase in distance from the ACL origin and the femoral physis.

The coauthors of this chapter conducted an initial study of the anatomical relationship between the ACL femoral origin and the distal femoral physis in eight skeletally immature cadaveric knees [20]. There were two groups in the study: infants (1 and 11 months of age) and children (ages ranging from 8 to 11 years). Metallic markers were placed at the midpoint of the femoral ACL origin, and the distance from the ACL femoral origin to the distal femoral physis was measured using computerized tomography (CT) scans. The infant group had a mean distance of 6.3 mm (range 5.8–6.8 mm) from the ACL origin midpoint to the physis. Group 2 (ages 8–11 years) showed a mean distance of 8.3 mm (range 6.7–9.7 mm) (Fig. 3.6). In contrast to the findings of Behr et al. [4], this study suggested the distance between the ACL origin and the distal femoral physis may increase with growth and maturation.

Shea et al. [21] recently described the relationship of the ACL femoral origin to the most posterior aspect of the lateral femoral condyle and proximal aspect of the posterior physis in a group of 12 pediatric specimens (ages 7–11 years) using superimposed sagittal plane CT images. The median distance from the most posterior aspect of the ossified lateral femoral condyle to the midpoint of the ACL origin was 7 mm (interquartile range, 5–8 mm). This distance represented 14% of the total distance from the posterior aspect of the condyle to most anterior (14% anterior-posterior). The median distance from ACL origin midpoint to the proximal aspect of the posterior physis was 10 mm (interquartile range, 9–10 mm), which corresponded to 38% of the total distance from the proximal aspect of the LFC to the most distal aspect of the LFC (38% posterior-distal) to the total lateral femoral condyle height. The ACL origin was found to lie distal to the distal femoral physis in all cases. Furthermore, the same study provided the 95% confidence intervals of the true mean ACL origins (Fig. 3.7).

Tibial Spine and the ACL Insertion

The ACL can be separated into multiple bundles, but several groups have grossly separated the ACL into two distinct bundles. The work of Ferretti et al. and others has suggested that separating the ACL into anteromedial and posterolateral bundles is a reasonable distinction for better understanding the anatomic and functional aspects of the ACL [7, 17, 18]. The tibial spine is associated with the two bundles of the ACL, the anteromedial (AM) and posterolateral (PL). The posterolateral bundle

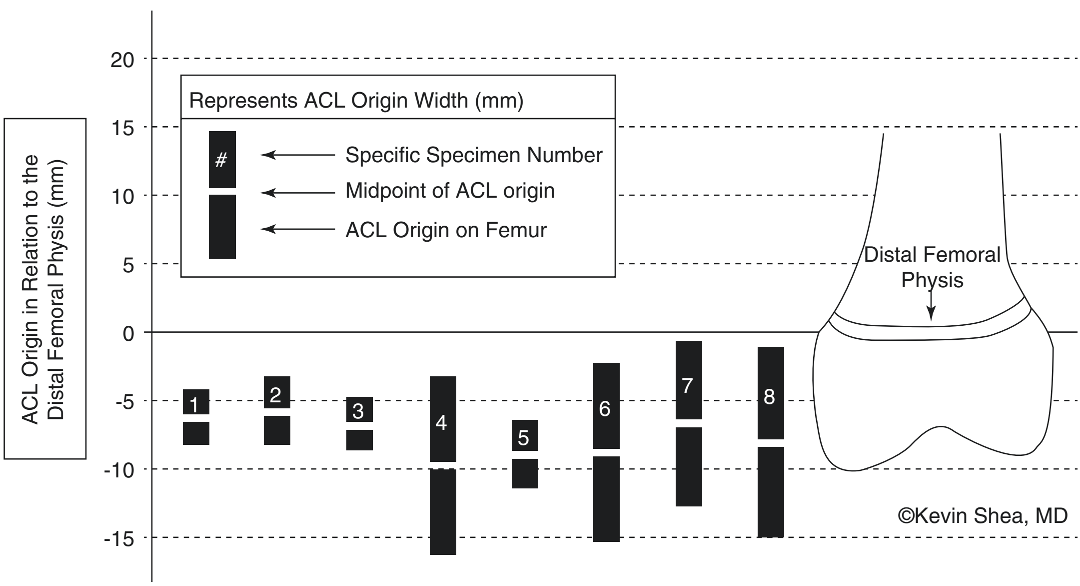

Fig. 3.6 Measurement ACL midpoints in relation to the distal femoral physis. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

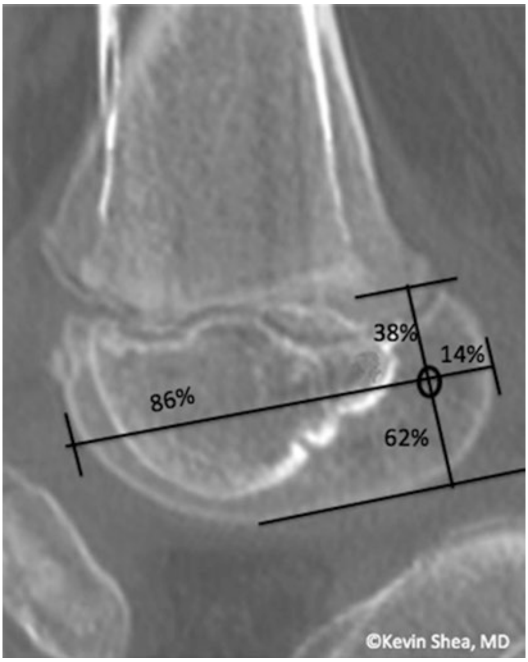

Fig. 3.7 Merged CT images showing the 95% confidence intervals for ACL origin. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

inserts into the posterolateral ACL footprint in close proximity to the lateral aspect of the tibial spine, while the AM bundle is located anterior and medial to the PL bundle (Fig. 3.8) [7, 17]. A study conducted by Siebold et al. [22] demonstrated that in relation to the mid-substance of the ACL, the tibial attachment site is larger in diameter and also shows a characteristic "c shape." Siebold et al. [22] looked at the mid-substance in 20 cadaveric specimens. The mid-substance of the ACL had a "ribbon-like" or "flat" appearance with a width of 9.9 mm and thickness of 3.9 mm. Along the medial aspect of the tibial spine, the ACL insertion showed a close anatomic relationship to the anterior aspect of the anterior root of the lateral meniscus. The width and the thickness of the "c-shaped" insertion were 12.6 mm and 3.3 mm, respectively. In contrast to previous studies [23–27], it was found that the ACL fibers inserted in the anteromedial and posteromedial parts of the tibia, but not the posterolateral part. The authors hypothesized that anatomic ACL reconstruction techniques may require a tibial tunnel resembling the native "c shape" of the ACL footprint.

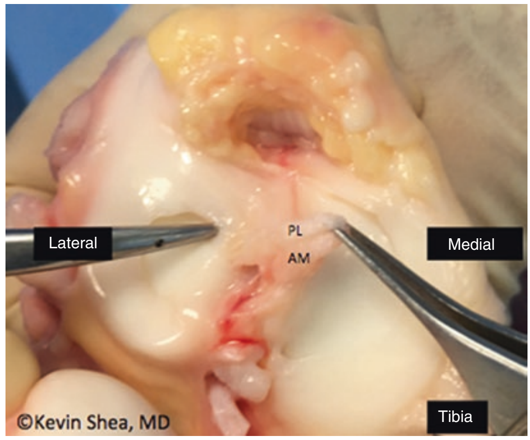

Fig. 3.8 A 2-year-old cadaveric specimen showing the posterolateral (PL) and anteromedial (AM) bundles of the ACL in a left knee. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

Previous MRI-based research has measured the anterior and posterior limits, center point, and angle of roof of the ACL in skeletally immature children [19]. For males, in relation to the anterior-posterior tibial width, the values for anterior limit, center point, posterior limit, and roof angle of the ACL were 28%, 43%, 59%, and 36.8°. In relation to adult males, the corresponding values were 27%, 43%, 59%, and a 40° roof angle. The study saw minimal age and gender variability. For skeletally immature females, similar values included 28%, 46%, and 63% and 18° roof angle. Adult female had corresponding values of 28%, 44%, and 60%, with a roof angle of 35° (Fig. 3.9). In the skeletally immature and adult knee, the anatomical landmarks are proportionate regardless of size differences.

Functional Anatomy of ACL

As the primary stabilizer of the knee, the ACL is responsible for resisting anterior translation and rotation of the tibia on the femur. During activities of daily living, the ACL experiences minimal stress. The anteromedial and posterolateral bundles that attach to the tibia make up the ACL (Fig. 3.8). The posterolateral bundle originates in close proximity to the anterior articular cartilage

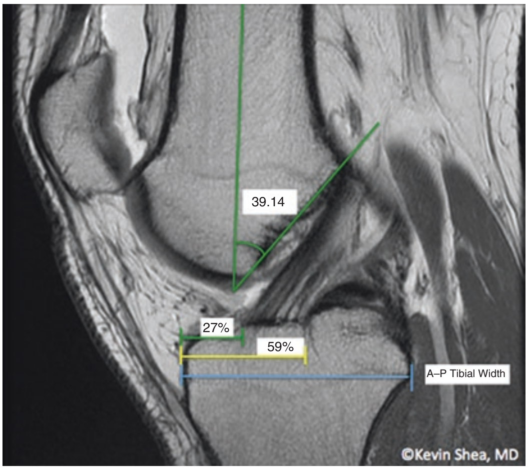

Fig. 3.9 MRI showing the measurements of the anterior limits of the tibia to the anterior-posterior fibers of the ACL and total anterior-posterior limits of the proximal tibia. Adapted from Tibial Attachment of the Anterior Cruciate Ligament in Children and Adolescents: Analysis of Magnetic Resonance Imaging. *Knee Surg Sports Traumatol Arthrosc.* 2002;10 [15]:102–108. Shea KG, Apel PJ, Pfeiffer RP, Showalter LD, Traughber PD. Published with kind permission of © Kevin Shea 2017. All Rights Reserved

of the lateral femoral condyle, while the anteromedial bundle originates proximally in the intercondylar ridge. The anteromedial bundle inserts onto the femur superior to the posterolateral insertion (Fig. 3.3) [7, 17, 18]. Under maximal anterior tibial loads and simulated muscle loads, the ACL has been shown to be maximally loaded within 30° flexion [28]. These bundles function as reciprocals, as the anteromedial bundle is tight at high-flexion angles and the posterolateral bundle is tight at low-flexion angles [29].

Li et al. [28] investigated elongation of the ACL during flexion in an MRI-based study. The length of the anteromedial bundle at 30°, 60°, and 90° of flexion was 32.5 ± 2.8 mm, 30.7 ± 2.0 mm, and 30.2 ± 1.8 mm, respectively, and 32.5 ± 3.7 mm in full extension. The corresponding posterolateral bundle values were 26.3 ± 4.1 mm (30°), 23.5 ± 2.3 mm (60°), 24.1 ± 2.9 mm (90°), and 27.6 ± 5.2 mm (full extension). They found little change in anteromedial bundle length between full extension and 90° of flexion. Consistent lengths of the anteromedial bundle within full extension and 90° flexion may indicate an approximate isometry of the ACL anteromedial bundle.

Under weight-bearing conditions, both bundles are stretched at low-flexion angles. Kurosawa et al. [30] found that in the range of 0°–60° knee flexion, the quadriceps muscle contraction resulted in stretching of both the anteromedial and posterolateral bundles. Their work also showed that the ACL antagonized the quadriceps force from 10° to 60° of knee flexion.

Anatomic Considerations for ACL Reconstruction: Avoiding Physeal Injury

Historically, ACL reconstruction was often delayed until skeletal maturity or near skeletal maturity in pediatric patients due to the potential for iatrogenic physeal damage and growth disturbance in patients with open growth plates [31]. However delayed reconstruction has been shown to increase the risk of chondral and meniscal damage [32–34], as well as the risk for sports-related disability [35] as a result of chronic ACL deficiency. In addition, several physeal sparing reconstructions have been described with good outcomes [14, 15, 36–41]. Still, pediatric ACL reconstruction remains a challenging procedure, particularly in techniques utilizing all-epiphyseal femoral tunnels, and the difficulty of these reconstructions is highlighted by the number of structures at risk during tibial (Fig. 3.10) and femoral drilling (Fig. 3.11b).

Previous anatomic studies [42] which utilized three-dimensional modeling of 6, 7, 8, and 9 mm tunnels to quantify the potential for physeal damage in single-bundle (2.4–5.4% of total physeal volume was removed) and double-bundle (3.7–6.5% of physeal volume was removed) adult reconstruction techniques highlight the risk of performing non-physeal-respecting techniques in the skeletally immature (Fig. 3.12). All-epiphyseal femoral tunnels may be more technically challenging than those used in adult reconstruction techniques. The popliteus, LCL, articular cartilage, and physis are all at risk for iatrogenic damage if ACL tunnels are not placed correctly (Fig. 3.13).

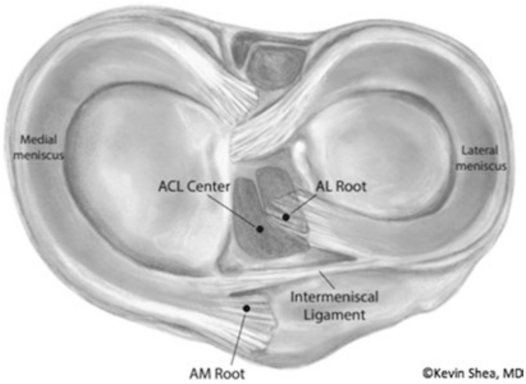

Fig. 3.10 Axial view of the tibial plateau anatomy. The anterior root of the lateral meniscus (AL root) and ACL insertion site lie in close proximity with one another, with the ACL insertion medial and anterior to the AL root. Adapted from Anatomy of the Anterior Root Attachments of the Medial and Lateral Menisci: A Quantitative Analysis. Am J Sports Med, 2014, Volumen 42: No. 10: 2386–2392. Christopher M. LaPrade, BA, Michael B. Ellman, MD, Matthew T. Rasmussen, BS, Evan W. James, BS, Coen A. Wijdicks, PhD, Lars Engebretsen, MD, PhD, and Robert F. LaPrade, MD, PhD

3D modeling studies continue to be a useful tool in evaluating tunnel placement and may help determine optimal reconstruction technique. A study by Xerogeanes [43] used a large number of MRI reconstructions to compare two different tunnel orientations: [14] from the ACL femoral footprint to the popliteus tendon and [15] from the ACL footprint to the lateral epicondyle. Xerogeanes recommended drilling to a point just anterior to the popliteus tendon as this acts as a reproducible landmark but warned against possible damage to the popliteus using this technique. Recently, the authors of this chapter used CT reconstructions to simulate 7 mm all-epiphyseal tunnels in skeletally immature knees and to analyze the “safe zone” on the lateral aspect of the femur (Fig. 3.12). The “safe zone” is defined by a lateral condyle drill hole aperture that missed the LCL, anterolateral ligament (ALL), posterior condyle articular surface, and popliteus tendon (Fig. 3.11b). This anatomic study found that a

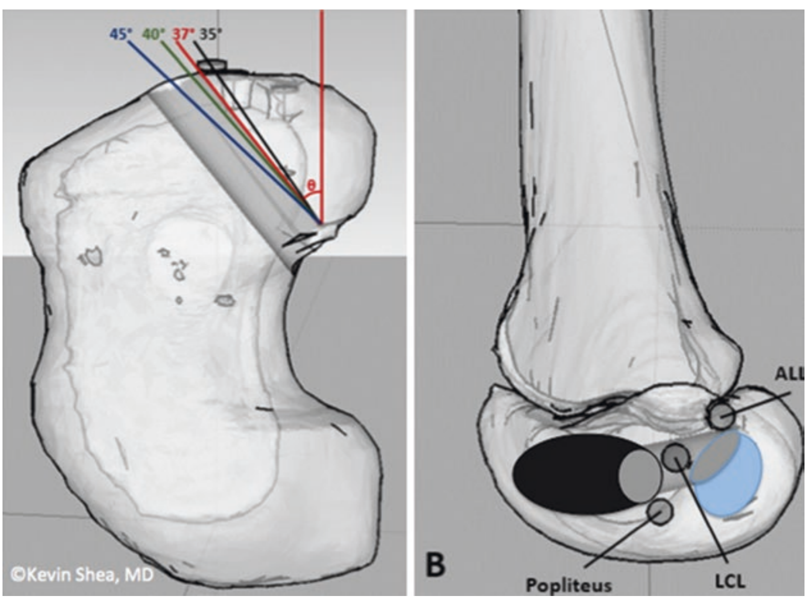

Fig. 3.11 An 8-year-old male, left knee, axial (Panel **a**) and lateral (Panel **b**) views. Within the femoral epiphysis, a 7 mm “anterolateral” directed tunnel was placed anterior to the LCL, ALL, and popliteus attachments. Drilling angle between 35 and 45° with respect to the posterior femoral condylar axis places the tunnel within the more anterior “safe zone,” defined by the *black ellipse*. The most posterior safe zone can avoid the LCL and other structures at risk, by entering the more posterior “safe zone” defined by the *blue ellipse*

drill hole starting in the ACL footprint angled anterior to the LCL had a larger safe zone compared to tunnels placed with a direct lateral trajectory toward the LCL. With a condyle width of greater than 40 mm, both anterolateral and direct lateral tunnels have a larger safe zone, and full-length tunnels can be placed safely with either orientation (Fig. 3.11). An alternative to full-length drill holes through the condyle is to use partial-length tunnels, which avoid the risk of direct injury to lateral ligament/tendon structures (Fig. 3.11b).

To improve tunnel placement during all-epiphyseal technique, a lateral C-arm or other image capture device may be required. A surgical technique uses an appropriate diameter drill hole that matches the ACL graft size diameter with a partial-length tunnel starting anterior to the LCL origin. In contrast to adult reconstruction, in which the minimum soft tissue graft size should generally be 8 mm [44], tunnels as small as 6 mm can be used in younger, smaller patients. In addition, intraoperative compression of ACL grafts can allow surgeons to use smaller tunnels while still achieving optimal graft strength [45]. Proceeding with caution, the tunnel should be created to minimize the risk of causing significant damage to the LCL, ALL, popliteus tendon, distal femoral physis, and posterior condyle articular cartilage (Figs. 3.11 and 3.13) [21].

All-epiphyseal tibial drilling techniques involve placing a tunnel within the ACL attachment footprint [14]. With the ACL inserting in close proximity to the anterior horn of the medial and lateral meniscus, there is a small margin for error for drill hole placement (Fig. 3.14). Anderson et al. [14] used a technique involving passing a 6–8 mm quadruple tendon graft through

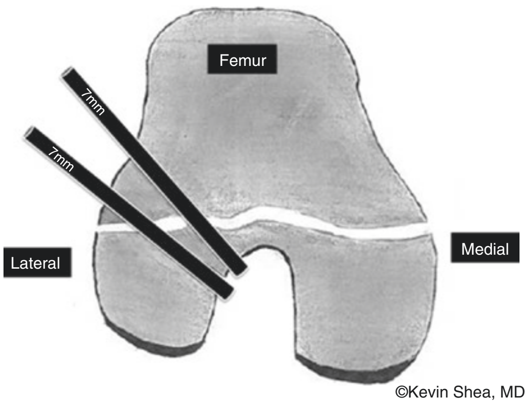

Fig. 3.12 Model showing 7 mm drill tunnel placement through the physis. Adapted from Volumetric injury of the physis during single-bundle anterior cruciate ligament reconstruction in children: a 3-dimensional study using magnetic resonance imaging. *Arthroscopy.* 2009;25 [18]:1415–1422. Shea KG, Belzer J, Apel PJ, Nilsson K, Grimm NL, Pfeiffer RP

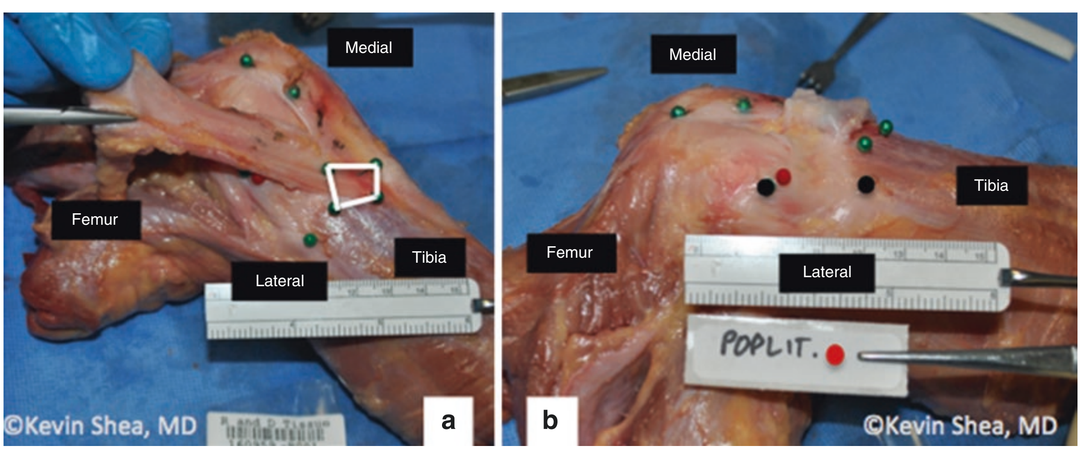

Fig. 3.13 (**a**) Side views of a disarticulated 5-year-old male, left knee. Metallic push pins mark the proximal, distal, medial, and lateral extents of the iliotibial band insertion (**a**, *white box*). (**b**) The iliotibial band has been reflected, revealing the LCL and popliteus insertion/attachment on the femoral condyle. LCL (*black pins*) and popliteus tendon (*red pin*) are identified

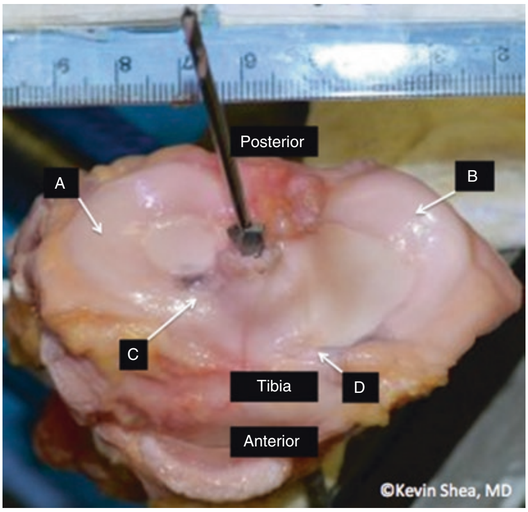

Fig. 3.14 Top-down view showing all-epiphyseal tibial tunnel placement. Lateral meniscus body (**a**), medial meniscus body (**b**), anterior horn of the lateral meniscus (**c**), and anterior horn of the medial meniscus (**d**) are shown. This drill hole orientation/position can avoid the following: (1) anterior meniscus horns/root regions, (2) the joint surface, (3) the proximal tibia physis

a tunnel located at the free edge of the lateral meniscus and posterior footprint of the ACL of the tibia (Fig. 3.14). Both cadaveric and three-dimensional modeling studies have shown that these drill holes can be placed safely, avoiding injury to the articular joint surface, the tibial physis, and the anterior meniscus root regions (Fig. 3.10). This all-epiphyseal ACL reconstruction procedure has shown excellent outcomes, without physeal growth disruption [14].

Some surgeons have avoided physeal injury by using the over-the-top procedure on the femur with an over-the-front position on the tibia [46–48]. Micheli et al. [48] created an algorithm suggesting a preference of treatment modalities for skeletally immature children that have a complete anterior cruciate ligament tear. For asymptomatic patients, the researchers suggested restricting activity and waiting until skeletal maturity to undergo reconstruction. For symptomatic patients, those requiring meniscal repair, or males 14 and older and females older 13 and older, they recommend transphyseal reconstruction with a hamstring autograft. Males younger than the age of 14 and females younger than the age of 13 are suggested to undergo iliotibial graft extra-articular and intra-articular physeal sparing techniques. Their technique involves passing the iliotibial band graft around the lateral femoral condyle and over-the-top position, through the intercondylar notch. The graft continues over a groove in the tibial spine region, passes underneath the transverse ligament of the anterior horns of the menisci, and sutures it to the periosteum of the proximal aspect of the tibia.

Future studies comparing management strategies for ACL injuries in pediatric athletes are needed to better understand the optimal treatment for these young patients using physeal sparing techniques. Prospective studies, including randomized controlled trials and more likely high-quality prospective outcome registries, will be necessary to determine optimal techniques for management of ACL injuries in the skeletally immature.

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The Epidemiology of Pediatric ACL Injuries

4

Krishn Khanna and Nirav K. Pandya

The Youth Sports Culture

Organized youth sports participation has increased tremendously over the past decade with a concurrent drop in school-based physical education [1]. According to the National Council on Youth Sports, nearly 60 million youth between the ages of 6 and 18 participated in organized athletics in 2008 compared with 52 million in 2000 [1, 2]. The National Federation Of State High School Associations has conducted a high school athletics participation survey every year since 1970, and the trends reflect this phenomenon [3]. In the 1969–1970 school year, there were approximately 850,000 high school football players and 50,000 high school soccer players. This number increased to 1.1 million and 790,000 in 2014. This 16-fold increase in the number of soccer players over the last 45 years is even more dramatic when only females are considered. In 1971, only 700 females played soccer, whereas in 2014, there were 375,000 female soccer players in high school.

As a result, a sports culture has developed in our young patients who rather than play a wide variety of sports during the early stages of physical development are specializing in a single sport at younger ages [1, 4, 5]. This has resulted in sporting activity centered on skill development (pitching, kicking, shooting) rather than generalized fitness. This culture has developed even with multiple advocates for delayed specialization [1, 6–9].

Correlated directly with this culture has been an increase in the rate of injury. Rose et al., in a study of 2721 high school athletes, found there was a direct correlation of injury risk with increased weekly hours of sports participation [1, 10]. This is particularly important when considering ACL injuries as the knee is the most commonly injured joint in the young athlete [10]. Hall et al. examined 546 female basketball, soccer, and volleyball players and found that those athletes involved in a single sport had 1.5-fold relative risk increased risk of patellofemoral pain, Osgood-Schlatter disease, and Sinding-Larsen-Johansson syndrome compared with multisport athletes [1, 11]. This is critical as an association has been reported between the development of patellofemoral pain and a subsequent risk of developing ACL injuries later in adolescence [12].

Once thought to be rare, the youth sporting environment has seen a rapid increase in the incidence of pediatric and adolescent ACL injuries [13]. The increased rate of ACL injury in the young age group has been postulated to be due to a desire for early, single-sport specialization coupled with a demand for peak performance during a time of change, particularly physiologi-

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cally, when neuromuscular control and physical fitness may be lacking [14]. In addition, these injuries may now be more readily diagnosed with the availability of MRI imaging [15], particularly with parental demand for such studies.

This chapter aims to examine the factors in the epidemiology of ACL injuries in young athletes, as well as present the risk factors and prevention strategies.

Trends in ACL Injuries

The knee is the second most commonly injured joint in children and the most commonly injured in athletes [16]. Of these knee injuries, approximately one fourth are ACL injuries [17]. Though initially thought to present as tibial eminence fractures, intra-substance ACL tears are now seen with increasing frequency even in skeletally immature patients [18]. Numerous studies have been conducted analyzing the true incidence of ACL ruptures. Even with a large increase over the past several years in database research, a national registry which tracks the exact number of ACL injuries in the United States does not exist.

In the general population, there is an annual estimated incidence of 1 in 3000 Americans suffering an ACL ruptures [19]. A large study analyzing insurance data from a company specializing in soccer injuries found that 22% of all sports injuries occurred in the knee, and of these knee injuries, 31% were ACL tears. The study found that the incidence of ACL injuries has a very distinct correlation with age, comprising only ~1% of all injuries around age 10 and climbing to 13% at age 18 [20]. The increasing trend in the under 20 age group (a change from prior epidemiologic data) was shown by Mall et al. [21]. They performed an analysis of national surveys using billing codes from 1994 to 2006 and found that the incidence of ACL injuries had increased by nearly 130%, with approximately 33 per 100,000 person-years in 1994 up to 43.5 per 100,000 person-years in 2006. Much of this increase came from patients under the age of 20, with rates of 12.22 per 100,000 person-years in 1994 to 17.97 per 100,000 person-years in 2006. This is not surprising given the activity level of these youth and the demands they place on their knee.

Perhaps the most comprehensive look at the true incidence of ACL tears in the young-age, active cohort comes from the National High School Sports-Related Injury Surveillance Study, spearheaded by Comstock et al. The data collection, originally developed as a corollary to the NCAA Injury Surveillance System, uses a large national sample of high school athletes to perform epidemiologic analysis of all time-loss injuries in this population. The 2015 report showed that 1.2 million injuries occur from high school sports, over 160,000 involving the knee. ACL injuries are the second most common, behind MCL injuries, and account for a quarter of all knee injuries [17].

A study using this same data set looked specifically at the epidemiology of knee injuries from 2005 to 2010 [22]. They found that approximately 20% of knee injuries required surgery, and of those 65% were for ligamentous injuries. ACL injuries were season ending in nearly half of the athletes who sustained them. Another study using the same data set showed that 76% of ACL injuries resulted in surgery [16]. It also commented on the mechanism of injury with player-to-player contact accounting for 42.8% of injuries and noncontact accounting for 37.9%. The injury mechanisms due to contact occurred with the ground or playing apparatus. This mechanism is different from what is often reported in other studies analyzing adult ACL injuries where noncontact mechanisms resulted in the majority of ACL injuries.

Yet, many of these larger epidemiologic studies solely contain data in regard to age and not degree of skeletal maturity, a key component in determining the type of intervention in this population. Although there has been much recent interest on the skeletally immature population, this still group accounts for only 0.5–3% of ACL injuries [23].

Werner et al. examined trends in pediatric ACL injuries via an analysis of a private insurance claims database from 2007 to 2011. The diagnosis of pediatric ACL injuries each year was compared with the increase seen in adults. From 2007 to 2011 in both the 10–14-year-old and 15–19-year-old age cohorts, there were significant increases in the incidence of ACL injuries when compared to adults; the 10–14-year cohort increased by 19% and the 15–19-year cohort by 18% [18]. These same trends were also seen when examining pediatric ACL reconstructions using the New York Statewide Planning and Research Cooperative System over the course of 20 years, from 1990 to 2009 (Fig. 4.1). Though geographically limited, the authors found a steady increase in pediatric ACL reconstructions in the state, with rates of 17.6 per 100,000 in 1990 to 50.9 in 2009 [24].

As a result, not only is there an increase in the incidence of ACL injuries occurring in the pediatric population but also reconstruction as the method of treatment, perhaps due to the desire to both prevent chondral damage and return patients to sport.

Sport-Specific Risks

An essential part of understanding the increasing trend of pediatric ACL injuries is not simply understanding the rise of single-sport specialization but also the risk factors associated with specific sports that are played by pediatric athletes.

The National High School Sports-Related Injury Surveillance Study found the incidence of knee injuries to be 2.98 knee injuries per 10,000 athletic exposures, with an athlete exposure

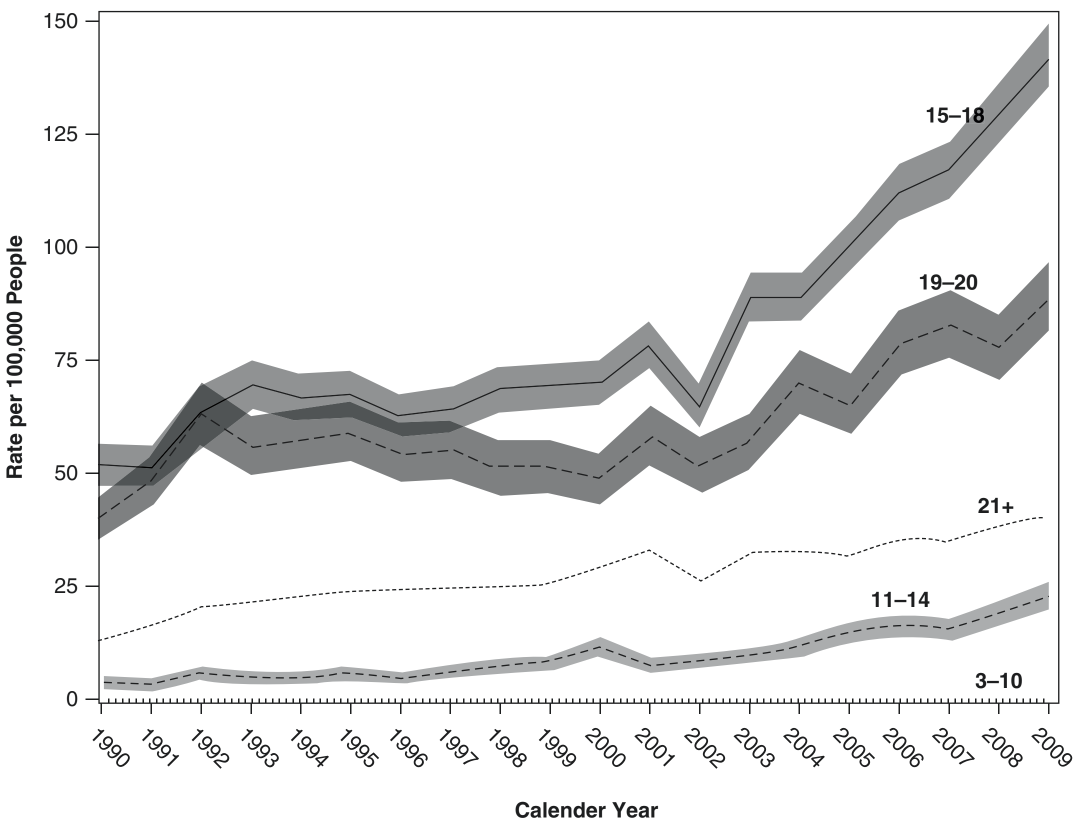

Fig. 4.1 Rate of anterior cruciate ligament reconstructions per 100,000 people stratified by age group in the pediatric population (aged 3–20 years) in New York State, 1990–2009. Shaded areas indicate 95% confidence intervals for rates. (With permission from Dodwell ER, Lamont LE, Green DW, Pan TJ, Marx RG, Lyman S. 20 Years of Pediatric Anterior Cruciate Ligament Reconstruction in New York State. Am. J. Sports Med. 2014;42:675–80.)

defined as a single practice or competition [22]. As may be expected, competition had a significantly higher risk of leading to a knee injury than practice (RR = 3.5) in nearly every sport. Boys football, girls soccer, and girls gymnastics had the highest rates of knee injuries: 6.3, 4.5, and 4.2 injuries per 10,000 athletic exposures, respectively. In competition, these numbers increased drastically for football, girls soccer, and girls gymnastics: 21.1, 10.8, and 9.4 injuries per 10,000 competitive exposures, respectively. ACL injuries comprised 25.4% of all knee injuries, and the highest numbers were seen with the same sports: boys football and girls soccer had 1.17 ACL injuries per 10,000 athletic exposures, and girls gymnastics had 1.14.

In addition, Gornitzky et al. performed a review of the literature to determine specific ACL injury rates in high school patients per 1000 athletic exposures (Table 4.1). A total of 700 ACL tears in over 11 million exposures were analyzed. Football and soccer were again found to be the sports with the highest incidence of ACL injury, with 0.089 and 0.099 injuries per 1000 athletic exposures, respectively. These values are similar to those quoted in the National High School Sports-Related Injury Surveillance Study. Other sports with increased rates of the ACL injury were basketball (0.055 ACL injuries per 1000 exposures), lacrosse (0.063 ACL injuries per 1000 exposures), and field hockey (0.048 ACL injuries per 1000 exposures) [25].

Hence, one could argue that special attention should be placed toward these sports in regard to injury prevention.

Gender Differences

In addition to risk as it relates to the specific sport played, gender also represents a risk factor for ACL injury. The difference in risk for ACL tears based on gender has been quoted in numerous studies, ranging from two to nine times greater for women than men [25]. This same difference is seen throughout the literature for pediatric ACL injuries [15–18, 20, 22, 23, 25–32]. Database analyses have verified these differences as well. Comstock et al. in the National High School Sports-Related Injury Surveillance Study found that female ACL tears comprised 35.1% of knee injuries, whereas male ACL tears comprised

Table 4.1 ACL tear incidence and risk per season by sport and sex (With permission from Gornitzky AL, Lott A, Yellin JL, Fabricant PD, Lawrence JT, Ganley TJ. Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes: A Systematic Review and Meta-analysis. Am. J. Sports Med. 2015;0363546515617742)

ACL tear incidence and risk per season by sport and sex[a]										
	Female				Male					
Sport	Incidence[b]	95% CI	Risk per season[c]	95% CI	Incidence[b]	95% CI	Risk per season[c]	95% CI	RR[d]	95% CI
Basketball	0.091	0.074–0.111	0.9	0.7–1.1	0.024	0.016–0.034	0.2	0.2–0.3	3.8	2.5–5.8
Field hockey	0.048	0.013–0.124	0.4	0.1–0.9						
Football					0.089	0.079–0.101	0.8	0.7–0.9		
Lacrosse	0.070	0.026–0.152	0.5	0.2–1.2	0.058	0.023–0.119	0.4	0.2–0.9	1.2	0.3–4.2
Soccer	0.148	0.128–0.172	1.1	1.0–1.3	0.040	0.029–0.055	0.3	0.2–0.4	3.7	2.6–5.3
Softball/ baseball	0.027	0.016–0.043	0.2	0.1–0.3	0.003	0.001–0.010	0.03	0.01–0.1	7.9	2.3–41.7
Volleyball	0.018	0.010–0.029	0.1	0.1–0.2						
Wrestling					0.021	0.012–0.034	0.2	0.1–0.3		
Overall	0.081	0.073–0.091	0.7	0.6–0.7	0.052	0.047–0.057	0.4	0.4–0.5	1.6	1.3–1.8

[a]ACL, anterior cruciate ligament; RR, relative risk
[b]Incidence expressed as ACL tears per 1000 exposures
[c]Calculated risk per single athletic season per athlete expressed in percentage
[d]Female RR per exposure as compared with males calculated for sex-comparable sports where possible

only 19.0% of all injuries [17]. These differences hold true even when controlling for the sport played. A study analyzing insurance data from a company specializing in soccer injuries found that of all knee injuries, 37% of ACL tears were female and 24% were male [20].

There are a number of theories behind the causation of this gender differential risk which have been thoroughly examined in the adult and pediatric literature. The differences can be divided into intrinsic anatomic factors of the knee, extrinsic biomechanical factors of the surrounding muscles, and hormonal factors [33, 34]. The first intrinsic factor often cited is the increased Q angle in female [35]. A second risk factor is narrow notch width. A narrow notch is thought to result in impingement of the ACL, placing the athlete at risk for rupture. Notch width values of <17 mm have been found to be associated with increased ACL injury [36], and women have been found to have narrower notch width indices when compared to men. This has also been verified with CT imaging [37].

Extrinsic factors, namely, the biomechanical forces exerted on the knee joint by the quads and hamstrings, are also thought to contribute to the increased risk for ACL injuries seen in females. Female athletes preferentially fire their quads over their hamstrings when encountering anterior tibial translation. This is different from nonathletes and male athletes who compensate for this translation with hamstring activation [38, 39]. This differential neuromuscular activation also results in different jumping and landing mechanics. Studies have found that female athletes have a tendency of landing from a jump in increased extension, thus increasing the forces that are exerted across the knee and increasing the chances of an injury [40]. Laxity of the musculature and capsule of female knees relative to males has also been implicated in allowing for the rotational moment leading to ACL injury [41].

Fortunately, interventions exist to correct these extrinsic differences and can be particularly beneficial for young female athletes [42–46]. The most consistently successful intervention is the implementation of a neuromuscular training program, which includes strengthening, stretches, and warm-ups, focusing on increasing the control of certain muscle groups and improving the biomechanics of landing [44]. In a recent meta-analysis, Myer et al. found that the impact of these prevention programs was influenced by the age of the participant. Those who participated in the prevention program had half the probability of an ACL injury than those who did not, and participants in their mid teens (14–18 years) had a 72% reduction in their risk of ALC injury compared to late teens (18–20) who had a 52% reduction in their risk [46].

Associated Injuries

Once the culture in which these injuries take place is understood and the risk factors are identified, it is important to note that additional injuries can oftentimes be just as debilitating for the pediatric athlete who has many years of high-impact sporting activity ahead of them. These include medial and lateral meniscus tears as well as chondral injuries.

Werner et al. in their private insurance claims database analysis from 2007 to 2011 found the incidence of concomitant injuries/treatment increased over the same time period as ACL injuries. Increases in the meniscus repair and debridement from 2007 to 2011 in the 10–14-year and 15–19-year cohorts were significant when compared to adults. Approximately 50% of all patients from ages 15 to 19 with ACL tears who underwent intervention also had a partial meniscectomy, and 25% of patients from 10 to 19 had a meniscal repair [18].

The incidence of these secondary injuries increases with the amount of time the knee remains unstable [47–51]. Millett et al. demonstrated that delays in surgery as little as 6 weeks were associated with an increased incidence of medial meniscus tears [47]. Lawrence et al. found similar results in delays greater than 12 weeks as well as an increased incidence of lateral hemi-joint chondral injuries [48]. More recently, Newman et al. further analyzed the risk factors for these secondary injuries and found that in younger patients (<14 years of age), a delay greater than 3 months was most predictive of secondary chondral injuries [51]. To achieve more granularity in this timing, Anderson et al. classified repairs into acute (<6 weeks after injury), subacute (6–12 weeks), and chronic (>12 weeks) and found worsening damage of both the cartilage and meniscus with increased time [49]. Thus, when examining pediatric ACL injuries, care should be taken to recognize that there is a significant incidence of secondary injuries which are exaggerated by delays in care, perhaps reflecting the trend toward more surgical intervention in this population.

Outcomes

Although the treatment of these injuries will be covered extensively in the following chapter, it is essential to note that treatment of these injuries is critical. A number of recent studies have examined the outcomes of ACL reconstructions in pediatric patients, both skeletally immature and mature, and have found positive results [52–56]. Traditionally, ACL injuries in skeletally immature athletes were treated conservatively with bracing and activity modification until the patient was near maturity, for the fear of physeal injury with growth disturbance.

In 2002, Aichroth et al. published a prospective study examining the outcomes of ACL ruptures in children and adolescents who were treated with and without surgery. Of the patients treated conservatively, nearly half showed radiographic signs of degeneration before they reached 20 [57]. The marked degeneration seen in pediatric ACL deficiency can likely be attributed to the noncompliance with activity modifications and exuberant sporting activity that these patients engage in despite the inherent instability of the knee.

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Assessment of Skeletal Maturity

5

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General Principles

Understanding skeletal maturity is the key when planning safe anterior cruciate ligament (ACL) surgery in a growing adolescent. The growth plates of the knee remain open until approximately the age of 19 in males and 17 in females; however, there is little growth after the age of 16 in males and 14 in females. Historically, when treating a child or adolescent with an ACL injury, surgeons have used the chronological age, skeletal age, and physiologic age of the patient to determine the safest treatment. Skeletal age and physiologic age are more accurate than chronological age, and both skeletal age and physiologic age have been used to decide whether to perform a physeal-sparing ACL reconstruction, a transphyseal reconstruction with a soft tissue graft, or a transphyseal reconstruction using a bone-patella tendon-bone graft. Skeletal age may be determined by multiple techniques: an anterior-posterior (AP) radiograph of the left hand and wrist compared to the Greulich and Pyle atlas, the Tanner and Whitehouse method, the shorthand bone age assessment method, or AP and lateral radiograph of the knee compared to the Pyle and Hoerr atlas. Physiologic age is typically determined by the Tanner staging system. Each of these techniques is discussed in more detail below. Using the skeletal age and/or physiologic age, there are several methods to determine growth remaining and potential leg length discrepancies. The most commonly used are the Menelaus arithmetic method and the Anderson-Green (growth remaining) method. Lastly, the biologic marker in female patients of the onset of menses is also helpful. Once a female athlete has started menses, about 2 years of skeletal growth remains. A similar biological growth marker in males does not exist. By becoming familiar with techniques for measuring skeletal age and physiologic age and for determining growth remaining, the orthopedic surgeon can plan and implement the optimal treatment for the patient while minimizing the risk of growth plate injury.

Skeletal Age

Greulich and Pyle Method

Skeletal age is most commonly determined from an AP radiograph of the hand and wrist compared to the Greulich and Pyle atlas [1]. The atlas was published in 1959 based on radiographs obtained between 1931 and 1942 of over 1000 children in Ohio taken at intervals of 3–12 months from birth to skeletal maturity. Greulich and Pyle used these

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radiographs to create an atlas standard for skeletal development based on the changes that occur at the physes of the hand and wrist bones. The atlas includes a separate section for males and females to account for the differences in development by gender (Fig. 5.1). Age estimates based on the developing skeleton are derived from four events: bone measurements, the appearance of ossification centers, the fusion of the epiphysis, and the morphological changes that epiphyses undergo during maturation [2]. By obtaining a left hand and wrist AP radiograph and matching that image to the one most closely resembling it in the atlas, one can determine the skeletal age of the child. Greulich and Pyle include standard deviations demonstrating the extent of variation that was observed in skeletal development. The accuracy of the Greulich and Pyle atlas has been questioned because the ethnicity, diet, and socioeconomic factors of children in 1950 in Ohio when the atlas was first published are not the same as in children in various locations today [3]. Ancestry and nutrition affect growth and development [4, 5]. Ethically it is no longer possible to repeat the collection of longitudinal radiographs which allowed for creation of maturational atlases in the past. However, today, the ease of obtaining a left hand and wrist AP radiograph and the availability of the atlas make the Greulich and Pyle technique the most common method of determining skeletal maturity for orthopedic surgeons.

Fig. 5.1 Left hand and wrist bone age of a 12-year-old female athlete who has had menstrual periods for 15 months demonstrating an advanced skeletal age of 13

Tanner and Whitehouse Method

The Tanner and Whitehouse method also uses a left hand and wrist AP radiograph to determine skeletal age [6]. Certain bones are “regions of interest.” Twenty regions of interest (ROIs) in the hand are examined. Each ROI is divided in three parts: epiphysis, metaphysis, and diaphysis. The development of each ROI is divided into discrete stages, and a numerical score is given for each stage of each bone. By adding the scores of all ROIs, an overall maturity score is obtained and a skeletal age is determined. One author suggests that the Tanner and Whitehouse method may be more accurate than the Greulich and Pyle atlas [7]. In fact, the Tanner and Whitehouse method is used in pediatric endocrinology to determine response to hormone therapy. However, the complexity of this method and the added time to make the calculations are prohibitive for most orthopedic surgeons.

Shorthand Bone Age Method

The shorthand bone age (SBA) method is a simplification of the Greulich and Pyle method. This method was published in 2013 by Heyworth and is based on a single left hand and wrist AP radiograph [8]. Rather than an atlas, two charts are used one for males and one for females. Certain specific findings on the hand and wrist radiograph correlate with specific ages. When using the SBA technique, a single radiographic finding that correlates with skeletal age is identified rather than multiple findings as per the Greulich and Pyle method. The SBA method can be used to determine bone age for males age 12.5 through 16 and for females age 10 through 16 (Fig. 5.2a, b). These ages correspond nicely to the ages of clinical concern with pediatric ACL injuries. Heyworth et al. reported that the SBA method was a simple and clinically efficient alternative to the traditional Greulich and Pyle method [8].

Pyle and Hoerr Method

Alternatively, rather than using an additional radiograph of the left hand and wrist, skeletal age can be estimated from the anterior-posterior and lateral knee radiographs compared to the Pyle and Hoerr atlas [9]. This atlas was published in 1969. The organization and design of the atlas follow that of the more commonly known atlas of Greulich and Pyle. Knee radiographs were performed on thousands of children at 3-month intervals from early childhood to maturity on the same children in Ohio that had been utilized to create the hand and wrist atlas. The Pyle and Hoerr atlas was designed by examining knee radiographs in chronologic order to identify progressive maturity indicators and assign a skeletal age. The authors recognized the differences in developmental timing between males and females, but, unlike the Greulich and Pyle atlas, the Pyle and Hoerr atlas published only one set of radiographs for both genders. Each radiograph was assigned two skeletal ages, one for males

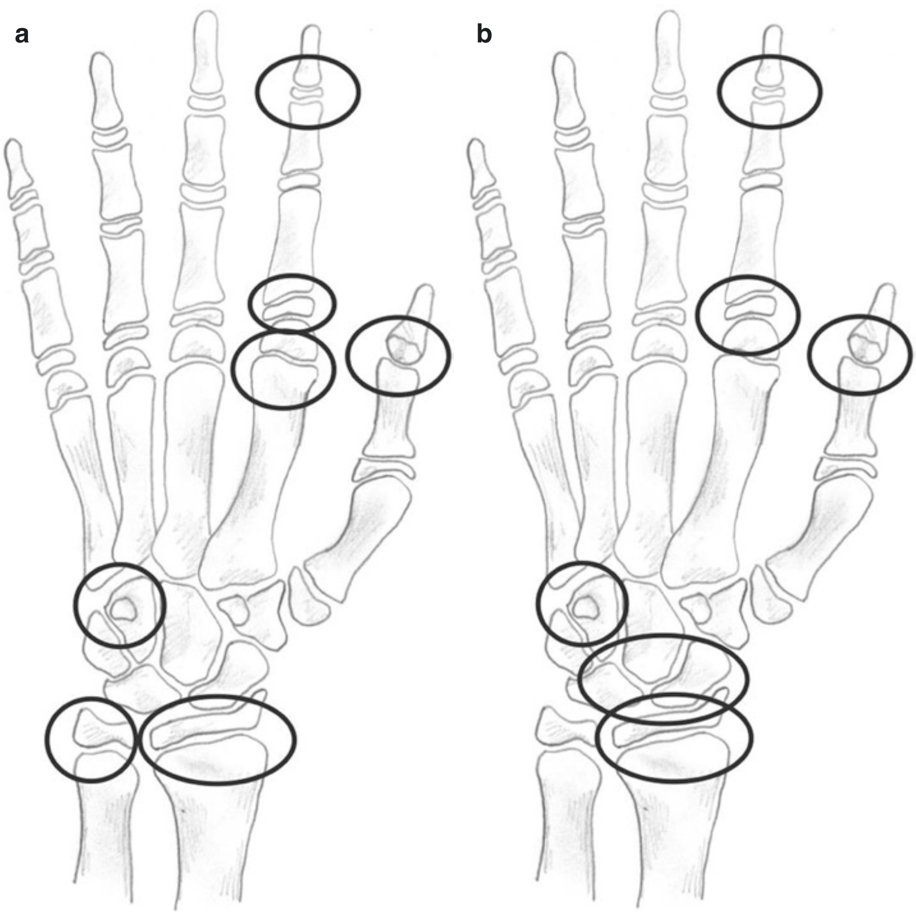

Fig. 5.2 Shorthand bone age in (**a**) females and (**b**) males. Radiographic findings that correlate with encircled windows correlate with skeletal age noted in Ref. [8]

and one for females. The authors reasoned that the process of maturational changes and the order of appearance of maturational indicators were the same for the two sexes [9]. The Pyle and Hoerr atlas did not include standard deviations. Similar criticisms about ethnicity, diet, and socioeconomic factors relate to the knee atlas as to the hand and wrist atlas. In addition, the knee atlas has not been tested as extensively as the hand and wrist atlas and has not gained widespread popularity. However, if the Pyle and Hoerr atlas is available to the treating surgeon, knee bone age can be considered a useful alternative to the use of more traditional left hand and wrist radiographs.

Physiologic Age

Tanner Staging

Tanner staging is a method to define the physical measurements of a child's development based on genitalia and pubertal hair [6, 10–12]. For girls, the breast stages are as follows: stage 1, elevation of the papilla only; stage 2, breast bud and enlargement of the areola; stage 3, enlargement of the breast and areola; stage 4, projection of the areola to form a secondary mound; and stage 5, mature stage. The pubic hair stages for girls are as follows: stage 1, no pubic hair; stage 2, sparse growth; stage 3, darker and coarser hair; stage 4, adult-type hair but no spread to the medial surface of the thighs; and stage 5, adult quantity and type (Fig. 5.3). The genitalia stages for boys are as follows: stage 1, prepubescent; stage 2, enlargement of the scrotum and testes and change in texture of the scrotal skin; stage 3, growth of the penis, testes, and scrotum; stage 4, further enlargement and development of the glans; and stage 5, adult size and shape. The pubic hair stages for the boys are as follows: stage 1, no pubic hair; stage 2, sparse growth of hair at the base of the penis; stage 3, darker and coarser hair; stage 4, adult-type hair but no spread to the thighs; and stage 5, adult quantity and type (Fig. 5.4).

Although Tanner staging is helpful and provides information regarding the physiological age of the patient, Tanner staging does not correlate with skeletal age [13]. In addition, Slough et al. reported that most orthopedic surgeons are unable to accurately and reliably determine Tanner staging [14]. If Tanner staging is indicated in the athlete's workup by the treating orthopedic surgeon, then evaluation of Tanner staging by the primary care physician or by an endocrinologist may be helpful. In addition, one author reported that the teenage patient can reliably self-assess their Tanner stage using Tanner's standard photographs [15].

Estimation of Potential Leg Length Discrepancy

The growth plates of the distal femur and proximal tibia provide more longitudinal growth to the child's lower limb than any other growth plates. For example, the distal femoral growth plate provides 9 mm of growth per year, and the proximal tibial growth plate provides 6 mm of growth per year. Iatrogenic injury to these growth plates in a young athlete with drill holes during an ACL reconstruction can potentially cause significant shortening or angulation of the limb. There are four common methods to estimate leg length discrepancy: the Menelaus arithmetic method, the Anderson-Green growth remaining method, the Moseley straight-line graph method, and the Paley multiplier method. Each will be described in detail below.

The Menelaus arithmetic method described in 1966 is the simplest method and is based on general principles when determining how much growth remains around a patient's knee [16]. The principles are skeletal growth ends at age 16 in boys and at age 14 in girls, and the distal femur provides 9 mm of growth per year, and the proximal tibia provides 6 mm per year. Although the Menelaus method does not take into account the fact that the growth rate of the physis is not constant, this method is appealing to most orthopedic surgeons because of its simplicity—the Menelaus method does not require special graphs or complex calculations.

The Anderson-Green growth remaining method is based on data from 100 children in

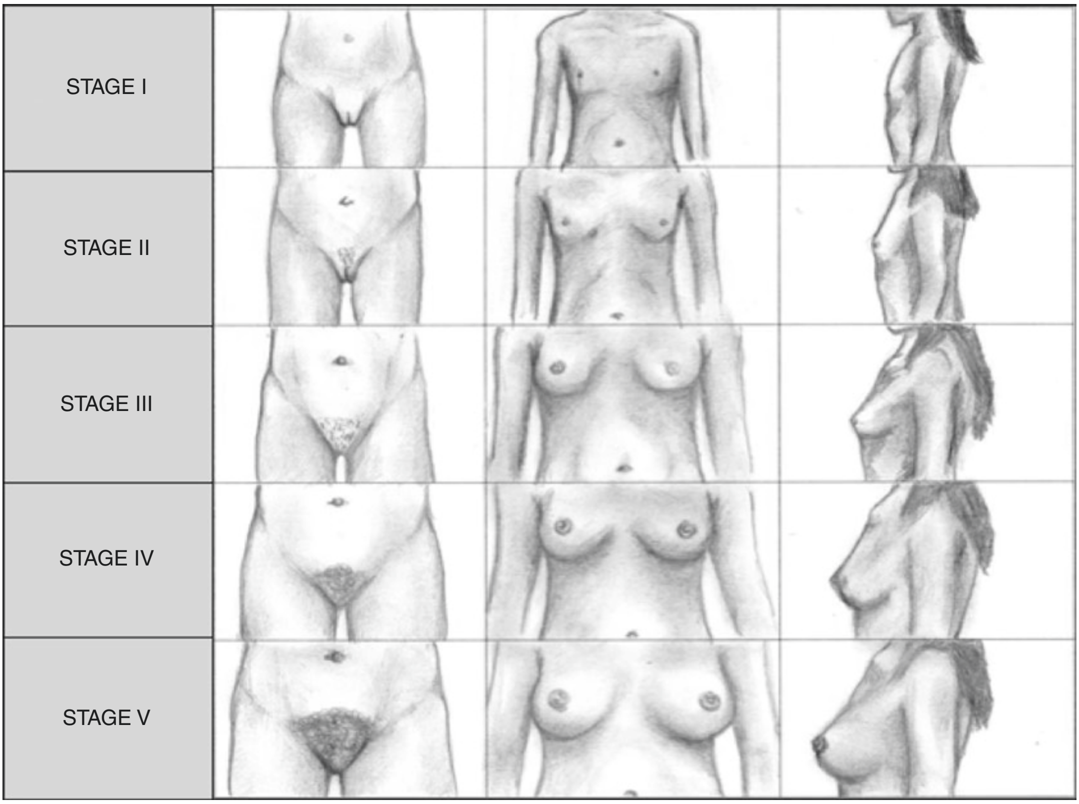

Fig. 5.3 Female Tanner staging including breast, areola, and pubic hair development

1963 [17]. Skeletal age was plotted against growth remaining of the distal femur and the proximal tibia with one chart for boys and one for girls. Each Anderson-Green graph has five lines, one for the mean, one for 1 standard deviation above and below the mean, and one for 2 standard deviations above and below the mean. This method requires the use of left hand and wrist radiographs for bone age via the Greulich and Pyle atlas and then using the bone age to plot the graph. The Anderson-Green information was collected on a small group of patients in one area more than 50 years ago. As such, the charts are helpful but cannot be regarded as completely accurate today.

The Moseley straight-line graph method was described in 1977 as a way to improve the growth remaining method [2]. The data from the Anderson-Green growth remaining method was mathematically reformatted into straight-line graphs representing limb lengths. Although the Moseley method is slightly more accurate than the growth remaining method [2], the use of the Moseley method for ACL surgery is limited by the need to plot multiple data points over time. In addition, both the growth remaining and straight-line graph method are based on data collected on children at Boston Children's Hospital in the 1940s and 1950s and may not be as accurate when used for different ethnicities today [18].

Lastly, the Paley multiplier method is the most recent way to estimate leg length discrepancy [19]. This method is based on multiple limb length databases to calculate a multiplier for each limb that can be used with a patient's chronological age to determine the growth remaining. Bone age data is not utilized. Unlike the Moseley technique, the multiplier method allows prediction based on a single point in time. Paley has published different tables of multipliers for males and females. Overall, the multiplier technique is simple and as accurate as the other techniques [20].

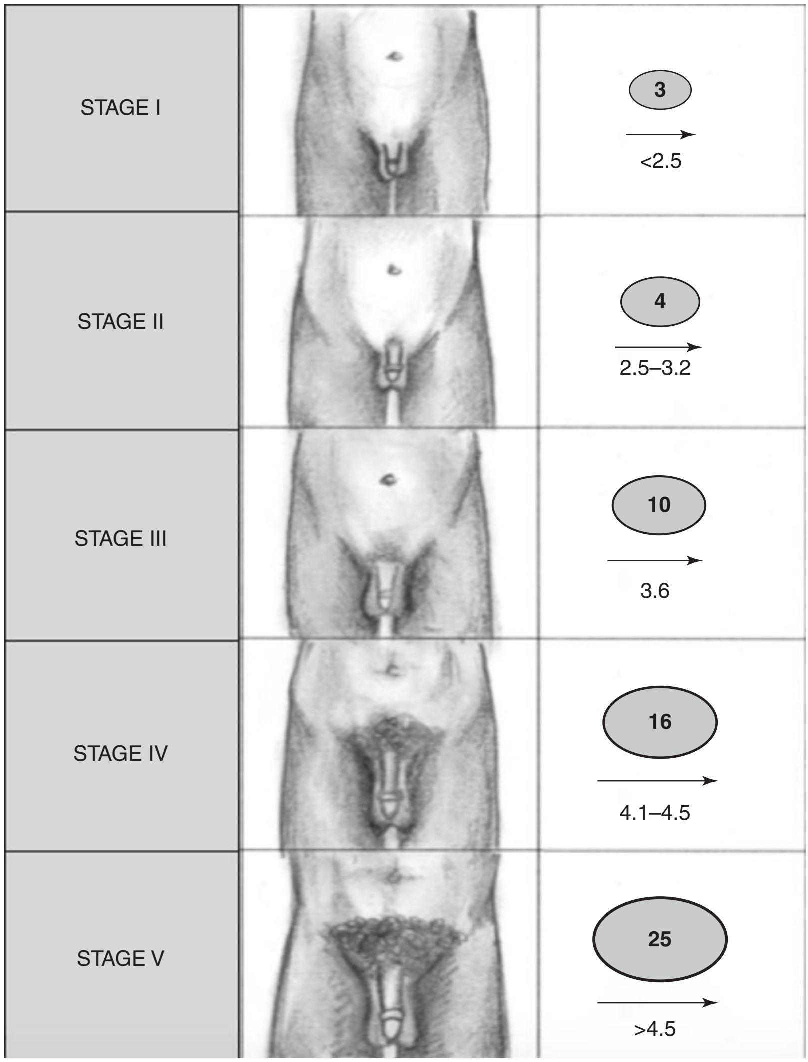

Fig. 5.4 Male Tanner staging including pubic hair distribution, penile shaft length and width, and testicular diameter and volume

Conclusion

Orthopedic surgeons performing ACL reconstructions on skeletally immature athletes must understand the potential risks to the growth plate, the methods of measuring skeletal maturity, and the methods for estimating growth remaining. Using the information provided in this chapter, one can more prudently proceed with safe treatment of an ACL tear in a skeletally immature patient. The authors currently utilize the following algorithm. In a child with a bone age of 12 years old or less in a male and 11 years old or less in a female and Tanner stage 1 or 2, a physeal-sparing or all-epiphyseal ACL reconstruction technique is recommended. In an adolescent with a bone age of 13–15 in a male or 12–13 in a female and a Tanner stage 3 or greater, a transphyseal ACL reconstruction with a soft tissue graft with fixation at the metaphysis is recommended. Lastly, in an older adolescent with closing physes with a bone age of 16 or older in a male and 14 or older in a female and Tanner state 4 or 5, a transphyseal reconstruction with bone-patella tendon—bone or a soft tissue graft can be utilized. The authors utilize a left hand and wrist AP radiograph to determine the skeletal age of the patient either by the use of the Greulich and Pyle atlas or the shorthand bone age assessment. The projected growth remaining is determined by the use of the Menelaus technique or Paley multiplier technique. When indicated, physiologic age by Tanner staging is performed by a primary care physician. By carefully determining the skeletal age and growth remaining, one can offer the patient and her family a graft choice and ACL reconstruction technique that minimize the risk of growth injury.

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Clinical Evaluation of ACL Tear

6

Julien T. Aoyama, Jermonte Lowe, Anthony C. Capraro, and Lawrence Wells

Introduction

The anterior cruciate ligament or ACL is a structure in the knee that serves to control both anterior translation of the tibia on the femur and rotation of the knee joint. ACL injuries are fairly common with an estimated 80,000–250,000 incidences a year with 0.5–3% of those occurring in children and adolescents [1–3]. It was previously thought that ACL tears were predominantly found only in older populations, with pediatric and adolescent patients suffering more from tibial avulsion injuries rather than true midsubstance tears of the ligament. However, recent studies have shown that midsubstance ACL tears in pediatric patients have in fact slowly become more common [4]. A recent study by Ganley et al. looked at high school athletes and found that on average if they play a sport all four seasons for 4 years, they have an 11.2% and 6.4% risk of tearing their ACL for girls and boys, respectively [5]. This injury rate goes up even higher for certain sports such as girls' soccer, girls' basketball, and girls' football. While some believe these rising incidences of ACL tears are due to increasing numbers of young athletes focusing more and more on a single sport while doing so year round, others believe that it is due to increased awareness and more accurate diagnoses of pediatric ACL tears [6].

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Diagnosis

The types of functional ACL injuries can include tibial spine avulsion fractures to partial ACL tears to complete ACL tears, with partial tears ranging from 10 to 50% of all ACL injuries [7]. And although ACL injuries are one of the most well-researched orthopedic injuries to date, there are still many debates about the best treatment options for these injuries, including nonoperative vs. operative, surgical technique and graft choice [8]. In this chapter we will limit discussion to the clinical evaluation of diagnosing an ACL tear.

Many factors can lead to challenges in making an accurate ACL injury diagnosis in a pediatric patient. A range of ACL injury types as mentioned above coupled with the difficulty in effectively gathering information about injury conditions due to the age of patients along with fear of pain or difficulty in cooperating during physical exam can all lead to making an accurate diagnosis challenging [3]. And while diagnosing complete ACL tears can be relatively more straightforward, diagnosing partial ACL tears can prove especially challenging in pediatric patients. The injury history of a partial ACL tear may not be terribly revealing or suggestive; patients do not always report the classic symptoms or injury mechanism seen often in

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full ACL tears, and clinical exam, arthrometry (KT-1000), and radiographic imaging results may be subtle or limited in their utility. As with any diagnosis, an accurate ACL tear diagnosis is best determined after correlating all the available information: the patient history, physical examination, imaging studies, and any arthrometric measurements that may be available [1]. The following pages outline each of these aspects of the clinical evaluation in further detail.

Patient History

A physician should always elicit and review previous medical history when evaluating a patient to help determine the correct diagnosis. It should be noted whether there have been any prior injuries to the knee, previous treatments, and all outcomes of those treatments if received. Building an understanding of the previous history gives a better idea of what may be causing or contributing to the current patient condition and aids accurate diagnosis. The next step should be to obtain the history of current injury from the patient, including the mechanism and circumstances surrounding the injury. For older patients, obtaining an accurate history and mechanism of injury may be more reliable, but for younger pediatric and adolescent patients, correlation with a parent or other witness can prove invaluable in building an accurate understanding of the injury circumstances [3]. Nowadays especially at many sporting events, video footage is available, and the videos that patients bring in can be particularly elucidating. Even videos on cellphones can be helpful in determining the mechanism of injury as most phones these days have high-quality cameras.

The most common injury mechanism for an ACL tear is a noncontact pivoting movement, while the foot is planted with the knee in slight flexion [1, 3, 8]. Other possible but less common mechanisms of ACL injury include hyperextension with valgus or rotational force and, far less commonly, extreme hyperflexion or hyperextension of the knee [4, 8]. Often seen during sports such as football, soccer, or basketball, patients will describe how they tried to change speed or direction quickly and felt their knee give away [4]. Common history elements for ACL tears include running, jumping, cutting, “snapping,” “buckling,” “giving out,” or “popping” sensations in the knee [1, 3, 8]. Inability to bear weight, inability to return to play, swelling, and hemarthrosis are usually strong markers of a significant knee injury, and it should be noted whether the patient fell at the time of their injury, whether they were able to get back up on their own or required assistance, and whether they were able to return to sport activities at that time [3, 8]. While pain, swelling, and instability after an ACL injury often prevent weight bearing, it is not unheard of that patients with tears, especially partial tears, are able to return to competitive play within a week or sometimes even the same game. In fact some studies have found that upwards of 15% of patients with ACL tears, whether partial or complete, were able to return immediately to their sport after injury [9].

Physical Examination and Concomitant Injuries

After history has been obtained, a physical examination should be performed. The patient should be wearing shorts during examination rather than long pants, which even when rolled or held up obscure the knees, thighs, and entire lower extremity from being evaluated all at once. The physical exam should begin with a general standing alignment evaluation. Any underlying leg length inequalities and/or anatomic genu varum or genu valgum should be noted at this time. The contralateral side should be evaluated first, followed by the affected side in order to establish baseline for the patient.

Inspection for any ecchymosis, swelling, and/or knee effusion of the affected side may then begin. If there is traumatic effusion and radiographs have not been performed, yet they should be performed prior to physical exam to prevent potentially displacing a nondisplaced tibial spine fracture [8]. Once radiographs have been reviewed, the patient may be safely examined.

As mentioned above, acute hemarthrosis of the knee is usually a strong indication of a serious knee injury. In adults around 67% of those with acute hemarthrosis have some degree of ACL tear whether partial (26%) or full (41%) [10]. Studies in children have found that rate is slightly lower around 47% for ages 7–12 but more similar around 65% for adolescents 13–18 [11]. Still others have found these rates to range vastly from as low as 29% in younger populations 18 or younger to over 72% when a wider range of 16- to 44-year-olds are included [9, 12].

Once inspection for ecchymosis, swelling, and/or knee effusion has been noted, a palpation exam may be performed [1, 3, 13]. In cases where the exam is limited due to excessive effusion, the knee can be aspirated first [1]. While palpation of the ACL is not possible, palpation to other structures can provide important information about possible concomitant injuries. In fact around 16% of patients with ACL tears have associated meniscal tears, 30% have medial collateral ligament tears, and 2% have lateral collateral ligament tears [10, 14]. Palpating along the medial and lateral joint line can assess for possible meniscal injury, and palpation at the medial and lateral ligament insertion sites can assess for MCL and LCL injuries. The MCL and LCL can also be assessed further with valgus and varus stress tests, respectively. These tests should both be performed with the knee in extension and once at 30° of flexion. Opening of the joint in extension and at 30° flexion implies posterior capsular injury, whereas isolated collateral ligament injury would lead to joint opening at 30° of flexion. Palpation to the medial and lateral borders of the patella along with a patellar translation test can also be performed on patients with a suspected patellar dislocation [3]. Patellar dislocations can be fairly similar in presentation to the ACL tear, with some studies showing almost identical incidences of these injuries in patients who present with acute hemarthrosis (29% ACL tears and 25% patellar dislocations) [12].

Following palpation exam, basic range of motion of the knee should be examined. Limited flexion or extension ability as well as complaints of "locking" or "catching" can suggest concomitant meniscal injuries or chondral loose bodies. These are more commonly seen in full ACL tears than in partial tears [1]. If locking or catching is found on range of motion exam, further meniscal pathology should be examined with tests such as the McMurray's or Thessaly test. As with any diagnosis, diagnosis for concomitant injuries should be diagnosed only after correlating all available information.

After preliminary inspection, palpation, and range of motion exams have been performed, the physician should perform the specific cruciate ligament tests. The anterior drawer, Lachman (a modified anterior drawer test), and pivot shift test are the three major physical exam tests performed on patients with suspected ACL tears [4].

A brief look through history shows that the Lachman test, named after Dr. John W. Lachman, has actually been repeatedly described by various physicians over the years. As early as 1875, Greek physician George Noulis wrote:

> When the leg was then moved forward and backward, it was found that the tibia will slide anteriorly and posteriorly. When only the ACL was severed, movement of the tibia could be shown when the knee was "barely flexed."

However, it wasn't until 1976 that this universal test became more established after being given its name by Dr. Lachman's student and mentee, Dr. Joseph Torg [15]. In a clinical setting, the Lachman test is the most sensitive of the three tests [16]. With the knee at 30 degrees of flexion and the leg in slight external rotation to relax the hamstring, the lower leg is translated anteriorly. A positive test is when the tibia moves forward and the concavity of the patellar tendon becomes convex [4]. Severity is graded on a three-point scale I, II, or III with a categorical grade of A (firm) or B (soft, absent, or ill defined) [17]. Grade I mild instability is defined as 3–5 mm of translation, grade II moderate instability is defined as 5–10 mm of translation, and grade III severe instability is defined as greater than 10 mm of translation [18]. The Lachman test (as well as the anterior drawer and pivot shift tests) should always be compared to the contralateral side for comparison. Some patients such as those with ligamentous laxity will translate considerably on exam per baseline, and so comparison with the contralateral side will establish this baseline and prevent false positives.

The anterior drawer test, the second most sensitive in a clinical setting, is similar to the Lachman test but performed at 90° instead of 30 [16]. The origin of the test is somewhat unclear, but Malanga et al. note that the same George Noulis who first described what is now called the Lachman test also described the anterior drawer test in his same 1875 doctoral thesis:

> *With the patient's leg flexed [in large degrees of flexion], the thigh can be grasped with one hand at the lower leg with the other hand keeping the thumbs to the front and fingers to the back. If the lower leg is held in this grip and then moved backwards and forwards, it will be seen that the tibia can be moved directly backwards and forwards* [19].

Again, the patient's lower leg is translated anteriorly to check for ACL laxity. A positive test is laxity compared to the unaffected side.

The third test, the pivot shift, is the least sensitive of the three in an acute setting but more useful in the chronic setting or during examination under anesthesia. It is often not performed in the clinic during acute presentation because it is painful for patients to withstand while alert and often causes guarding of the subluxation caused by the maneuver [3, 16]. The pivot shift test is both a clinical phenomenon and a physical sign [19]. Early descriptions of the clinical phenomenon by Hey Groves in 1920 and Palmer in 1938 were later described as a physical sign by Galway et al.:

> *The leg is picked up at the ankle with one of the examiner's hands, and if the patient is holding the leg in extension, the knee is flexed by placing the heel of the other hand behind the fibula over the lateral head of the gastrocnemius…As the knee is extended, the tibia is supported on the lateral side with a slight valgus strain applied to it. The femur falls backwards, as the knee approaches extension and the tibial plateau subluxes forward. In fact, this subluxation can be slightly increased by subtly internally rotating the tibia, with the hand that is cradling the foot and ankle. A strong valgus force is laced on the knee by the upper hand. This impinges the subluxed tibial plateau against the lateral femoral condyle, jamming the 2 joint surfaces together, preventing easy reduction as the tibia is flexed on the femur. At approximately 30° of flexion, and occasionally more, the displaced tibial plateau will suddenly reduce in a dramatic fashion. At this point, the patient will jump and exclaim, "that's it!"* [20]

A modern description begins with the patient's knee fully extended, and while internally rotating the tibia with one hand, the other hand applies valgus stress while gradually flexing the knee [4]. A positive test is if the subluxed anterior tibia snaps back into alignment around 20–40 degrees of flexion due to the pull of iliotibial band [4, 21]. The test is graded I, II, or III with grade I determined by the presence of a glide during the shift, grade II by the presence of a clunk during the shift, and grade III by the presence of gross shifting [22, 23]. For all three tests, physicians should be aware of guarding on exam where the patient voluntarily or involuntarily contracts their leg muscles to prevent painful translation. Guarding can lead to false negatives on cruciate ligament stress testing because true ligament laxity is not being assessed.

Overall, comparing the three tests shows that the Lachman test is the most accurate for diagnosing ACL tears in patients who are alert, with sensitivity ranging from 80% to 99% and specificity at around 95%. Sensitivity of the anterior drawer test on the other hand is relatively low, ranging from 22.2% to 41% in patients who are alert and 79.6% to 91% when performed under anesthesia. It's worth noting that the results of the anterior drawer test seem to be affected by what concomitant injuries are present, namely, the sensitivity of the anterior drawer test seems to increase with loss of secondary restraints of anterior stability in the knee. In one study 54% of those with no other injury, 67% of those with medial meniscus tears, 82% of those with lateral meniscus tears, and 89% of those with MCL injuries had an ACL tear [19]. The relatively low sensitivity of the anterior drawer test on these alert patients should caution examiners from ruling out an ACL tear based only on a negative anterior drawer test (tests should always be correlated, in general) [19]. On the other hand, a positive anterior drawer should be taken as strong evidence of an ACL tear as the specificity of the anterior drawer test is high at around 92% [24]. The pivot shift test, as mentioned above, is not performed as often on patients who are alert due to pain, discomfort, and guarding. Sensitivity of the pivot shift test in patients who are alert can be as low as 35%. However, under anesthesia sensitivity of the pivot shift test is much higher ranging from 84% to 98%, and specificity is around 98% [19].

Arthrometry

Partial tears of the ACL are not always detected on physical exam tests. In fact a study by Hole et al. showed that both the Lachman and pivot shift tests often fail to identify an ACL partial tear, even when up to 75% of the ligament is torn [7, 25]. Thus particularly in partial tear cases where physical exam or imaging studies are unclear, arthrometric measurements can be helpful in providing additional information on the extent of ACL injury.

Since the 1980s, the KT-1000 test has been widely used to examine patients' anterior tibial translation as compared to the unaffected side due to its ease of use [26]. The device measures the anterior translation of the tibia with respect to the femur at 30 degrees of flexion and at various forces. The amount of anterior translation on the unaffected side is used as the patient's baseline, and the difference in translation between the affected and unaffected sides gives the final measurement value in millimeters.

However, studies have found the KT-1000 to be operator dependent and be poorly reproducible, and its results are also debated with some saying that a side-to-side difference of 3 mm is representative of an ACL tear while others look for 5 mm of difference [7, 8, 27]. It's important to note also that a normal KT-1000 measurement by itself does not necessarily preclude injury to a portion of the ACL [1]. Still, due to its ease of use and utility in most cases, KT-1000 tests are often obtained, and it is best to simply use these measurements in supplement with the physical tests and other parts of the clinical exam [28].

Other arthrometric devices have been introduced to help standardize measurements. The GeNouRoB device was introduced by Robert et al. in 2009 to standardize the position of the knee and obtain more accurate translation measurements [7]. Displacement of the anterior tibial tubercle is much more precise as it measures to 0.1 mm [26]. The mechanical advantages of GNRB lie in its feedback programming that restrains thrust force when the hamstring is contracted beyond rest. Hamstring contraction could very well influence results. Also, a neutral knee position is well standardized when using the GNRB [26]. The radiological Telos stress device also seems to be more precise than the KT-1000 [28]. However, the drawbacks of this device are that it exposes patients to radiation and is fairly expensive. When comparing the GNRB and Telos, research has concluded that there is a highly significant difference between the differential laxity of complete and partial thickness tears, with the GNRB being more precise than the Telos regardless of the loading pressure applied [28]. Considering this data, it is important to complete a full exam including Lachman test, anterior drawer test, pivot shift test, radiographs, and MRIs to determine whether a tear is partial or complete and whether the patient needs surgical or nonsurgical intervention.

Radiographic Evaluation

While X-rays cannot directly assess the ACL, it is helpful for assessing potential concomitant injuries, such as tibial spine fractures, Segond fracture, and osteochondral injuries. Prior to physical exam if no radiographic studies have been performed, X-rays are usually first obtained to rule out and prevent potentially displacing a tibial avulsion fracture which is commonly seen with ACL injuries [8]. MRIs are also customarily obtained to further evaluate the extent of the ACL tear as well as concomitant injuries. The next chapter is reserved for the radiographic evaluation of an ACL tear and will discuss this in further detail.

Surgical Arthroscopy

Surgical arthroscopy is an invasive but more definitive way to diagnose and treat ACL tears, and while knee arthroscopy has been shown to be safe for use in both children and adolescents, it should be used fairly judiciously [7, 9, 11]. Some have argued for the use of surgical diagnostic arthroscopy in all pediatric patients with knee hemarthrosis due to its low morbidity and consistent ability to precisely diagnose ACL tears as well as concomitant intra-articular injuries, and some do not even consider arthroscopy to be a surgical procedure [12, 13, 29]. These factors have led some to use arthroscopy liberally on younger patients with knee problems and have unfortunately led to a significant number of "normal" arthroscopies [12]. To study exactly how useful surgical arthroscopies are, a study by Harilainen et al. followed 328 patients who presented with acute knee hemarthrosis and looked at how many of them underwent an arthroscopy that actually influenced the treatment decision based on clinical examination only. What Harilainen found was that 113 (34%) of those patients had arthroscopies that were deemed "useless" in that they provided no change to the treatment plan that would have been pursued from clinical examination alone [30]. Thus experience in performing the clinical exam, particularly appreciating the quality of the end point in the Lachman test, is important and can prevent sweeping and unnecessary use of anesthesia or surgical arthroscopy to reach a diagnosis [21]. Physical examination of the knee coupled with an MRI study is often sufficient to accurately diagnose an ACL tear. However, in cases where all exams are inconclusive or they suggest a partial ACL tear, diagnostic arthroscopy can be a definitive way to determine ACL integrity through direct visualization [7].

Summary

An accurate diagnosis of an ACL tear is imperative so that proper treatment of the patient may be pursued, whether operative or nonoperative. As discussed above, this requires corroboration of the patient history with physical examination, arthrometric measurements, and any radiographic studies available [13]. The more experience a physician has in performing the clinical examination, most importantly the Lachman, anterior drawer, and pivot shift tests, the more accurate their diagnoses will become, but the best practice is always reached when the physician considers all available information in making the final diagnosis [31].

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7 Radiologic Evaluation of ACL Tear and ACL Reconstruction

Andrew H. Schapiro and Andrew M. Zbojniewicz

Imaging of ACL Tear

Prior articles and textbooks have highlighted the imaging findings of complete anterior cruciate ligament (ACL) tears and tibial eminence fractures. Therefore, although we will briefly summarize the pertinent imaging characteristics of complete ACL tears and tibial eminence fractures, we will focus much of our review on identification of partial ACL tears. Partial ACL tears are less frequently discussed in the ACL imaging literature, but are nonetheless important to understand in the evaluation of the pediatric ACL. We will conclude with a review of the important concomitant pathologies that may be seen with ACL tears.

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Normal Anatomy

The first step in being able to identify an ACL tear is to understand the normal anatomy and imaging appearance of the ACL. The ACL is composed of two discrete bundles, each named for the location of its insertion on the proximal tibia. The anteromedial bundle is taut with knee flexion and arises more proximal on the lateral femoral condyle, while the posterolateral bundle is taut with knee extension and internal rotation and arises more distal.

Both bundles can be well differentiated on coronal and axial magnetic resonance imaging (MRI) sequences. Within the proximal portion of the ligament, the bundles should have hypointense signal on fluid-sensitive sequences (Fig. 7.1). A thin stripe of hyperintense signal is frequently evident between the two bundles on fluid-sensitive sequences that is normal and should not be mistaken for injury (Fig. 7.2).

In the sagittal plane, a thick black line along the anterior aspect of the ligament aids in identification of the anteromedial bundle (Fig. 7.3). Care should be taken not to rely on only this single image to determine the integrity of the ligament, as the posterolateral bundle is not well depicted, and therefore a partial thickness ACL tear might not be recognized (Fig. 7.4).

Complete Tear

MRI is an accurate imaging modality to assess for complete tear of the ACL, with reported sensitivity of

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83–95% and specificity of 95–100% [1]. Both primary and secondary signs of tear have been described.

Primary signs of complete ACL tear include ACL discontinuity, abnormally increased intrasubstance ACL signal intensity, enlarged mass-like morphology of the ACL, abnormal orientation of ACL fibers, and non-visualization of the ACL [1]. The most accurate primary signs of ACL tear are discontinuity of the ACL and abnormal orientation of ACL fibers, each with reported positive predictive values of 100% [2]. ACL discontinuity is reported to be visualized best in the sagittal and axial planes, but anecdotally we have found the coronal and axial

Fig. 7.1 Axial T2-weighted fat-suppressed image from a 12-year-old girl showing the normal hypointense signal within the proximal ACL

Fig. 7.3 Sagittal T2-weighted fat-suppressed image from the same 12-year-old girl demonstrates a normal appearance of the anteromedial bundle of the ACL highlighted by a *thick black line* along the anterior surface (*arrows*)

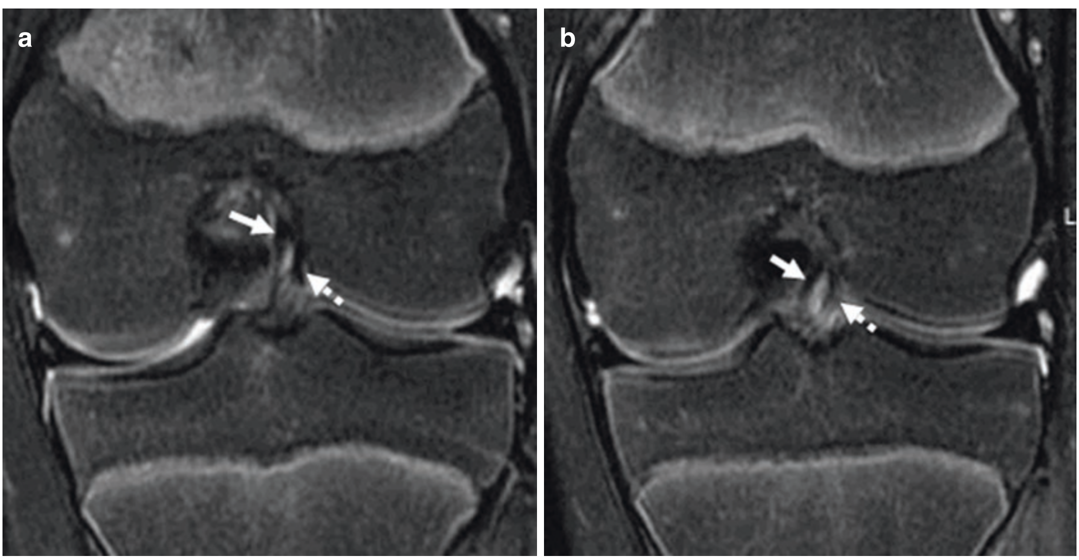

Fig. 7.2 Sequential coronal T2-weighted fat-suppressed images from the same 12-year-old girl show (**a**, **b**) the normally hypointense anteromedial bundle (*arrow*) and the normal hypointense posterolateral bundle (*dashed arrow*) with normal linear hyperintense signal between the two bundles. This should not be mistaken for injury

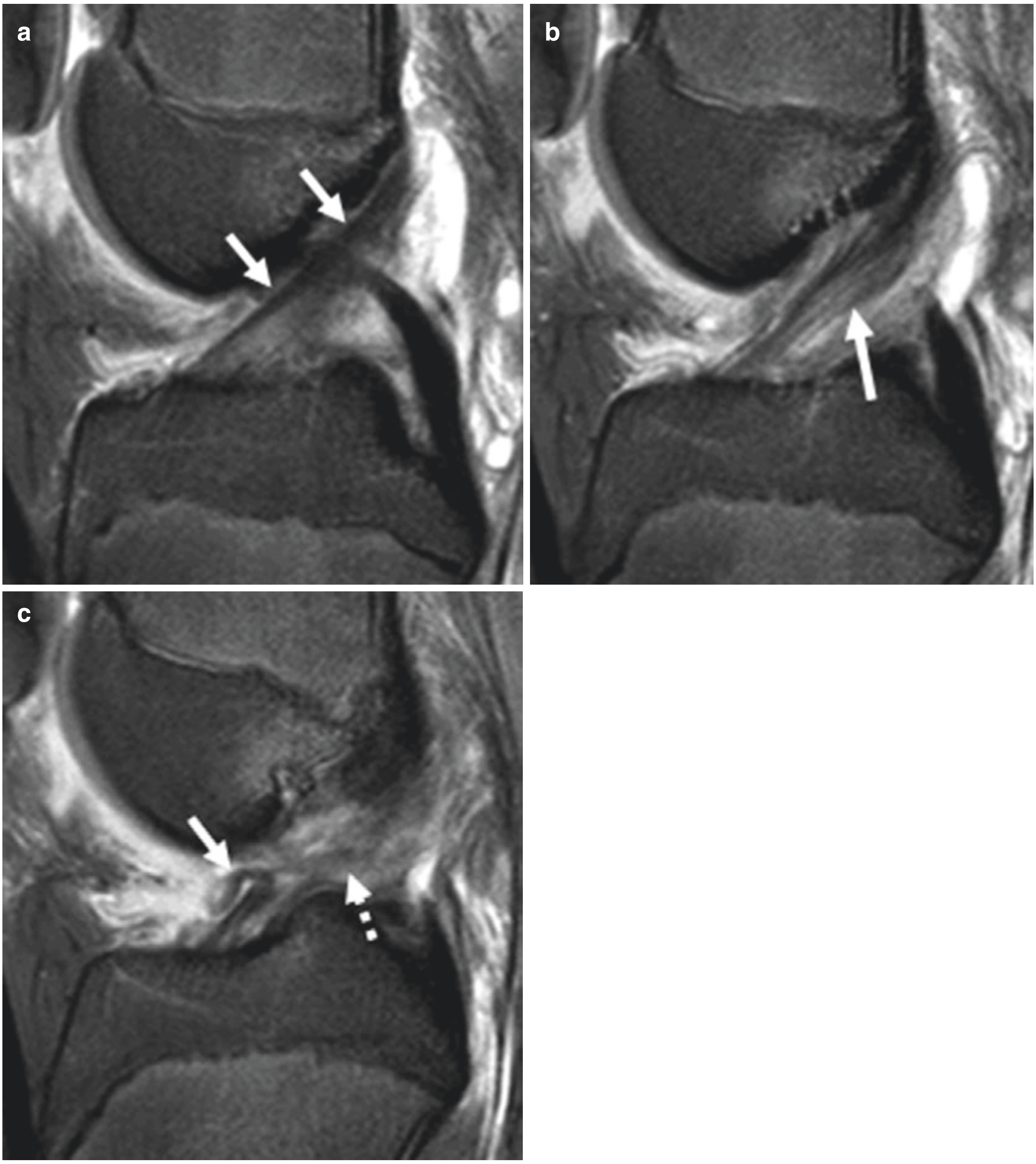

Fig. 7.4 (**a**) Sagittal T2-weighted fat-suppressed image from a 14-year-old boy shows the normal appearance of the anteromedial bundle of the ACL, which is intact (*arrows*). (**b**) Same patient one slice lateral demonstrates hyperintense intrasubstance signal with thickening although fibers still appear intact. (**c**) One further slice lateral demonstrates complete distortion of the posterolateral bundle (*dashed arrow*) with torn fibers of the posterolateral bundle flipped forward (*arrow*). Note also the avulsive marrow edema pattern at the roof of the notch. This was a partial tear of a single bundle and approximates to less than or equal to 25% of the total ligament

planes to better demonstrate the continuity or discontinuity of the ACL bundles [3]. Additionally, straight sagittal sequences do not account for the normal oblique orientation of the ACL, which can result in misdiagnosis or lack of recognition of a clinically important tear (Fig. 7.5). While adding a degree of obliquity when prescribing the sagittal sequence has been promoted as a method to accommodate for the orientation of the ACL, it increases the overall scan acquisition time [4].

Discontinuity must be evaluated both within the substance of the ligament and at the origin from the femur. The "empty notch" sign refers to an ACL that has been completely torn from its femoral ori-

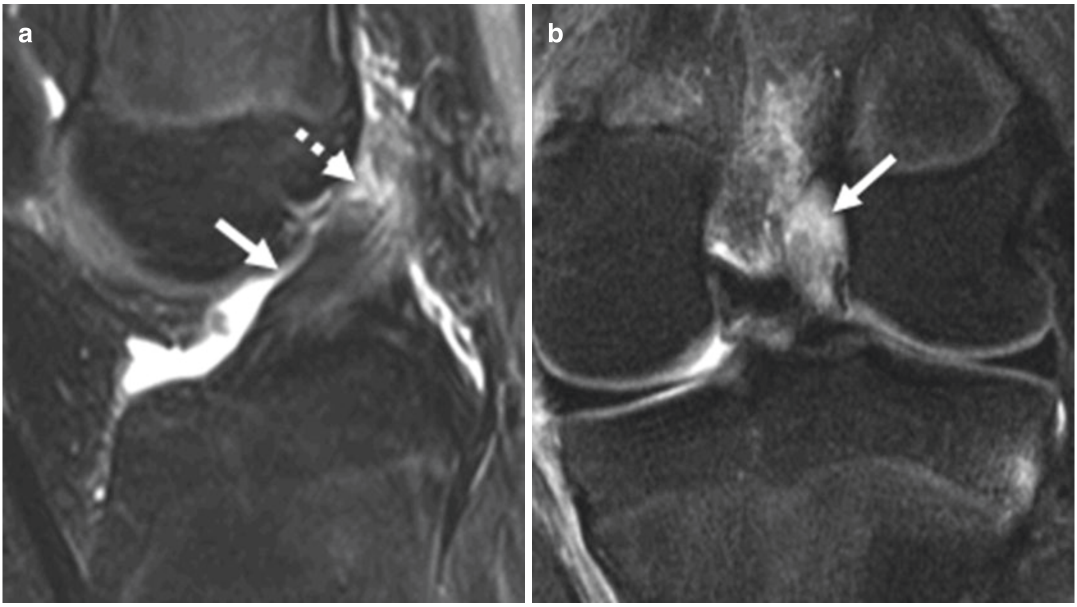

Fig. 7.5 (**a**) Sagittal T2-weighted fat-suppressed image in the a 14-year-old boy demonstrates a normally oriented ACL with preservation of the black stripe anteriorly (*arrow*); however, there is abnormal hyperintense signal at the proximal ligament (*dashed arrow*) that on this one view may be misinterpreted as a partial thickness tear. (**b**) Coronal T2-weighted fat-suppressed image through the proximal ligament demonstrates the "empty notch sign" indicating a functionally complete proximal tear of the ligament from its origin. The ACL was grossly unstable at surgery and subsequently reconstructed

gin at the lateral intercondylar notch and is best seen on coronal or axial sequences (Fig. 7.5) [5].

Abnormal orientation of ACL fibers can be characterized as abnormal vertical orientation of proximal ACL fibers, abnormal horizontal orientation of distal ACL fibers, or abnormal bowing of the ACL (Fig. 7.6). An angle of greater than 15° between the roof of the intercondylar notch and the proximal ACL and an angle of less than 45° between the tibia and distal ACL are suggested to be highly accurate for the diagnosis of complete ACL tear [6]. In addition, torn distal ACL fibers can sometimes flip anteriorly, a finding that can present clinically with decreased knee extension following ACL tear [7].

Secondary signs tend to have a high specificity, but lower sensitivity for complete ACL tear [3]. They have been shown to have no added benefit in the determination of whether an ACL is completely torn or is intact when compared to primary signs alone [8]. Reported secondary signs of ACL tear include anterior translation of the tibia, uncovering of the lateral meniscus posterior horn, osseous injury, buckling of the posterior cruciate ligament

Fig. 7.6 Sagittal T2-weighted fat-suppressed image from a 14-year-old boy shows abnormal horizontal orientation of the distal ligament (*arrow*) within the intercondylar notch

(PCL), reduced PCL angle, posterior PCL line, and the posterior femoral line [1, 3, 6, 9–13].

Anterior translation of the knee is assessed on the midsagittal image of the lateral compartment of the knee. Abnormal anterior translation is present when the posterior aspect of the lateral tibial plateau is subluxated anteriorly 5 mm or more relative to the posterior aspect of the lateral femoral condyle. This finding is reported to have sensitivity of 58% and specificity of 93% for complete ACL tear. With 7 mm or more anterior tibial translation, the specificity increases to 100% [13].

Greater than 3.5 mm of uncovering of the tibial surface of the lateral meniscus posterior horn due to anterior translation of the tibial plateau has reported sensitivity of 44% and specificity of 94% for ACL tear [6].

Bone contusions and/or impaction fractures that result from a pivot shift mechanism ACL tear are typically seen at the anterior to central aspect of the lateral femoral condyle and the posterior aspect of the lateral tibial condyle [10–12]. Often there is additional contusion or fracture of the posterior aspect of the medial tibial condyle, thought to be due to a contrecoup force [9]. Less commonly, osseous injury can be seen along the anterior femoral and tibial condyles from a hyperextension mechanism of ACL injury.

Duration of bone contusions after injury has been studied predominantly in adult patients. In a study of 30 patients with acute knee injury (20 with ACL tears) and mean age 28 years old, all bone contusions were still present at 12–14 weeks [14]. An additional study in adult patients with older mean age of 43.5 years demonstrated a median healing time of 42 weeks [15]. However, in that study concomitant osteoarthritis was shown to nearly double healing time, suggesting that bone contusion healing time may be shorter in pediatric patients.

The presence of subchondral bone depression in association with bone contusion may have important clinical implications. When subchondral bone depression is present in the setting of pivot shift mechanism osseous injuries, there is increased association with meniscal injury in the same compartment and worsened functional outcome at 1 year (Fig. 7.7) [16]. Persistence of subchondral bone depression, as well as articular cartilage thinning, has been observed in patients 2 years after initial ACL injury, even following a successful ACL reconstruction [17].

Fig. 7.7 Sagittal T2-weighted fat-suppressed image from a 15-year-old boy shows hyperintense signal within bone marrow consistent with pivot shift bone contusions in the anterior central lateral femoral condyle and posterior lateral tibial condyle. In addition there is a subchondral bone depression related to impaction fracture in the lateral femoral condyle (*arrow*) and lateral meniscal tear (*dashed arrow*)

Avulsion fractures can also occur in the setting of ACL injury and can often be identified on radiographs immediately following the injury. The Segond fracture is an avulsion fracture at the anterolateral proximal tibia that is highly associated with ACL injury [18]. The etiology of the Segond fracture has caused much consternation over the years, but more recent anatomic studies indicate that a distinct ligament, the anterolateral ligament (ALL), is the ligament associated with this avulsion fracture [19]. However, this ligament is unable to be reliably identified as a discrete structure on MRI, and it has been suggested that the term “lateral capsular ligament” be used as a generic term referring to the portion of the lateral knee stabilizers that includes the ALL [18]. An additional, less common avulsion fracture seen in association with cruciate ligament injury occurs at the insertion of the arcuate ligament complex on the fibular head. This fracture is seen radiographically as a linear lucency through the fibular head, a finding known as the “arcuate sign,” and indicates a posterolateral corner injury (Fig. 7.8) [20].

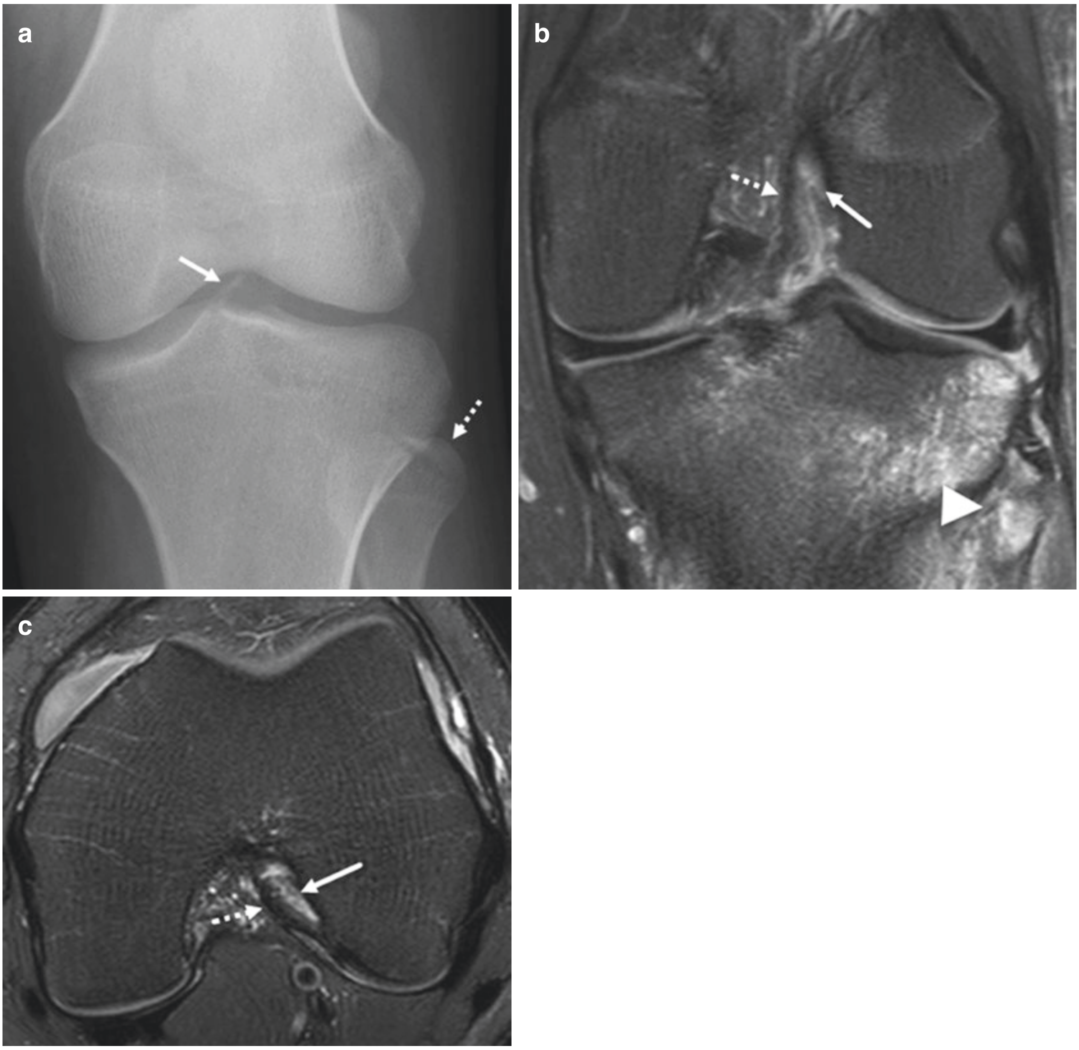

Fig. 7.8 (**a**) Anteroposterior radiograph of the left knee from a 14-year-old girl shows a tibial eminence avulsion fracture (*arrow*) as well as an avulsion fracture at the fibular head (*dashed arrow*). (**b**) Coronal T2-weighted fat-suppressed image in the same patient reveals a complete tear of the posterolateral bundle (*arrow*). The anteromedial bundle (*dashed arrow*) is wavy in contour and was associated with the eminence avulsion. Note the edema pattern in the fibula associated with the avulsion fracture (*arrowhead*). (**c**) Axial T2-weighted fat-suppressed image shows the corresponding appearance with complete tear of the posterolateral bundle (*arrow*) and intact anteromedial bundle (*dashed arrow*)

Tibial Eminence Fracture

Tibial eminence fractures can occur via the same mechanisms as ACL tears, but instead of the weak link being the ligament itself, the bone at the distal ACL insertion is avulsed. This type of injury overwhelmingly occurs in skeletally immature patients, typically 8 to 14 years old [21, 22]. Rarely, these fractures can be associated with concomitant injury of the ligament itself (Fig. 7.8). The following classification scheme based on the position of the avulsed fragment has been developed by Meyers and McKeever to assist management: type 1, non-displaced; type 2, posterior hinge; type 3, completely displaced; and type 4, comminuted [23, 24]. Identification of intermeniscal ligament or meniscal entrapment between the fragment and donor bone, typically in type 2 and type 3 fractures, is crucial, as it can preclude closed reduction and necessitate an open procedure [22].

Partial Tear

Imaging can play an important role in the diagnosis and characterization of partial ACL tears, as physical examination findings can be quite variable, ranging from ligament stability to complete ACL insufficiency [25]. In addition, accurate characterization of partial tears has important treatment implications, as lower-grade injuries may be successfully treated conservatively, while higher-grade injuries are more likely to progress to ligament insufficiency and require surgical intervention. It is reported that a tear that involves less than 25% of the ACL thickness carries a 12% risk of progression to ACL insufficiency, whereas a tear that involves greater than 75% thickness carries a risk as high as 86% [25] .

In general, the reported sensitivity, specificity, and accuracy of MRI in the diagnosis of a partial ACL tear are lower than that for complete ACL tear. At 1.5 Tesla (T), MRI sensitivities range from 62 to 81% and specificities range from 19 to 97% [26, 27]. In a study of patients with partial ACL tear confirmed at arthroscopy who were imaged at either 1.5 T or 3 T, accuracy rates of just 25–53% for diagnosis of partial tear are reported [28].

Higher-field strength MRI can improve diagnosis of partial ACL tear, with reported sensitivities, specificities, and accuracies at 3 T of 77–87%, 87–97%, and 87–95%, respectively [29, 30]. Axial oblique plane MRI has also been promoted as a method to improve diagnosis of partial ACL tear, but the added benefit of axial oblique plane imaging over standard three-plane imaging has not been shown to be statistically significant [29]. Isotropic three-dimensional (3D) MRI sequences have shown no significant benefit over standard 2D sequences [31].

Primary signs of partial ACL tear include attenuation of the ACL, hyperintense intrasubstance signal with at least some intact fibers, posterior inferior bowing of the ACL, distortion of ACL morphology without obvious ACL discontinuity, and bundle discontinuity/isolated bundle (Fig. 7.3) [27, 28, 30, 32, 33]. Unfortunately, the ability of these findings to differentiate a normal from a partially torn ACL and a partially torn from a completely torn ACL is variable. Given this difficulty, some authors have advocated dividing ACL tears into stable (stable partial ACL tears) and unstable (unstable partial and complete ACL tears) categories rather than the traditional normal, partial tear, and complete tear categories, arguing that this has more practical value in determining management strategy [32, 33]. When discrimination of stable from unstable ACL injury on MRI is considered, studies with surgical correlation have shown that an attenuated ACL, abnormal intrasubstance signal, and elliptical morphology suggest a stable ACL injury, whereas distorted, cloudlike ACL morphology, an isolated intact single bundle, and non-visualization of the ACL suggest an unstable ACL injury, with sensitivities of 77–100% and specificities of 92–96% [32, 33].

Another way to quantify severity of a partial thickness ACL tear is to first determine if only one or both bundles are involved. If one bundle is intact, but one is completely torn (e.g., with signs of discontinuity or abnormal bowing), the tear is considered to involve 50% of the total ligament. If one bundle is completely torn, and the other bundle is attenuated and has increased intrasubstance signal intensity on fluid-sensitive sequences suggesting a partial tear, then this injury approximates to 75% of the total ligament. If there is only partial tear of a single bundle manifested by mild increased intrasubstance signal intensity, attenuation of the bundle, or fiber discontinuity in only part of a single bundle, then the tear involves less than or equal to 25% of the ligament (Fig. 7.3). Although these estimates are unlikely to be completely accurate, they can be a useful guide to therapy, as the severity of tear has been shown to impact clinical management and prognosis [25].

Secondary signs on MRI used to diagnose complete ACL tears also have been evaluated in the diagnosis of partial ACL tears. In one study there was improved sensitivity and specificity for the diagnosis of partial ACL tear from 62% sensitivity and 19% specificity with primary signs alone to 81% and 51%, respectively, when both primary and secondary signs are considered [26]. However, when evaluating whether an ACL injury is a stable partial tear or an unstable partial or complete tear, secondary signs can be seen in both types of tears and may actually decrease diagnostic ability of MRI relative to use of primary signs alone [28, 33]. The most specific secondary signs for unstable tear are anterior tibial translation, uncovering of the lateral meniscus posterior horn, and abnormal PCL buckling with specificities of 100%, but these signs had low sensitivity of 23%. Bone contusions are nonspecific and can be seen in both stable and unstable tears [33].

Concomitant Injuries

An in-depth consideration of all concomitant injuries that may be found in the setting ACL injury is beyond the scope of this chapter. However, we will review several important findings that accompany ACL injury, namely, posterolateral corner injury, medial collateral ligament (MCL) tears that may require acute surgical repair, and meniscal tears.

Posterolateral corner injury can have a negative impact on the longevity of an ACL graft if not initially recognized (Fig. 7.9). Specifically, untreated clinical grade 3 (most severe) posterolateral corner injuries are associated with higher forces on the graft and can contribute to ultimate graft failure [34]. On MRI, complete tears of two or more structures at the posterolateral corner have been proposed to correlate to clinical grade 3 injuries [35]. Specific structures at the posterolateral corner that are important to evaluate on MRI include the fibular collateral ligament, the popliteus musculotendinous unit including the popliteofibular ligament, and the posterolateral joint capsule. Thickening and intermediate signal intensity on T2-weighted fat-suppressed images within a ligament is indicative of partial thickness tear, while complete tear is diagnosed when discontinuity is present. Secondary signs of posterolateral corner injury include bone marrow edema pattern or fracture at the fibular styloid, bone contusions of the anterior medial femoral condyle, and lack of a substantial joint effusion presumed due to tear of the posterolateral capsule with subsequent leakage of fluid [35].

Most MCL tears heal without consequence, although may require acute repair or reconstruction. Specifically, osseous avulsion of the MCL from the medial epicondyle and tear of the distal MCL from the tibia, either with interposition beneath the medial meniscus or retraction superficial to the pes anserine tendons that results in a Stener-like lesion, can necessitate surgery (Fig. 7.9) [36, 37].

Although many different meniscal tear patterns can be seen with ACL injury, two in particular deserve mention, namely, peripheral tears of the posterior horn lateral meniscus and root tears or complete radial tears.

Tears at the posterior horn of the lateral meniscus are commonly missed in the context of ACL injury likely due, at least in part, to the known “pseudotear” that can occur at the meniscal origin of the meniscofemoral ligament [38, 39]. Tear should be suggested when peripheral abnormal signal intensity is present at the posterior horn of the meniscus on four or more 3-mm-thick slices located lateral to the posterior cruciate ligament (PCL) [39].

Meniscus root tears, which involve the attachment of the meniscus to the tibia, and complete radial tears result in disruption of the normal hoop stress function of the meniscus, and can lead to increased axial compressive forces transmitted to articular cartilage and to eventual osteoarthritis [40]. Root tears in particular are important to identify because the posterior joint space is not routinely evaluated at arthroscopy and injury in this area may be missed [40]. This type of tear is becoming increasingly recognized even in young patients, and lateral root tears in particular have been associated with ACL tear (Fig. 7.9) [33].

Imaging of ACL Reconstruction

While the imaging findings of partial or complete ACL tear in the pediatric population are similar to those seen in adults, the normal expected postoperative appearance following reconstruction can differ depending on the degree of skeletal maturity and reconstruction technique used. In this section, we will introduce the various reconstruction techniques utilized in pediatric patients across the spectrum of skeletal maturity and discuss their normal postoperative imaging appearances. We also will highlight major differences between children and adults with respect to the normal postoperative appearance of various ACL reconstruction techniques and will review the MRI findings of postoperative complications.

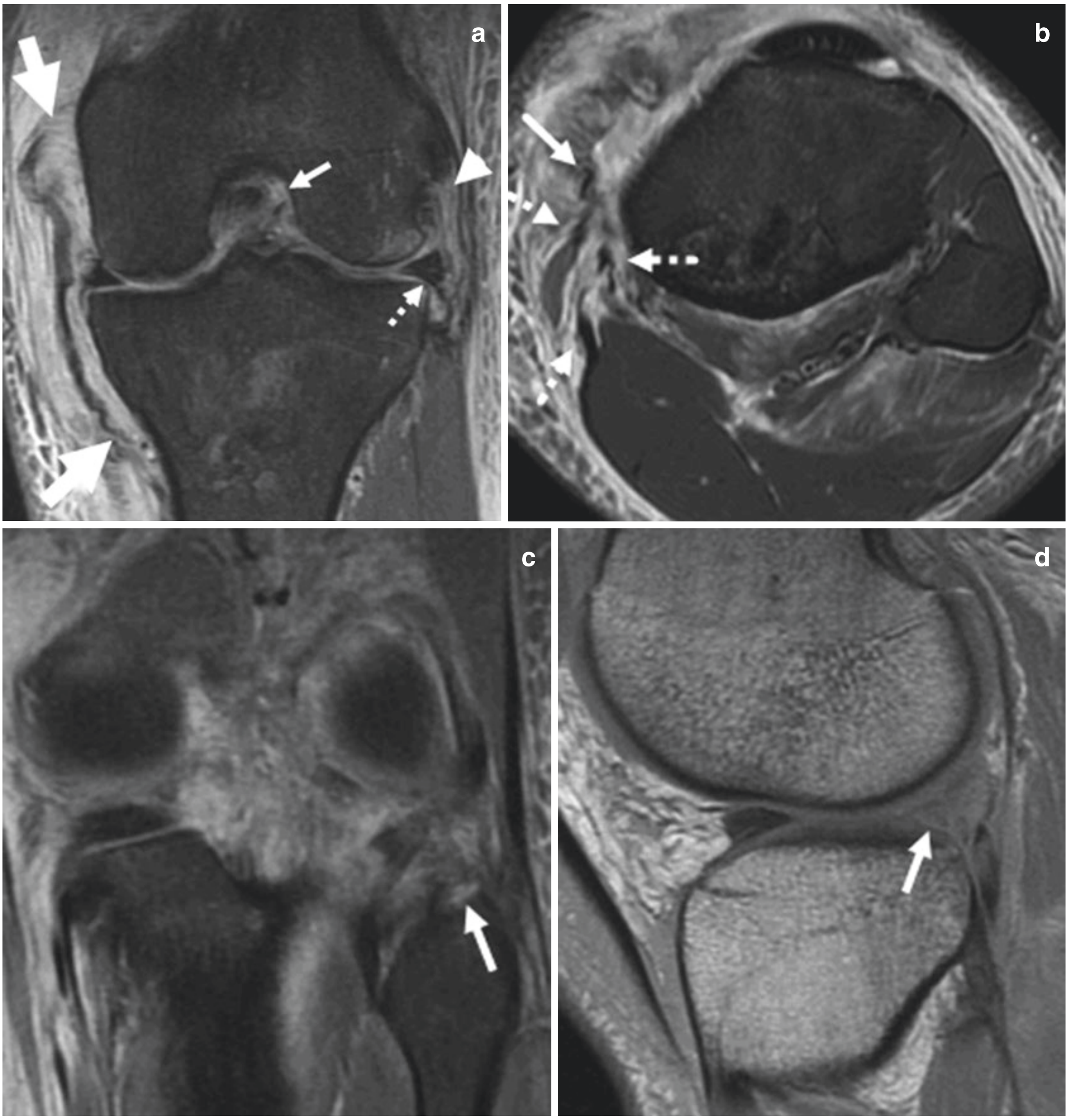

Fig. 7.9 (**a**) Coronal T2-weighted fat-suppressed image from a 17-year-old boy demonstrates complete ACL tear (*arrow*) as well as complete proximal and distal tears of the superficial medial collateral ligament (MCL) (*thick arrows*). The proximal retraction and wavy appearance of the distal MCL are associated with a Stener-like lesion. There is also a high-grade tear of the fibular collateral ligament (*arrowhead*) and abnormal extrusion of the lateral meniscus (*dashed* arrow). (**b**) An axial T2-weighted fat-suppressed image shows the MCL (*arrow*) superficial to the pes tendons (*dashed arrows*). (**c**) A more posterior image shows a complete avulsion of the popliteofibular ligament from the fibular styloid (*arrow*). There was also complete tear of the posterolateral capsule in this patient with high-grade posterolateral corner injury. (**d**) Sagittal proton density (PD) image in the lateral compartment shows a “ghost sign” which is associated with complete radial tear or root tear of the posterior horn

General Reconstruction Concepts

While either bone-patellar tendon-bone or hamstring grafts can be used for ACL reconstruction in skeletally mature patients, hamstring tendon grafts are preferred in skeletally immature children in order to reduce the risk of physeal bridging and consequent growth arrest and/or angular deformity. A hamstring tendon graft usually entails harvesting the semitendinosis and gracilis tendons and then folding and suturing them together to form a four-strand or five-strand graft. Although either autografts or allografts can be used, autografts are most commonly used in skeletally immature patients [41].

Grafts can be fixed to the femur in several different ways. They can be fixed at the joint surface, a technique known as aperture fixation, or they can be fixed away from the joint line, a technique known as nonaperture fixation. Fixation with full-length interference screws is a type of aperture fixation in which the tip of the interference screw is at the level of the bone tunnel orifice at the joint space. Suspensory fixation and transfixation techniques are types of nonaperture fixation. In suspensory fixation, the graft is "suspended" by a metallic button and synthetic material loop from the most superficial aspect of the tunnel. With transfixation, pins oriented perpendicular to the tunnel traverse and fix the graft at the middle of the tunnel [42].

Although postoperative imaging appearance of the graft depends to some extent on the technique used, a couple of general features should be reviewed. Intermediate intrasubstance signal intensity on proton density- or T2-weighted images within the graft can be a normal finding in the postoperative period that has been attributed to graft revascularization, synovialization, and "neoligamentization" [43]. While this finding was traditionally thought to resolve in the normal graft by 18–24 months after surgery, small persistent areas that involve less than 25% of the cross-sectional diameter of the graft can be seen after this time period and do not correlate with graft dysfunction or functional limitations [43]. Another postoperative finding that can be seen in the normal hamstring tendon graft is linear intermediate to hyperintense T2 signal intensity oriented along the longitudinal axis of the graft that reflects fluid between the strands of the folded hamstring tendon graft [44].

Reconstruction Techniques and Their Postoperative Imaging Appearances

Conventional (Adult) Reconstruction

The same technique used in adults can be used in older adolescents with closed or closing physes. In this technique, the femoral and tibial tunnels traverse the physis or physeal scar (Fig. 7.10). While techniques for fixation to the femur described previously are variable, fixation to the tibia is primarily via interference screws, either metallic and radiopaque or radiolucent. Spiked washers, staples, and sutures with button may be used in conjunction with interference screws to increase strength and stiffness of fixation [45].

Fig. 7.10 Anteroposterior radiograph of the left knee of a 15-year-old male who had conventional, adult-type ACL reconstruction demonstrates femoral and tibial tunnels that traverse the respective physes. The femoral tunnel (*arrowheads*) opens in the desired location above the lateral femoral condyle between 1 and 2 o'clock. A metallic button (*arrow*) fixes the graft at the cortex of the lateral distal femur. The smaller caliber of the femoral tunnel segment closer to the cortex and wider caliber of the segment closer to the notch that contains the tendon graft are typical of suspensory fixation. A partially radiopaque interference screw traverses the physis within the tibial tunnel (*dashed arrow*)

On an anteroposterior (AP) radiograph or coronal plane MRI of the knee, the distal aspect of the femoral tunnel should open cephalad to the lateral femoral condyle, between the 10 and 11 o'clock positions for the right knee and between 1 and 2 o'clock positions for the left knee [46]. On lateral radiographs or sagittal plane MRI, the posterior margin of the femoral tunnel should be at the point where the posterior cortex of the

Fig. 7.11 Sagittal gradient echo image from an 18-year-old female who had prior conventional ACL reconstruction shows the hyperintense signal femoral tunnel in satisfactory position at the junction of the physeal scar (*arrow*) and posterior femoral cortex with thin rim of overlying cortex

distal femur and the distal femoral physeal scar intersect, leaving a 1–2 mm cortical rim of the posterior femur covering the tunnel (Fig. 7.11) [43, 46].

On AP radiographs or coronal plane MRI, the tibial tunnel should open proximally at the intercondylar eminence [46]. On lateral radiographs or sagittal plane MRI, the anterior margin of the tibial tunnel should be located posterior to the Blumensaat line which is drawn along the roof of the intercondylar notch and extends to the proximal tibia [41].

On coronal plane MRI, the fibers of the graft should be oriented at an angle of less than 75° from a horizontal line drawn through the lateral proximal tibia (Fig. 7.12) [43].

Transphyseal Reconstruction

In the transphyseal reconstruction technique, the femoral and tibial tunnels are placed in the same locations as those for conventional reconstruction in the skeletally mature patient. However, in transphyseal reconstruction only the soft tendon graft traverses the physis, rather than an interference screw or bone block as in conventional reconstruction. Suspensory fixation is used for femoral fixation, and tibial fixation is performed

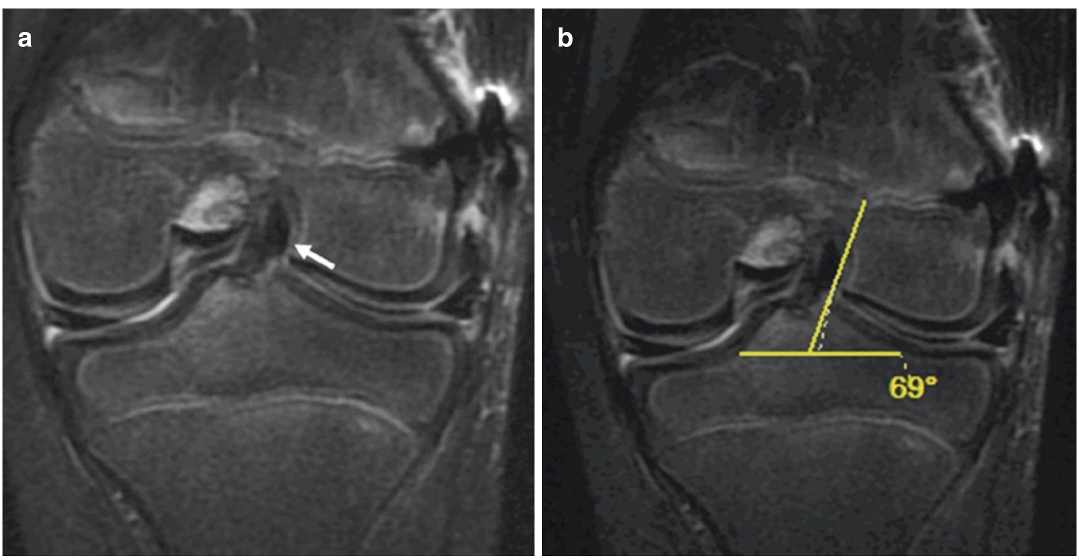

Fig. 7.12 (**a**) Coronal T2-weighted fat-suppressed image of the left knee of an 11-year-old boy shows a normal-appearing hamstring graft exiting the femoral tunnel (*arrow*) and coursing into the intercondylar notch. (**b**) Within the intercondylar notch, the graft has appropriate orientation, with angle of less than 75° relative to a horizontal line through the lateral proximal tibia

Fig. 7.13 Anteroposterior radiograph of the right knee of a 14-year-old male who is status post transphyseal ACL reconstruction. The femoral tunnel traverses the physis as in conventional ACL reconstruction and opens above the lateral femoral condyle between 10 and 11 o'clock. A metallic button is present at the cortical end of the tunnel consistent with suspensory fixation (*dashed arrow*). The tibial tunnel also traverses the physis, but unlike in conventional reconstruction, a shorter interference screw was used that is located entirely distal to the proximal tibial physis (*arrow*)

with a shorter interference screw that is located entirely within the metaphyseal segment of the tibial tunnel that is distal to the physis (Fig. 7.13) [47, 48]. As no interference screw or bone block crosses the physis, the risk for physeal bridge formation and growth arrest is diminished [41]. Two studies of patients 11.6–16.9 years of age who had undergone transphyseal ACL reconstruction found no clinically detectable leg length discrepancy or radiographically detectable angular deformity [47, 49]. However, in one of these studies, a 12% incidence of bone bridge formation was identified on postoperative MRI [49]. In addition, growth can be slowed by tension or tethering across the physis without formation of a physeal bridge, similar to that seen when a staple or tension band plate is used across the physis to treat leg length discrepancy [47, 48]. Because of these potential risks, transphyseal ACL reconstruction typically is used for patients who are past peak growth velocity.

The only difference in the postoperative imaging appearance of the transphyseal ACL reconstruction technique from the conventional technique is the shorter tibial tunnel interference screw that is located entirely distal to the physis. Therefore, the same imaging criteria described for conventional reconstruction can be used to assess the adequacy of transphyseal reconstruction.

Combined Intra-Articular Extra-Articular Technique

The most common and most studied of the physeal-sparing approaches is the combined intra-articular extra-articular approach that utilizes the iliotibial band for the graft [50, 51]. For this reconstruction technique, the distal tibial attachment of the iliotibial band is left intact at Gerdy's tubercle, and the more proximal iliotibial autograft is detached, wrapped around the posterior aspect of the femur, passed through the knee joint beneath the transverse intermeniscal ligament, and subsequently fixed to the proximal medial tibial metaphysis by sutures to the periosteum. The graft is fixed to the femur by sutures to the intermuscular septum and periosteum of the lateral femoral condyle. Although this technique has a long track record with good results, the graft positioning is nonanatomic.

As no tunnels are drilled and no hardware is used, there are no characteristic radiographic findings. The appearance on MRI has not been specifically described, but familiarity with the technique will allow the radiologist or orthopedic surgeon to determine if the construct appears appropriate on follow-up imaging.

Transepiphyseal Technique

The transepiphyseal ACL reconstruction technique represents another of the physeal-sparing approaches in which the femoral and tibial tunnels are contained entirely within the epiphyses. The proximal aspect of the graft is fixed to the femoral epiphysis by suspensory fixation without traversing the physis. In the original version of this technique, the distal aspect of the graft exits the entirely epiphyseal tibial tunnel anteriorly, crosses over the anterior aspect of the proximal tibial physis, and is anchored to the proximal tibial metaphysis [50]. Even though the distal aspect of the graft does not violate the physis, the metaphyseal fixation still theoretically puts the patient at risk for growth arrest due to tethering across the physis [52].

In order to avoid the risk of growth disturbance, modified versions of the transepiphyseal technique have been developed with purely epiphyseal fixation at both the femoral and tibial ends. In one of the versions of this technique, two adjacent completely epiphyseal tibial tunnels are created (Fig. 7.14). The graft is passed out of the joint space through one tunnel, looped anterior to the proximal tibial epiphysis, and then passed back into the joint space to the femur via the other tunnel. The only true graft fixation in this version of the technique is at the femoral epiphysis by suspensory fixation or interference screw [52]. In another version of this technique, only a single all-epiphyseal tibial tunnel is created, and an interference screw or other fixation device is used for tibial fixation (Fig. 7.15) [53].

The entirely epiphyseal course of the femoral tunnel results in a more horizontal orientation than in the conventional repair. However, the tunnel should still open at the posterior lateral intercondylar wall to achieve isometry. On lateral radiographs or sagittal plane MRI, the femoral tunnel should be located within one quarter of the distance from posterior to anterior femoral condyle (Fig. 7.16) [41].

In the split tunnel version of the technique, two tibial tunnels will be seen on imaging. However, regardless of whether one or two tibial tunnels are created, the tunnel(s) should open at the tibial eminence on AP radiographs or coronal plane MRI. On lateral radiographs or sagittal plane MRI, the anterior margin of the tibial tunnel(s) should be located posterior to the Blumensaat line, just as in conventional reconstruction. The goal of this technique is to achieve isometry, so the orientation of the graft itself should mimic the normal orientation of an intact ACL.

Fig. 7.14 Anteroposterior radiograph of the right knee of a 10-year-old boy who had an all-epiphyseal ACL reconstruction shows a horizontally oriented epiphyseal femoral tunnel (*arrows*) and two epiphyseal tibial tunnels adjacent to each other (*dashed arrows*). A radiolucent interference screw is present within the femoral tunnel

Fig. 7.15 Anteroposterior radiograph of the left knee of a 17-year-old female who had an all-epiphyseal ACL reconstruction shows a horizontally oriented epiphyseal femoral tunnel (*arrows*), but only a single epiphyseal tibial tunnel with metallic fixation device (*dashed arrow*)

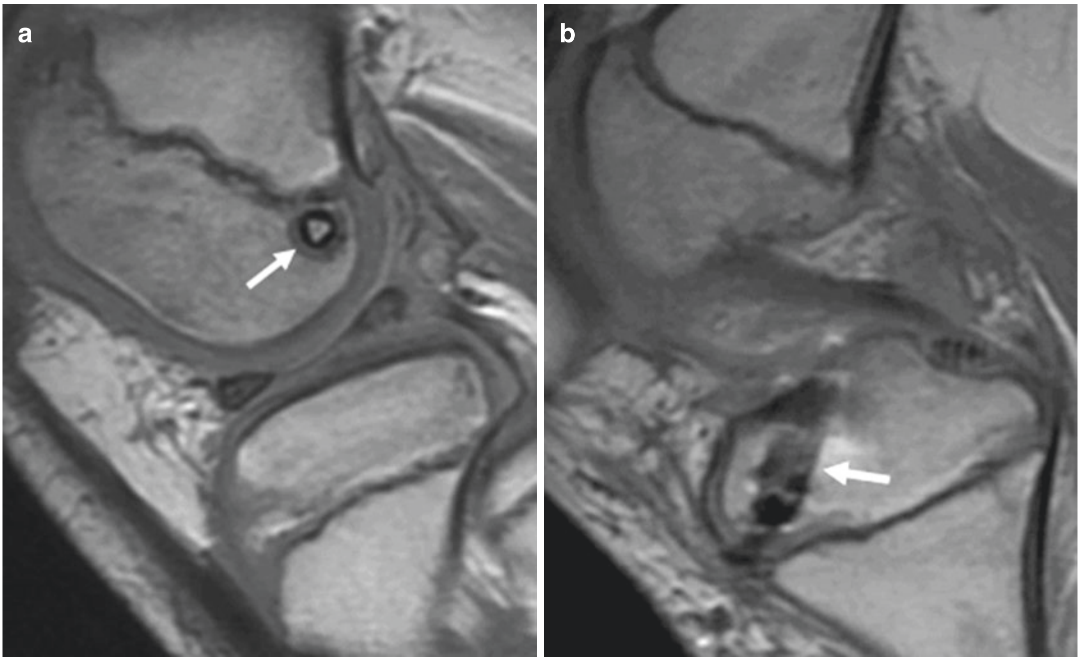

Fig. 7.16 (**a**) Sagittal proton density weighted image from a 9-year-old male who had an all-epiphyseal ACL reconstruction shows appropriate placement of the epiphyseal femoral tunnel within one quarter of the distance from posterior to anterior femoral condyle (*arrow*). (**b**) A more medial image shows an epiphyseal tibial tunnel (*arrow*)

Hybrid Technique

In patients who are approaching skeletal maturity, a combination of transphyseal and physeal-sparing techniques known as the hybrid technique can be used. In this technique an epiphyseal femoral tunnel and a transphyseal tibial tunnel are created [41]. The risk of growth disturbance is considered lower than with conventional or transphyseal techniques due to the relatively smaller contribution of the tibia to growth about the knee compared to the femur [53]. Expected imaging findings will be those of the transepiphyseal or all-epiphyseal techniques at the femur and those of the transphyseal technique at the tibia.

Complications

Although the data are limited, complications that occur in the setting of adult ACL reconstruction can be expected to occur also in children. However, one notable risk of ACL reconstruction specific to the skeletally immature population is that of postoperative growth disturbance.

Growth Disturbance

In skeletally immature patients, any insult to the physis can manifest as growth disturbance, either in the form of an angular deformity when only an eccentric portion of the physis is injured or in the form of a generalized growth disturbance when a large portion or entire physis is involved. In the setting of ACL reconstruction, growth disturbance at the physis can occur either as physeal bridge formation or as tethering effect across the physis [41].

Risk of physeal bridge formation is greatest when bone plugs or interference screws traverse the physis, which is why these techniques are avoided in skeletally immature patients who have substantial growth potential. However, there is still a small risk of bridge formation even when the soft tendon graft is the only thing traversing the physis [49], as in the transphyseal ACL reconstruction technique.

In addition to the risk of physeal bridge formation, there is risk of growth disturbance due to a tethering effect by a graft that is fixed across the physis to the metaphysis, as in transphyseal, transepiphyseal, and hybrid reconstructions [52]. This phenomenon is similar to that seen when a staple or plate construct is placed across a physis in order to slow growth in the setting of bone length discrepancy.

Growth recovery lines can aid in the detection of growth disturbance on radiographs and MRI. As a marker of prior insult to the physis, growth recovery lines are increasingly and uniformly displaced away from the physis as new bone is formed in the absence of substantial growth disturbance. At a site of substantial physeal insult, new bone formation is hindered, and the growth recovery line is not displaced over time from the physis. Instead, the growth recovery line will converge on the physis at that site [54]. This finding is particularly useful in the setting of focal growth disturbance but can be quite subtle in the setting of generalized growth disturbance in which much of the physis is involved.

Physeal bridges can have different appearances on radiographs and MRI depending on their composition. Osseous bridges will appear as areas of increased sclerosis at the physis on radiographs. Fibrous bridges will not be seen directly on radiographs as they are radiolucent, and secondary findings of growth disturbance will have to be relied upon. On MRI, there will be loss of the normal T2 hyperintense cartilage signal at the physis, with marrow signal intensity traversing the physis in the setting of an osseous bridge and T1 and T2 hypointense signal traversing the physis in the setting of a fibrous bridge [55].

Evaluation for angular deformity and leg length discrepancy is particularly important in the setting of growth disturbance and can be assessed using full-length radiographs of the lower extremities with the patient in a standing position. Leg length discrepancy following ACL reconstruction does not result from growth stunting alone, but can also be secondary to accelerated growth of the postsurgical knee from stimulation of the periosteum or hypervascularity associated with drilling near the physis [48, 52].

Graft Laxity

Increased laxity of the ACL graft can occur following ACL reconstruction [44]. In the early postoperative setting, this is more commonly a result of loss of fixation, particularly at the femoral site. On MRI loss of fixation can appear as abnormal redundancy of the graft, loss of fiber orientation along the Blumensaat line, and increased graft fibers outside of the normal expected graft location in the intercondylar region [41].

Later in the postoperative period, increased graft laxity may be the result of complete graft tear or graft stretching [44]. In a meta-analysis of ACL reconstruction in children and adolescents, a 4.8% incidence of graft tear was reported [56]. While tear may simply be related to recurrent injury, certain grafts may be predisposed to tear if they are not placed in isometric position throughout the full range of motion of the knee [46]. Placement of the femoral tunnel too far anteriorly is the most common technical mistake that can lead to eventual graft failure [57]. However, both femoral and tibial tunnels can be malpositioned in many directions, each leading to a different consequence depending on location and range of motion [57]. For example, an abnormally vertical femoral tunnel can lead to rotational instability, while a tibial tunnel placed too posterior can lead to excessive tension during knee extension or laxity during flexion [57].

MRI findings of graft tear are similar to those described for native ACL tear (Fig. 7.17). However, one should be careful about the interpretation of hyperintense graft signal on a fluid-sensitive sequence as a sign of tear in the absence of obvious fiber discontinuity. ACL grafts normally can have hyperintense intrasubstance signal due to synovialization for 24 months and possibly longer following surgery [43]. In addition, fluid signal intensity normally can be seen between the multiple strands of a folded tendon graft (Fig. 7.18) [51]. Within 24 months of surgery, the secondary signs of ACL may be particularly helpful in distinguishing normal graft maturation from graft tear [46]. In particular, a typical pivot shift bone contusion pattern seen with native ACL injury should

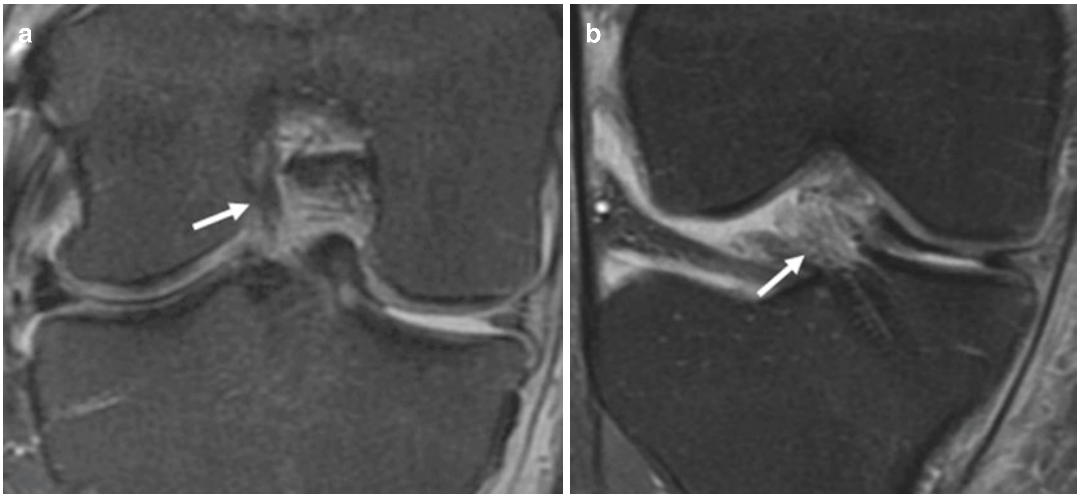

Fig. 7.17 (**a**) Coronal T2-weighted fat-suppressed images of the right knee of a 16-year-old female 1 year after ACL reconstruction shows normal-appearing graft fibers proximally (*arrow*). (**b**) However, a more anterior image of the distal graft (*arrow*) demonstrates enlarged mass-like graft morphology and abnormal orientation of graft fibers compatible with graft tear

Fig. 7.18 Coronal T2-weighted fat-suppressed image of the left knee of an 18-year-old male who had ACL reconstruction with a hamstring tendon graft demonstrates linear fluid signal oriented along the long axis of the graft (*arrow*). This is a normal appearance for a tendon graft due to fluid insinuating between the strands of the hamstring tendon graft and should not be mistaken for a tear

raise suspicion for graft tear. Findings of graft stretching include increased fiber redundancy and loss of fiber orientation along the Blumensaat line (Fig. 7.19).

Fig. 7.19 Sagittal T2-weighted fat-suppressed image from a 12-year-old female 1 year after ACL reconstruction shows an abnormally redundant, posteriorly bowed graft that is no longer oriented along the Blumensaat line (*arrows*) suggesting graft laxity. No tear was identified, suggesting graft stretching as the cause for laxity

Decreased Range of Motion

A decreased range of motion of the knee following ACL reconstruction may be the result of graft impingement, arthrofibrosis, intra-articular bodies, or graft ganglion cyst formation.

Graft impingement most commonly occurs when the tibial tunnel is placed too far anteriorly, anterior to the Blumensaat line with the knee in extension [58]. Alternatively, impingement can result from chronic tightening of the posterior capsular restraints and consequent anterior tibial translation that may follow ACL injury [46]. In either setting the roof of the intercondylar notch prematurely contacts the graft prior to the knee reaching terminal extension. Another form of impingement is sidewall impingement, which can occur if the tibial tunnel is placed too far laterally or medially [44, 57]. Graft impingement may ultimately result in graft laxity or tear [59]. MRI findings that suggest graft impingement include increased signal intensity in the anterior two-thirds of the graft and posterior bowing of the graft caused by contact with the intercondylar roof anteriorly (Fig. 7.20) [58].

Arthrofibrosis can be focal or diffuse. In the focal form, nodular intermediate to low signal

Fig. 7.20 Sagittal T2-weighted image from a 13-year-old male with history of ACL reconstruction shows increased signal in the distal graft relative to proximal graft and posterior bowing of the distal graft at a site of contact with the anterior intercondylar roof (*arrow*) compatible with graft impingement

Fig. 7.21 Sagittal T2-weighted fat-suppressed image from a 17-year-old female who presented with decreased knee range of motion shows nodular intermediate to hypointense signal (*arrow*) along the anterior aspect of the distal graft (*dashed arrow*) consistent with focal arthrofibrosis

intensity typically is seen along the anterior distal end of the graft (Fig. 7.21) [44, 46]. In the more diffuse form, there is mass-like intermediate to low signal intensity tissue that encases the graft, that extends into the infrapatellar fat pad with ill-defined, spiculated margins, and that involves a thickened posterior joint capsule [46].

Intra-articular bodies are a less common cause of decreased range of motion that may be seen on radiographs if radiopaque and can be identified on MRI as filling defects within joint fluid (Fig. 7.22).

Ganglion formation within the graft is a rare cause of decreased range of motion. A late complication following ACL reconstruction, ganglia typically form in the tunnel segment of the graft, more commonly the tibial tunnel, and may extend proximally into the joint space or distally into the pretibial soft tissues [44]. If intra-articular ganglia grow large enough, they may limit knee range of motion. On MRI ganglia should have fluid signal intensity and lobular morphology. However, small amounts of

Fig. 7.22 Tunnel view radiograph of the right knee of a 12-year-old female who had an all-epiphyseal ACL reconstruction 1 year prior shows displaced metallic buttons within the intercondylar notch used for suspensory fixation. Subsequent MRI (not shown) demonstrated an associated graft tear, and the displaced endobutton was removed at the time of graft repair

fluid can be seen normally within the femoral and tibial tunnels following ACL reconstruction within the first 2 years following surgery. These normal areas of fluid accumulation should show linear fluid signal intensity between the graft and the tunnel wall or between the tendon graft fibers and should not have a lobulated morphology [41].

Infection

Infection is rare following ACL reconstruction. Imaging findings are those seen with osseous, joint, or soft tissue infection in any other setting and include joint effusion, synovitis, bone marrow edema, bone erosions, soft tissue edema, and soft tissue abscesses or sinus tracts [44, 46]. Postsurgical evolving hematoma may mimic an abscess, but clinical findings of infection will be absent.

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Conservative Treatment of ACL Tear

8

Henry Ellis, Lorenzo Vite, and Philip Wilson

Introduction

Nonoperative management of a complete anterior cruciate ligament (ACL) injury in a pediatric patient has been reported with inconsistent and variable outcomes. Approximately 22–71.4% of skeletally immature ACL injuries may require operative treatment following a trial of nonsurgical management due to persistent instability [1–4]. Large effusion, concomitant injuries, and symptomatic instability may have influenced which patients with ACL injury sought evaluation in the past. This may be different currently with a higher focus on the pediatric athlete and increased recognition of an ACL injury.

After an ACL injury, 40.7–44% of patients will return to their same level of activity [5, 6]. Several authors have suggested high rates of meniscal and chondral damage following delayed operative or nonoperative treatment after ACL injury [7–11]. This has led to a paradigm shift in the treatment of pediatric ACL injuries toward operative management with physeal sparing and physeal-respecting techniques [12]. However, many young athletes could still avoid surgery if proper nonoperative treatment is implemented.

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Incidence

The reported incidence of pediatric ACL reconstruction has increased over the last 20 years [13] with a rate of 2.42 ACL injuries per year per 10,000 14-year-old children [4]. High school athletes have an overall incidence of an ACL injury of six to seven per 100,000 athletic exposures [14, 15]. This may depend on the sport, level of competition, age, and gender of the athlete.

In the last two decades, the reported incidence of ACL tear has increased, particularly in pivoting sports (i.e., soccer, basketball, and handball). It remains unclear if the increased incidence is due to increased awareness and earlier presentation of young ACL injuries. In either case, young athletes may be particularly vulnerable to primary ACL tear and secondary related injuries due to their underdeveloped coordination, skills, and strength.

Indications for Nonsurgical Treatment of an ACL Injury in the Pediatric Patient

There are no rigid criteria dictating nonoperative or operative treatment of an ACL injury in the young athlete [16]; however, contraindications to nonoperative management of ACL reconstructions are well accepted (Table 8.1). Both nonsurgical and surgical treatments in youth present challenges. Level of competition, high daily

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Table 8.1 Contraindications for nonsurgical management of an ACL tear in the skeletally immature patient

Symptoms of instability following phase 1 and 2 of PT
Concomitant meniscus tear or chondral lesion(s)
Persistent flexion contracture secondary to cyclops lesion
Young athlete returning to a competitive pivoting sport[a]

[a]Relative contraindication based on literature consensus

activity level, and immature muscular development may lead to high reinjury rates in this age group regardless of initial injury management.

The particular injury location within the ligament may be an important consideration in determining treatment of the young athlete [17]. Proximal lesions may have the ability to heal on the femoral condyle without intervention, or they may be amenable to an arthroscopically initiated healing response [18, 19]. Distal lesions, in the form of a tibial spine fracture, can be treated non-operatively if non-displaced or with reduction and fixation for displaced lesions [20–22]. Intra-substance, or mid-substance, complete ACL tears in the young patient require additional considerations prior to treatment recommendations. In this age group, mid-substance tears have the worst reported functional outcomes [6].

In most patients, in the absence of a displaced associated cartilage or meniscus injury, a trial of nonoperative rehabilitation should be considered for the initial 6 weeks following injury [23]. This would allow adequate time for effusion resolution and recovery of motion. Afterward, the patient should be reexamined. Continued instability, recurrent injury, or limited function of the knee may be strong indications for an ACL reconstruction. Special considerations when establishing an instability history in the pediatric patient include evaluating compliance with initial nonoperative rehabilitation [24] and assessing ability to effectively describe true instability episodes [25].

Young patients with concomitant meniscal tear that require operative management may be contraindicated for nonoperative management of their ACL injury [16]. This is particularly true with medial meniscal injuries as the medial meniscus is the secondary stabilizer to anterior tibial translation [17, 26, 27]. Samora et al. [28] reported a relatively high incidence (69.3%) of meniscus tears in the skeletally immature patient with an ACL tear, of which 29% were medial meniscal tears. Another related internal derangement that may be a contraindication to nonoperative management is torn ACL fibers flipped into the notch causing a flexion contracture (i.e., cyclops lesion).

Low-demand patients who have no desire to return to competitive sports may be the ideal candidate for definitive nonoperative treatment of the complete ACL injury [29]. Athletes with partial ACL tears without functional instability by history or evidence of a pivot shift contusion pattern on MRI may also benefit from definitive nonoperative management [24, 30, 31]. As previously stated, most pediatric patients should undergo a round of rehabilitation (4–6 weeks) prior to indicating an ACL reconstruction [32]. This will allow the young athlete to demonstrate their dedication to proper physical therapy prior to a reconstruction, if indicated, or demonstrate them to be a pediatric patient who is able to cope with an ACL-deficient knee.

ACL-deficient copers exist within the population of those incurring ACL injuries. In ACL-deficient patients, approximately one-fifth of athletes may be able to return to their pre-injury level of athletic performance even without a brace and, thus, are labeled a coper [1, 3, 33]. A coper is a patient who can clinically, functionally, and biomechanically tolerate ACL deficiency without instability and return to pivoting sports without treatment. However, identifying these individuals in the pediatric population may be difficult. Pediatric individuals who may be copers may be less likely to display the signs and symptoms of ACL injury and therefore may not present for care: this potentially hidden population of copers may influence our current understanding of the ability to tolerate ACL deficiency in the population overall. The degree of ligamentous laxity or validated patient-reported outcomes cannot detect who can be a coper [34]. Compared to non-copers, copers may be younger and may have lower activity level [3, 35]. Non-copers may have a deficit in quadriceps strength, vastus lateralis atrophy, quadriceps activity deficit, and reduced knee flexion moments with a greater quadriceps and hamstring co-contraction [36].

Several authors have indicated that any patient, regardless of their age, who wants to return to sports, should not be considered for nonoperative treatment of ACL deficiency [29, 31, 37]. Parents and young athletes who choose nonoperative initial management of an acute ACL deficiency should be aware of the potential for future injury [23, 31]. Several authors have demonstrated an increased incidence of meniscal and chondral damage following delayed treatment of an ACL injury [4, 8–10, 38–41].

Nonoperative Treatment of Pediatric ACL Injury

Generally, an adult treatment algorithm for acute ACL injury should not be used for a pediatric patient. Central strategies, such as landing techniques and strengthening programs, have not demonstrated significant neuromuscular changes in the skeletally immature athlete [42, 43]. While strength training is a significant portion of nonoperative rehabilitation in the mature ACL-deficient patient [23, 32, 44], its use in a child has more efficacy when focused on neuromuscular activation and coordination as opposed to muscular hypertrophy [45].

In addition to meeting the physiologic needs of a growing athlete, a nonoperative rehabilitation program must also consider the psychological profile of a young athlete, addressing reduced focus, minimizing boredom, and maximizing compliance [42, 46, 47]. While accounting for these age-related mental factors, less complex proprioception and balance training may be used to address developing neuromuscular control. As proprioception training in isolation has not been shown not to be effective in this age group, spatial orientation, body stability, and appropriate fall techniques are tasks that may complement a pediatric-specific program [43, 48].

Few authors have described pediatric-specific rehabilitation programs for nonoperative ACL treatment [49–51]. Moksnes et al. [50] describe a specific four-phase program that is based on functional milestones with impressive outcomes in this age group [2]. This program was adapted from an adult-based protocol for nonoperative treatment of ACL injury [44], with special considerations added for the pediatric athlete. These include a slower progression toward jumping and running to reduce impact loading of the physis, less use of external loads, primarily home-based functional exercises, and a later return to pivoting sports.

Utilization of a clear timeline and functional milestones is appropriate for nonoperative ACL management in this age group. Using a modification of Moksnes protocol [50], a four-phase program, with each addressing specific milestones, should be implemented. The first phase addresses the acute phase of the injury, and the fourth phase transitions into age-appropriate injury prevention and maintenance (see Chap. 17). Phase two and three will address a program to achieve activities of daily living and return to desired athletic activity, respectively. A simple program in each phase will help promote compliance. A successful physical therapy program will focus on proper instructions, compliance, cryotherapy, joint mobility, gait reeducation, muscle strength training, neuromuscular function and balance, and bracing [52].

A rehabilitation program for a pediatric patient with an ACL injury should be followed through at least phase two prior to surgical decision-making. The initial two phases of physical therapy employed 2–3 sessions per week prior to advancement to phase three [23]. At that stage, one session per week or one session once every other week of supervised physical therapy is needed [50].

Early Management (Phase One: 1–3 Weeks)

Early management or phase one of rehabilitation of an ACL injury in a pediatric patient should focus on addressing acute hemarthrosis or effusion, regaining normal range of motion, and initiating reactivation of the quadriceps. Phase one should begin with guidance from a physician and evaluation of an MRI confirmation and specifying the location of the ACL injury and the absence of associated injuries (including a bucket handle meniscus tear, an osteochondral fracture, or a multi-ligamentous knee injury) [53]. A modified protocol may be required with concomitant injuries.

Protected weight bearing is recommended for the first 3–4 weeks, with a range of motion brace without motion restrictions [1, 29, 44, 51]. If limited weight bearing is desired due to the presence of an osteochondral contusion, this may be employed. Although toe-touch weight bearing is acceptable at this stage, a pediatric patient may have difficulty with understanding and appropriate compliance. Developing trust is important in this early stage to ward off inappropriate weight bearing on crutches. Crutch training could prevent patients from leaning on crutches as it can compress the nerve and blood vessels in the armpit. Cryotherapy and compression should be considered to manage any effusion, since this may limit a patient's recovery.

Flexion and extension exercises are employed without the brace, with severity of the effusion often dictating how fast each patient progresses. The introduction of modalities and anti-inflammatory techniques may be indicated at this time. Therapeutic techniques with anti-inflammatory effects may include electrical stimulation, ice, warm pad modalities, or ultrasound. Early motion recovery is achieved with focused rehabilitation on both flexion and extension. Achieving terminal extension is of paramount importance to reaching pain-free activities of daily living and more advanced functional goals. The focused extension program is initiated supine with an ankle foam roller (Fig. 8.1a). When pain and effusion are minimized, prone knee hangs

Fig. 8.1 Phase 1 exercise to be initiated during acute phase recovery of an acute ACL injury in pediatric patients. (**a**) Foam roller extension to be performed supine with gradual progression to a 3-pound cuff weight. Exercise is intended to assist with achieving terminal extension. (**b**) Prone knee hangs to be performed as tolerated when effusion is minimized. (**c**) Wall slides are performed supine with heel sliding on wall as tolerated. Emphasis must be placed on alignment. (**d**) Supine straight leg raise (SLR) to be initiated with contralateral leg flexed initially. Emphasis placed on maximal knee extension during each repetition

(Fig. 8.1b) are implemented without weights, with subsequent progression to weighted prone knee hangs by adding a 3-pound cuff weight distally. For flexion motion and early quadriceps eccentric contraction, wall slides and straight leg raises are also initiated (Fig. 8.1c, d). Initially, straight leg raise is performed in a supine position with the patient's head supported with elbows propped up in order to visualize the extremity during the exercise. Eyes are instructed to focus on the knee for visual feedback to prevent terminal knee extension lag. Initially, the contralateral knee is flexed to provide support and then progressed to extended once the patient is able to perform a straight leg raise without an extension lag. Following this, sitting straight leg raises are initiated. A stationary bike without resistance for 20 min per day can be implemented during this phase. Once the patient demonstrates knee flexion to 100°, adjust the bike seat height to allow slight knee flexion on downstroke and properly position patient to prevent valgus knee alignment during pedaling stroke. Early quadriceps activation may be improved with supine single leg press using elastic band to 20 (Fig. 8.2a).

Milestones for phase one include complete resolution of effusion, a straight leg raise without a lag, and full unrestricted motion. Completion of these milestones will allow progression to phase two no sooner than 1 week following the initial injury. Underwater or devices that reduce the effects of gravity provide an environment that allows the treating physical therapist to cue, train, and guide the client to develop a normal gait pattern. Utilizing these unloading modalities improves confidence and reduces joint pain.

Fig. 8.2 Advanced exercises used in phase one and two of nonoperative treatment of youth ACL injuries. (**a**) Supine leg press with elastic band is initiated utilizing elastic band for closed-chain exercises. Patient should be propped on elbows using elastic band with a preliminary motion of 0–30°. (**b**) Side-lying clamshell exercises performed on the side with an emphasis on a neutral pelvis. Placing the hand, the iliac crest will help stabilize and neutralize the pelvis. (**c**) Standing squat to sitting height with progression shown with 5-pound weights. Place a chair or stool behind the patient for support. (**d**) Single-leg mini-squat with elastic resistance. An emphasis on terminal knee extension should be made

Phase Two (1–6 Weeks)

Phase two should be considered and completed for all patients prior to surgical decision-making. The primary goal of this phase is to normalize activities of daily living (ADLs) by restoring muscle strength and early neuromuscular response [49]. This is accomplished with muscle strength training, plyometrics, and neuromuscular exercises. Early phase two programs may be initiated without weight-bearing activities. Strengthening quadriceps and hamstrings with closed chain exercises is started [1, 29, 50]. Progression of the supine single leg press with an increase in repetitions prior to an increase in resistance is recommended. Emphasis is placed on developing hamstring strength due to its role as a dynamic muscular backup to an AC-deficient knee. Recent evidence has supported the importance of gluteus medius and hip external rotators strengthening in prevention of future ACL injuries [50, 54]. Gluteus medius strengthening is accomplished with a lateral decubitus clamshell exercise (Fig. 8.2b). By instructing the patient to put their hand on the iliac crest, they will minimize rotation during this exercise.

When weight-bearing restrictions are removed, early neuromuscular control is progressed with terminal knee extension in single-leg stance: a mirror for visual feedback and assistance for balance may be useful (Fig. 8.2c, d) [50]. A narrow stance with an elastic band (TheraBand, Akron, OH) around the distal thigh for a single-leg hip external rotation exercise will activate hip rotators. Progressing to a shoulder-width squat will add difficulty. Attention is directed to correct a compensatory weight shift that may develop away from the affected lower leg. It is important to clear the joint above and below the knee for full active range of motion. For instance a loss of ankle dorsiflexion will cause a squat dysfunction.

A stationary bike and a swimming program may be emphasized here. Swimming programs are effective initially with a floatation device that allows for walking, such as a kickboard. Frog kicks should be avoided (i.e., kick used in breaststroke). Proprioception and balance training are initiated with single-leg stance, step-ups, and squatting that avoid dynamic valgus loading [12, 31]. Proximal hip strength is an important consideration during this phase.

A repeat examination by a trained healthcare professional should be performed prior to progressing to phase three in order to confirm no mechanical symptoms or effusion. In order to advance to phase three, the young patient should be able to complete normal stair walking and participate in daily activities. Any history of instability, activity-related pain, or signs of a residual effusion should be addressed by a physician.

Phase Three (4–20 Weeks)

Initiation of phase three is intended for those young athletes who are considering nonoperative management of an ACL injury [44]. Moksnes [50] stated that the primary goal of phase three is the ability to run without gait deviation or swelling. The athlete should be able to complete one-mile jog without fear or instability, and, if able to complete, progress to single-leg linear skipping and low-amplitude base hops to single-leg hop. The progression of phase three is primarily determined by the physical therapist.

An emphasis on neuromuscular control, balance, and proprioception is placed during the early stage of phase three. Simple balance routines with uneven surface training using equipment such as a wobble board, Bosu® balance trainer (Bosu, Ashland, Ohio), or an Airex® balance pad (AIREX, Switzerland) will aid in building neuromuscular control prior to single jumps and multi-hop plyometric movements. An Airex® balance pad with a slight knee flexion stance and perturbation with an elastic band will supplement the neuromuscular training. To be performed properly, the young patient will need to be upright with short arc of motion and shoulder in extension (see Fig. 8.3a).

Proper landing techniques are required for successful completion of this phase. Regular supervised jumping and landing are necessary in order to ensure symmetry and trunk alignment. Jumping drills should also focus on knee over toe position with quiet landings [44]. Primary jump and landing may be initiated on a level surface, with a hop onto a step or box added later (see Fig. 8.3b). The goal is to take off and land on the box without knee valgus. Gravity is arrested during the floor to box jump. In this stage, the athlete is not prepared to hop off the box. Running may be initiated with an antigravity treadmill, but traditional running should not start until 12 weeks following an injury [1].

Advancement to open-chain knee extension with resistance attached to proximal tibia for combined hamstring and quadriceps muscles may be emphasized within the home exercise program. Swiss ball bridges are effective in strengthening the gluteus maximus and hamstrings. A seated, elevated, resisted pattern triple flexion (hip, knee, ankle) lower extremity row, with opposite leg maintained in 90° knee flexion or knee extension, using a Thera-Band, provides strengthening of both extremities involved (see Fig. 8.3c, d).

Phase three milestones include running for 15 min without pain or effusion, single-leg hop with appropriate landing, and passing a functional test. Completion of phase three will typically demonstrate that an athlete may be functionally ready to return to sports based on their strength, balance, proprioception, and endurance. Some have advocated isokinetic testing in this age group at 60°/s [23, 50]. Isokinetic testing is a reliable form of testing strength in this age group [55, 56]. However, changes in isokinetic testing during development and maturation remain unclear [57]. A factor to consider in a young athlete is entering peak height velocity (PHV) along

Fig. 8.3 Phase three program intended to focus on neuromuscular control, balance, and proprioception. This phase is initiated once a nonoperative treatment for an ACL injury is pursued. (**a**) Single-leg stance on an uneven surface, progression shown with upper extremity elastic resistance perturbations. (**b**) Plyometric jump from floor to box with an emphasis on coronal knee alignment throughout motion. (**c, d**) Open kinetic chain hip and knee flexion with elevation of long sitting leg with contralateral static knee extension using elastic bands is initiated. Recommend initiation of exercises with contralateral leg in flexion to provide closed-chain support. Advance to extended contralateral leg when appropriate

the developmental principals of Long-Term Athlete Development (LTAD) [58]. During ACL rehabilitation, a young athlete may demonstrate a large side-to-side deficit due to ongoing physiologic maturation that may occur in the uninjured extremity; making side-to-side differences is difficult to interpret. Another functional test is the series of single-leg hop tests described by Noyes et al. [59]; however, these have not been validated in the pediatric population.

The use of the Y-Balance Test™ (Functional Movement Systems, Chatham, Virginia) has gained popularity due to its ability to quantify strength, balance, proprioception, and a side-to-side difference in young athletes [60, 61]. A patient is tested by performing an excursion movement in three directions with his or her lower extremity, while maintaining a single leg stance with the contralateral extremity. The amount of excursion is compared to the amount of excursion on the contralateral leg and to age-matched normative values.

When interpreting a Y-Balance Test™ (YBT), a composite score of less than 90%, a side-to-side difference of 4 cm or greater in the anterior direction, or a side-to-side difference of 6 cm in the posteromedial and posterolateral directions has been correlated with a 2.5–3.5 times increase in lower extremity injury rates [60, 62, 63]. This method was validated by Lehr et al. 2013 in collegiate athletes [64]. Previous injury is a major risk factor and thus included in the composite score calculation. A consideration of the type of primary sport is also used in the composite score. The goal is a composite score of 100% for each lower extremity to minimize risk of injury.

Although not validated in the pediatric population, some providers have begun to use YBT as a functional tool in pediatric patients [48, 65]. Consideration for return to sports following rehabilitation of an ACL injury in a young patient may include a YBT composite score of greater than 90% and a side-to-side anterior difference of less than 4 cm.

At the completion of phase three milestones, athletes should be evaluated by their physician for sport participation clearance. The use of a functional brace during all pivoting activities is recommended for a minimum of 6 months from original injury [66]. Consideration of psychological readiness for return to play is made at this time. Psychosocial factors such as coping resources, emotional distress, social support, athletic identity, and fear of reinjury may have important roles in the recovery process after sport-related injuries [67–75]. An athlete's psychological response to the injury and recovery process has an impact on return to sport and return to their previous level of activity after an ACL injury. Pediatric patients and their parents must be also counseled regarding the importance of reporting any activity-related effusion, mechanical symptom, or episodes of instability, as this may risk deterioration of joint function [49]. An annual YBT is recommended for ACL-deficient athletes [76].

Phase 4 (Maintenance Program)

Emphasis on maintenance program and injury prevention is paramount in this age group. An injury prevention program in the pediatric athlete interested in returning to pivoting sports should be tailored to be to the child's physical and mental maturation level. Age-specific programs are guided by the principles of LTAD [48, 50, 58, 77]. Chapter 17 will review injury prevention programs for the pediatric athlete.

Functional Brace

Historically, a functional brace was used as the primary treatment, along with activity modification, for an ACL injury in the skeletally immature athlete [24]. Today, the use of a functional brace remains an important adjunct to physical therapy in the nonoperative treatment of an ACL injury in this age group [6, 7, 17, 26, 39, 50, 51, 66, 78].

The use of a functional brace remains controversial in the treatment of the mature athlete with an ACL injury with or without a reconstruction. Half of all athletes with ACL deficiency will not be able to return to sports without a brace [33]. Although a brace may provide symptomatic relief of instability, a randomized trial in patients ages 18–50 years old with and without a brace did not demonstrate a difference in outcomes or conversion to surgery [32]. This may not be true for all sports or nonathletes [33]. Kocher et al. demonstrated a decrease in knee injuries in skiers who used a functional brace as opposed to those who did not while skiing. In this study, braced skiers had a 2% incidence of a new injury, while non-braced skiers had a 13% incidence ($p = 0.005$) [79].

Biomechanical models have demonstrated improvement in the anterior translation of the tibia with the use of the brace [80]. Rotational stability, particularly anterolateral rotational instability, is not supported by the use of a brace [81]. Regardless of the in vitro justification of the use of a functional ACL brace, a majority of patients with ACL deficiency have symptomatic relief with the use of a brace [33].

The use of a functional brace following an ACL tear in a skeletally immature patient is an important part of the treatment if they intend to return to athletic activity. Standard functional braces used in mature patients will typically not fit a young or prepubescent patient. The lack of physiologic quadriceps and gastrocsoleus muscle hypertrophy in the young ACL-deficient patient may not allow for standard ACL functional bracing that is commonly used in sports medicine practice. Few bracing manufacturers have developed pediatric-specific functional braces (see Table 8.2).

Outcomes Following Nonoperative Treatment of ACL Injury in the Pediatric Patient

A general consensus regarding nonoperative treatment in the ACL-injured patient has been reserved for the young patient who does not wish to play a pivoting sport and does not have residual instability. Retrospective studies have demonstrated a high incidence of continued instability and poor rates of return to athletic activity. A recent systematic review of operative versus nonoperative treatment of ACL injuries in the pediatric and adolescent age group revealed continued instability in 13.6% of injuries treated operatively compared to 75% of those treated nonoperatively [82]. Vavkin and Murray [83] combined ten studies ($n = 476$ patients) on nonoperative pediatric ACL injuries with a high incidence (mean 50.2%) of persistent instability and meniscal and chondral damage requiring further surgical procedures.

Some adult comparisons of operative and nonoperative treatment of isolated ACL injuries have included skeletally mature adolescents. If initially

Table 8.2 A list of available functional braces for the pediatric patient with an ACL injury

Manufacturer	Name of brace	Pediatric specific	Pediatric available sizes				Estimated cost (US Dollars)
			Thigh circumference (in.)	Joint line circumferance (in.)	Calf circumferance (in.)	Joint line medial to lateral Distance (in.)	
DonJoy Orthotics	Full Force	No	13–15.5	12–13	10–12		525
Bledsoe	Jet Pediatric	Yes	11–12.5			3–3.5	300
Townsend	Rebel[a]	No	12.5–15.5		11–12.5		475
Ossur	C180 Rocket	No		9.5–11		3–3.5	680

Provided are the smallest available size for the type of brace, typically extra small (XS). Listed braces are recommended by each manufacturer for the use in a pediatric patient even though they are not pediatric-specific braces (except for the Jet Pediatric brace). Manufacturers will commonly custom fit or adjust listed braces to fit a pediatric patient (i.e., add additional calf padding)

[a]Rebel also comes in Rebel Pro and Rebel Lite. Both of which may be used in a pediatric patient but are not specifically designed for pediatrics. Bolded texts indicate pediatric-specific functional brace

treated nonoperatively, skeletally mature patients may convert to surgical treatment 33–64% of the time [32, 44, 84]. Only 26–40.7% will be able to return to the pre-injury sporting level without surgical treatment of the ACL [6, 23, 33]. Retrospective reviews of pediatric patients with an ACL injury treated conservatively have demonstrated poor functional outcomes and return to play, and delayed treatment may increase the risk of future injury [5, 85]. In a small series of ACL injuries treated nonoperatively with open physis, 9 of 16 (56%) gave up their sports due to their instability [5].

New chondral and meniscal injuries may be seen with no or delayed surgical treatment [9, 10, 35, 82, 86]. After 2 years of nonoperative management of ACL injuries, one series reported more than half of adolescents had additional meniscal tears if returning to athletics [7]. Increased incidence in medial meniscal tears have been seen in those that undergo delayed (> 6 weeks or more) ACL reconstruction [8, 10, 11, 39]. Dumont reviewed 370 youth ACL reconstructions with a significant increase in medial meniscus tears in those with a delay of surgical treatment of 150 days or more [10]. In another retrospective series, young patients were 4.7 times more likely to have a medial meniscus tear if they had an instability episode while returning to sports with ACL deficiency [11]. Some have suggested an increase in irreparable meniscal damage with delayed treatment [9].

Streich et al. prospectively collected and compared pediatric athletes, Tanner stage 1 and 2, who were treated operatively and nonoperatively [1]. The decision to treat operatively with a transphyseal soft tissue reconstruction was based on whether intra-articular pathology was seen on MRI. In this study, 7 of the 12 (58%) patients treated nonoperatively underwent an ACL reconstruction due to persistent instability with six of them having new meniscal pathology. Only 16.6% of patients felt their knee was normal when treated without a reconstruction compared to 81.3% of those who underwent a reconstruction. The International Knee Documentation Committee (IKDC) subjective knee evaluation form was also different between the two groups (median 95 operative versus 87 nonoperative). In another study, Mizuta et al. also followed pediatric ACL injuries treated nonoperatively for a minimum of 36 months [26]. In this series, only one was able to return to their previous sports, and all patients reported symptoms of instability [26]. Graf et al. [7] and Aichroth et al. [85], in a combined series of 35 young nonoperatively treated ACL injuries, found that all patients reported instability, and the average time from return to sports to major instability event was 7 months (range 3–24 months) [7]. However, those who can return to sports without instability may have no difference in performance [3]. A comparative study between early ACL reconstruction, delayed reconstruction, and nonoperative treatment of an ACL injury in skeletally immature patients demonstrated that 62.5% of nonoperative patients had continued instability and poor function [87].

Difficulty with polarizing conclusions makes assimilation of all results difficult. Funahshi et al. ($n = 71$) found no difference in meniscal or chondral damage with delayed treatment in the skeletally immature patient with an ACL injury [4]. Others have reported similar trends [40]. A well-designed prospective cohort by Moksnes et al. of pediatric patients (less than 12 years of age) who underwent nonoperative treatment for a complete ACL injury with formalized physical therapy and return-to-play program had dramatically improved outcomes [2]. All patients had no activity restriction and were provided a functional brace. In this study, kids were transitioned to surgical treatment if they had no restoration of functional stability, multiple giving way episodes, unacceptable reduced activity level, or symptomatic meniscal pathology. At a minimum of a two-year follow-up, 78% of patients did not undergo an ACL reconstruction. The same authors, in a separate study, reported on routine MRI follow-up on 40 pediatric ACL-deficient patients [88]. Of the 13 patients who eventually underwent ACL reconstruction, the incidence of new meniscus tears was 46.2%, while those who did not undergo an ACL reconstruction and returned to pivoting sports had a 3.6% incidence of a new meniscus tear on screening MRI at a

Table 8.3 Reasons for failure of nonoperative treatment of an ACL injury that occurs in the pediatric knee

Failure to implement proper supervised physical therapy
Functional testing and clearance that focuses solely on strength
No functional brace
Noncompliance
Non-coper

minimum of 2 years. Others have also demonstrated that those with ACL deficiency who return to pivoting sports without instability (i.e., copers) do not have an increased risk of future meniscal injury [3].

There are several common reasons why one might fail nonoperative treatment of an ACL injury (Table 8.3). In consideration of the high failure rate of nonoperative treatment demonstrated historically, studies may not have had a structured process for patient selection, supervised rehabilitation program, functional clearance, and bracing following an ACL injury [1, 26]. Additionally, functional tests for clearance, when utilized, may have focused on strength, and not balance, proprioception, and neuromuscular control [5, 7, 26]. Finally, others have attributed failure of nonoperative treatment in the pediatric patient with an ACL injury to noncompliance of activity modification, therapy, or brace use [24].

Conclusion

Many studies have demonstrated the increased rate of associated joint injury incurred in the setting of ongoing ACL instability. Therefore, consensus for avoiding instability is clear, but the indications and role of nonoperative management in achieving functional stability in some patients remain less certain. Current evidence suggests that a nonoperative plan for ACL injury management may be appropriate for selected pediatric patients. The nonoperative plan must be as structured as an operative plan: patient selection, phased rehabilitation and conditioning, psychological coping assessment and resource management, ongoing monitoring for symptoms (instability, effusion, mechanical symptoms), appropriate functional clearance, appropriate brace use, and ongoing injury prevention training are all important components of a nonoperative treatment program. A willingness to comply with a phased, age-appropriate program and understanding of the possibility of conversion to operative management are paramount for the patient, parent, and physician in order to achieve good outcomes with nonoperative management of pediatric ACL injury.

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9 Partial ACL Injuries in Pediatric and Adolescent Athletes

Michael P. McClincy and Benton E. Heyworth

Introduction

Awareness of pediatric ACL injuries has increased substantially over the past two decades. Once thought to be a rare injury, several studies have now shown mid-substance ACL ruptures to be present in the majority of young athletes presenting with acute hemarthroses [1–4]. Numerous studies have shown poor compliance with recommended activity modifications, recurrent instability, and secondary injuries, such as meniscal tears and articular cartilage injuries, associated with non-operative management of ACL ruptures in the pediatric population [5, 6]. As a result, treatment of complete ACL ruptures in pediatric patients now typically consists of surgical reconstruction.

Management of "partial" ACL ruptures is much less clearly defined. A number of studies have shown partial thickness ruptures of the ACL to be quite common in pediatric athletes, with rates of partial tears ranging from a quarter to over half of all cases [1, 4, 7, 8]. In spite of this acknowledgment, to date only one study has focused on the management of partial ACL injuries in a pediatric population [8]. Therefore, the management of partial ACL ruptures in a pediatric population must be derived, in part, from adult literature on the subject.

Ultimately, the definitive management of partial ACL ruptures hinges on the decision between non-operative and operative management. In both the study by Kocher et al., which investigated pediatric patients, and the majority of the adult literature, the decision between non-operative and operative management depends on classifying the knee as functionally stable or unstable [8, 9]. It is often quite difficult to accurately estimate the long-term functional stability of a partially torn ACL. Therefore, this decision-making process must be developed based on the combination of the patient's history, physical examination, imaging, and other diagnostic studies, as outlined in the sections below. As a physician, consideration of *all* of these aspects of the patient's presentation—in the context of their functional demands—is paramount.

Anatomic and Biomechanical Considerations

A deeper level of understanding of ACL anatomy is important to understanding the mechanism of partial ACL injuries and their management. The ACL has been shown to be made up of two distinct but interconnected components, the anteromedial (AM) and posterolateral (PL) bundles, which are named according to

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S.N. Parikh (ed.), *The Pediatric Anterior Cruciate Ligament*,
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their tibial insertion [10–12]. The AM bundle consists of the anteromedial aspect of the ACL's tibial insertion and is found just anterior and lateral to the medial intercondylar tubercle, or medial tibial spine. The AM bundle is generally believed to be isometric throughout the knee range of motion. The exception to this rule involves the anterior-most fibers, which relax at prior to terminal extension to prevent impingement on the intercondylar notch. Due to its insertion site and isometry, the AM bundle is believed to be the primary restraint to anterior translation of the proximal tibia throughout the knee's range of motion [13]. It also supplies ancillary support against internal and external rotation forces [11]. When visualized arthroscopically, the AM bundle is readily visible at all knee positions due to its anterior position.

The PL bundle comprises the posterolateral portion of the ACL tibial insertion and is found just medial to the lateral intercondylar tubercle, or lateral tibial spine. Unlike the AM bundle, the PL bundle fibers are anisometric at varying degrees of knee flexion. During flexion, the PL bundle wraps around the AM bundle at the femur (Fig. 9.1) [12]. The PL bundle fibers are parallel and completely taut in full extension. The PL bundle fibers gradually relax during flexion until 90 degrees, at which point they again become tensioned. Due to its insertion site and anisometric tension, the PL bundle assists in regulating anterior translation in extension and is the principle restraint to tibial rotation at the extents of both extension and flexion [13, 14]. Arthroscopically, the PL bundle is more difficult to identify as the AM bundle obscures it. Previous

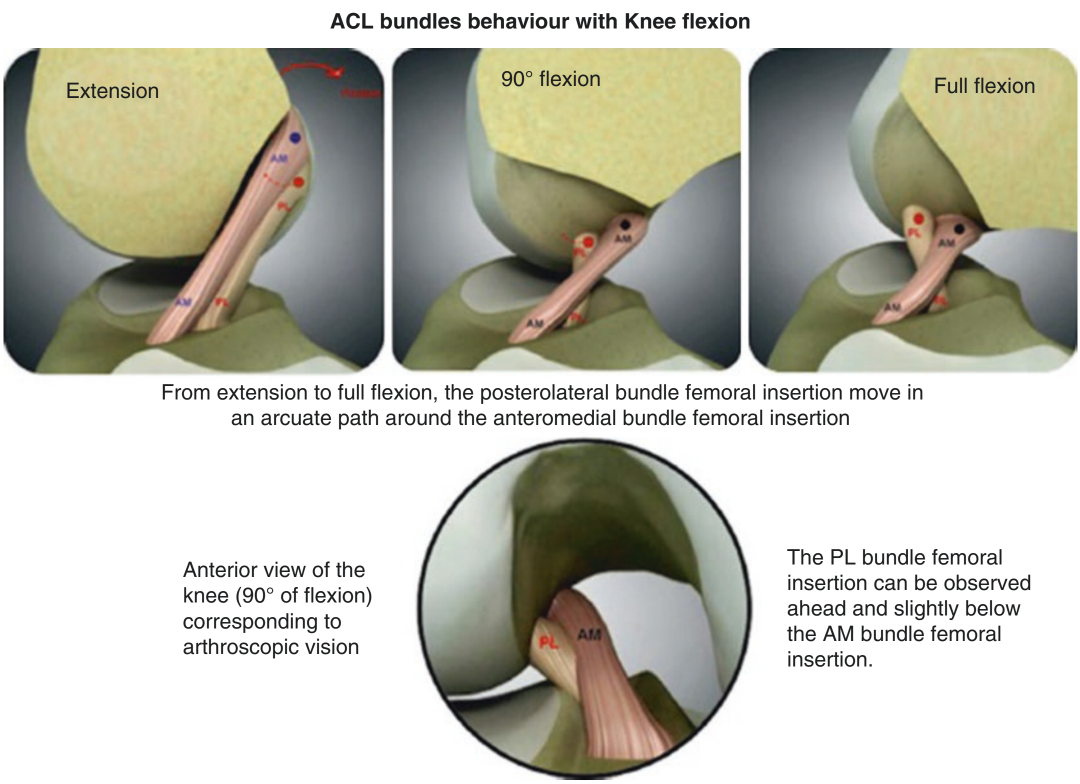

Fig. 9.1 Reprint of "Figure 1: Role of AM and PL bundles during knee flexion" from B. Sonnery-Cottet, P. Colombet. Partial tears of the anterior cruciate ligament. Orthopaedics & Traumatology: Surgery & Research 102 (2016) S59–S67

studies have showed Cabot's position (figure of four) to be beneficial in visualizing the PL bundle intraoperatively [15].

Because the anteromedial bundle remains taught with progressive flexion as the posterolateral bundle relaxes and the posterolateral bundle tensions in extension and internal rotation, this mechanism creates a reciprocal tensioning pattern that places each portion of the anterior cruciate ligament at risk for rupture, depending on the position of the knee and mechanism of injury. The AM bundle is more susceptible to injuries with the knee in flexion and would result in an increase in anterior translation in flexion, with little effect on hyperextension or rotational stability [10, 11].

Hyperextension and internal rotation place the PL bundle at greater risk for injury [10, 11]. Rupture of the PL bundle would lead to excessive anterior translation in extension, may result in an increase in hyperextension, and significantly compromise the rotatory stability of the knee both in extension (internal and external rotation) and mid-flexion (external rotation) [11].

Aside from the anatomic considerations of a two-bundle ACL, it is also essential to understand the structural properties of the native ACL and the structural changes it undergoes with injury. The fibers of the ACL can elongate upward of 50% compared to their resting length prior to catastrophic failure [16]. In such cases of elongation without ultimate rupture, substantial interstitial damage of the anterior cruciate ligament fibers can occur while still presenting as a visibly normal ligament. In line with the two-bundle concept, many studies have shown that the rupture of a single bundle in the ACL almost ensures that the "intact" bundle will have undergone aplastic deformation [16–18]. This concept calls into question the possibility of a truly "partial" rupture of the ACL and reinforces the difficulty of the task in determining which knee injuries will prove to be unstable over time.

Compounding the issue of interstitial damage is the finding that the ACL has little capacity to heal after injury [19, 20]. Ligamentous healing is directly correlated with vascular supply, which drives the reparative process. Multiple studies have shown that the injured ACL is devoid of necessary levels of vascular proliferation, likely due to disruption of its native epiligamentous blood supply following injury [21, 22]. It is generally accepted that ruptured fibers will resorb or scar into surrounding structures (such as the PCL or other synovial structures). The inadequacy of neovascularization raises concerns about the ability of microscopic damage to resolve and restore function in partial thickness injuries. It is notable that while ACL healing in skeletally immature individuals has shown greater success in an animal model, limited rigorous basic science or clinical evidence exists, and further studies are warranted [23].

Patient Evaluation

History

ACL injuries in children and adolescents often present with symptoms that are similar to those in adults. When interviewing pediatric patients, it is important to keep the patients actively involved in the interview process, even in cases where parents are able to provide much of the salient clinical information. Most partial injuries of the anterior cruciate ligament result from noncontact twisting injuries during sporting activities, rather than slightly higher energy collisions. Again, position of the knee will likely determine which portion of the ACL is ruptured, with AM bundle susceptible in flexion and PL in extension. The mechanism of injury involves the femur being externally rotated on a fixed lower extremity or the tibia being internally rotated relative to the femur as a valgus moment is applied to the knee joint [16, 24, 25]. Patients with partial ACL ruptures frequently recall an audible or appreciable sensation of a "pop" or tearing at the time of injury and generally are incapable of continuing in their sporting activity. After removal from their sporting activity, they frequently experience generalized knee pain that is difficult to localize, swelling, and difficulty with weight bearing activities and may experience a sensation of knee instability, which may be attributable to their ligamentous injury or the resultant joint effusion [9, 16, 26, 27]. Frequently, patients may report an inability to achieve terminal extension, which may be the result of avoiding pressure on the associated bone bruises or the mechanical phenomenon of a ruptured fragment extruding into the lateral joint space or adhering to the infrapatellar fat pad [28, 29].

Physical Examination

Physical examination is particularly crucial in cases of suspected partial ACL rupture, as the accurate clinical diagnosis is largely based on the degree of laxity detected on examination. Examination of children, specifically those presenting acutely after injury, can be difficult. Every examination should start with the contralateral extremity to put the patient at ease, permit an explanation and demonstration of relevant physical examination maneuvers, and also allow appreciation of native tissue laxity. When evaluating the injured extremity, always check for gross signs of trauma, including a hemarthrosis or effusion. A hemarthrosis commonly develops but is not required for diagnosis [30, 31].

Measurement of the anterior translation and rotatory stability of the injured knee is paramount. The anterior drawer, Lachman, and pivot shift are the most common methods used to assess the anterior translation and rotatory stability of the knee. Typically, these measurements quantify the degree of laxity present in the injured extremity and compare it both to normative thresholds as well as to the contralateral, uninjured extremity as an internal control [9, 32, 33].

When gauging anterior translation laxity, the Lachman test has superior sensitivity when compared to the anterior drawer test, and previous biomechanics studies have noted that the ACL undergoes greater strain at 30° of flexion compared to 90° [10, 11, 34]. Sectioning of the ACL also results in more anterior translation at 30° of flexion than at 90°. Of note, neutral rotation must be maintained to avoid interference by secondary stabilizers [34]. While the anterior drawer test is commonly described and performed as a means to assess ACL function, it can be an unreliable measure of anterior knee laxity [35, 36]. The anterior drawer test is complicated clinically by difficulty flexing the knee to 90° due to pain in acute cases, spastic contraction of the hamstring muscles dampening exam results, and greater support against anterior translation by secondary stabilizers at the 90° flexion position (including the osseous contour of the joint, the posterior meniscal horns, and the medial collateral ligament). Indeed, some authors feel that when an anterior drawer test is positive, secondary injuries should be considered [9].

While measurement of anterior translation is essential when considering ACL injuries, cadaveric and clinical data has called into question the reliability of the Lachman and anterior drawer exams in evaluating partial ACL injuries. Numerous studies have showed difficulty in distinguishing partial ACL tears from intact ACLs on examination alone [11, 18, 37]. Hole et al. showed that physical exam and KT-1000 testing was incapable of distinguishing between an intact ACL and a partial rupture involving an entire functional bundle (PL). They also noted that it was unlikely to distinguish between a fully ruptured ACL and one with a 75% partial rupture (entire PL and 50% AM). In a similar study, Lintner et al. found that sectioning of the AM bundle did not examine differently compared to an intact ACL, again using physical examination and KT-1000 testing [18].

The pivot shift test, therefore, is considered superior to both the anterior drawer and Lachman tests for defining anterior cruciate ligament insufficiency, particularly functional insufficiency. The pivot shift phenomenon results in a subluxation/reduction mechanism present only in ACL-deficient knees (either complete ruptures or "nonfunctional" partial ruptures). In ACL-deficient knees, the femur sags posteriorly to the tibia in extension due to gravitational pull. This position brings the iliotibial band anterior to the center of rotation of the knee in extension, but as the knee is flexed and the gravitational pull is negated, the femur spontaneously reduces atop the tibia. A palpable clunk is noted as the iliotibial band passes behind the center of rotation of the knee [38]. The test result is graded as 1+ (glide), 2+ (jump), or 3+ (transient lock). A positive result is indicative of anterior cruciate ligament deficiency, either by complete rupture or nonfunctional partial rupture. This test is especially useful for identifying anterior laxity that will become clinically disabling [8, 35, 38]. When specifically considering children, Kocher et al. highlighted subtle laxity on pivot shift testing (normal versus 1+ glide) as a strong predictor for the need for subsequent ACL reconstruction in arthroscopically diagnosed partial injuries in the pediatric age group. The major limitation of the pivot shift test is that it tends to be the most painful exam maneuver in the ACL evaluation. Especially in children, significant guarding should be expected and clinic testing may not provide an accurate representation of laxity. The exam can be repeated a few weeks after injury once the acute pain has abated; however, numerous studies recommend an evaluation under anesthesia to obtain a true sense of pivot shift stability [8, 38].

Diagnostics

Arthrometer Testing

KT-1000 arthrometer testing diagnostic of anterior cruciate ligament deficiency is defined as a maximum side-to-side difference of >3 mm, a maximum manual translation of >10 mm, or a compliance index of >2 mm with application of a 20-lb. force at 30° of knee flexion [39]. The primary author of that arthrometric study has later suggested that low-grade side-to-side differences (i.e., <3 mm) in KT-1000 measurements are suggestive of a partial ACL rupture and that side-to-side discrepancies >3 mm are very rarely found with partial injuries [9]. Cadaveric data corroborates this idea in showing that the average anterior laxity with partial ACL rupture is 1.3 mm [18]. Regardless, when the difference between partial and complete rupture measurements lies between 1.3 mm and 3 mm, the diagnostic strength of the tool is moderate at best.

Few clinical studies have included arthrometric data when evaluating partial ACL ruptures. Noyes et al. showed a trend toward progressive ACL deficiency in patients presenting with an initial side-to-side difference in laxity of >5 mm. Bak et al. reported that 71% of patients had a mean side-to- side difference of <2 mm with all remaining patients found to have a difference < 4 mm [40]. Fruensgaard and Johannsen reported an average difference of 2.8 mm in patients with clinically unstable knees and 2 mm in patients with clinically stable knees [41]. Other studies have shown conflicting results of low-level side-to-side differences (<3 mm) at injury presentation in predicting long-term stability of the knee and need for eventual reconstruction [37, 42, 43].

Newer arthrometer technology has shown improved capabilities of distinguishing between complete and partial ACL ruptures in isolated studies. Robert et al. showed a sensitivity of 80% and specificity of 87% with the use of the GeNouRoB arthrometer in accurately identifying partial ACL ruptures [44]. No studies are available regarding arthrometric data in children with partial ACL ruptures. Overall, arthrometric testing of patients is a reasonable tool to evaluate anterior translation but lacks the sensitivity and predictive power to be diagnostic. As a result, it has not found widespread application in most clinical settings.

Magnetic Resonance Imaging

MRI is the standard diagnostic tool to detect an injury to the ACL. MRI allows visualization of the ACL itself along with the other articular structures about the knee that are at risk in ACL-deficient athletes, including the menisci, articular cartilage, the medial collateral ligament (MCL), and structures of the posterolateral corner (PLC). It also allows visualization of the lateral-sided bone bruise patterns typical in cases of ACL rupture. While MRI has become the diagnostic imaging standard for ACL injuries, standard MRI performs poorly when attempting to discern complete versus partial ligament ruptures. Multiple studies have documented low sensitivity and specificity of conventional MRI in diagnosing partial thickness ACL ruptures [45–48]. In the lone study specific to pediatric patients, MR sensitivity was 71% for diagnosing partial ruptures [8].

The low diagnostic utility of MRI arises specifically from difficulty distinguishing between complete and partial ruptures. Both diagnoses feature high signal changes within the ligament, mass effect, abnormal ligamentous contour, and fiber discontinuity. However, to diagnose a partial rupture, it is imperative to show contiguous fibers [49]. Due to the oblique course of the native ACL, the typical axial, sagittal, and coronal MRI sequences do not adequately capture the ligament in full, making determination of fiber integrity difficult [50, 51]. Several studies have been performed with the inclusion of oblique imaging sequences in an effort to better capture the anatomic course of the ACL and have shown modest improvements over conventional MR imaging [45, 50, 52, 53]. Isolated studies evaluating the effect of magnet strength (1.5-T vs. 3-T) and novel imaging sequences have also been reported with varying degrees of success [54–57]. Clearly, more research is needed to improve our imaging capabilities for accurately identifying these injuries.

Diagnostic Arthroscopy

Diagnosis of partial ACL ruptures is quite difficult based on patient history, examination, and ancillary diagnostics, as discussed previously. As such, physicians may elect to perform a diagnostic arthroscopy in cases of suspected partial ligament ruptures to provide a definitive diagnosis [8, 18, 27, 29–31]. This option has multiple benefits, as it also permits an examination under anesthesia to best evaluate the functional competency of the ACL and permits a direct visualization of the ACL to discern the degree of ligament injury. Noyes et al. showed that diagnostic arthroscopy was the most accurate means of assessing the degree of ligament damage and showed that the degree of tear predicted the future development of insufficiency symptoms [27]. Kocher et al. showed that diagnostic arthroscopy was accurate in evaluating the degree of ligament injury and showed that ruptures with >50% of ligament involvement had a significantly higher rate of requiring delayed reconstruction. This study also demonstrated that anatomic *location* of tear was also important in a pediatric population, with posterolateral tears requiring eventual reconstruction at a higher rate [8].

While these studies have shown arthroscopic grading to be predictive of outcomes, interestingly, other studies have shown no correlation [41, 43, 58]. This juxtaposition of evidence highlights the difficulty in predicting overall function of the ACL after injury. As mentioned previously, normal-appearing ACL tissue may mask a substantial injury through either microscopic plastic deformation that prevents normal function or through providing misleading appearance of normality on arthroscopic evaluation. This scenario can arise when the ligament’s synovial sheath remains intact despite a sizable ligamentous rupture, normal appearance of the tibial insertion anatomy despite injury at the femoral wall origin, or scarring of injured ligament to the PCL, intercondylar notch, or other surrounding synovial tissues, giving the false appearance of tissue integrity. In each of these cases, the degree of injury is underestimated and can lead to a missed diagnosis of substantial injury [59]. This evidence suggests that arthroscopy may be used as a valuable tool in the diagnosis of partial ACL ruptures but should not be used in isolation to determine the eventual treatment pathway for patients. Instead, arthroscopic results should be considered in the context of the physical examination and imaging data to help refine the treatment of choice.

Treatment

Injury Grading

As described in the preceding sections, there is no perfect means by which to accurately diagnose a partial ACL tear, let alone determine its future functional performance. Noyes used arthroscopic findings, with partial tears classified as <25%, 50%, or 75% ligament ruptures, to determine the need for reconstruction [27]. DeFranco and Bach used a combination of findings to determine severity of injury, diagnosing [9] “functional” partial ACL ruptures based on the following four criteria: (1) asymmetry on

Lachman testing, (2) a negative pivot shift test on exam under anesthesia, (3) a low-grade KT-1000 arthrometer measurement (<3 mm), and (4) arthroscopic evidence of a partial anterior cruciate ligament injury. If the four qualities are met on a patient evaluation, the patient is diagnosed with a partial ACL rupture that has maintained the functional integrity of the ACL. Their system relied primarily on the pivot shift examination under anesthesia as the benchmark for determining ligamentous stability, as an asymmetric positive pivot shift of any magnitude indicated functional *incompetence* of the ACL, for which ACL reconstruction was advocated.

The pediatric literature by Kocher et al. showed outcomes results that reflected elements of the approaches of both Noyes and DeFranco/Bach. Their study noted that arthroscopic size of rupture was predictive of eventual need for reconstruction, with tears >50% failing nearly three times more frequently than those involving <50%, which parallels Noyes' observations. They noted a similar finding with anatomic location of tear at arthroscopy, with PL tears undergoing reconstruction three times more frequently than AM tears. The study also found trends toward instability predicting future need for reconstruction depending on examination findings. One hundred percent of patients with a subtly abnormal pivot shift examination (5/5 patients) underwent eventual reconstruction, while only one in four patients with a normal pivot shift required eventual reconstruction, similar to DeFranco and Bach's guidelines. On Lachman testing, patients with <3 mm difference underwent subsequent reconstruction in 9% of cases with patients with 3–5 mm difference required reconstruction in 38% of cases. Lastly, the study noted that age was a significant predictor, with *older* adolescents (>14 years old) which were found to be more likely to progress to ACL insufficiency symptoms than their younger counterparts [8].

Overall, we recommend a multimodal approach to diagnosing partial ACL ruptures and prescribing a specific treatment pathway. All patients who are felt to have a partial thickness ACL rupture due to injury mechanism and subsequent symptoms and examination findings, such as subtle asymmetric laxity, should receive an MR evaluation to evaluate the status of the ACL and other soft tissue structures of the knee. Based on this data, patients felt to have a clinically stable knee should enter a non-operative treatment pathway, which is described in later sections. Patients with borderline exam and MR findings concerning for potential ACL insufficiency should undergo an operative procedure involving an examination under anesthesia and diagnostic arthroscopy. Signs of ACL insufficiency on examination under anesthesia, specifically a positive pivot shift of any grade, should undergo subsequent reconstruction. If the knee proves stable on examination under anesthesia, arthroscopic findings with regard to size and location of tear should be considered in the context of the young athlete's functional demands to determine non-operative versus operative treatment. One of the challenges of this overall approach is the discussion with the family and patient, who may wake up with two extremely different treatment pathways pursued and postoperative courses. However, a thoughtful preoperative explanation of the goals of achieving the optimal balance of each patient's functional goals, while being mindful of both ligament preservation and joint preservation principles, should help families understand the complex nature of management of this specific subset of injuries.

Non-operative Management

Non-operative management should be reserved for patients with partial ACL tears that maintain the basic native function of the ligament. Kocher et al. described the non-operative pathway used in his pediatric cohort as follows: (1) weight bearing restriction of touchdown only for 6–8 weeks then advanced as tolerated, (2) a hinged knee brace was used to prevent hyperextension (the study protocol avoided passive terminal extension for 6 weeks and active terminal extension for 12 weeks), (3) a physical therapy program was started early in the recovery process and focused on hamstring strengthening for dynamic support, and (4) patients typically returned to play at 3 months from the time of injury and were expected to use a brace [8].

The majority of adult literature also endorses a brief period of limited weight and motion restriction accompanied by a progressive rehabilitation program [27, 30, 32, 33, 37, 40, 43]. Other authors advocate an accelerated course including early progressive weight bearing and initiation of a physical therapy protocol without motion restriction with the goal of preventing arthrofibrosis [9]. Overall, a rehabilitation program should include stepwise progression through range-of-motion exercises, lower extremity and core muscle strengthening, cardiovascular endurance training, perturbation training, and sport-specific skill training [60, 61]. Prior to clearance for return to sport, strength and functional performance tests should be performed to ensure the athlete's rehabilitation is optimized [62]. It is essential to maintain close observation on these patients throughout the rehabilitation and return-to-play period to ensure that functional knee stability is maintained.

Results of non-operative management of partial ACL ruptures have shown mixed results. Proponents of non-operative treatment define successful outcomes by avoidance of surgical reconstruction with good-to-excellent functional outcomes, maintenance or slight modification of activity level, and maintenance of subtle difference in ligamentous laxity [8, 27, 43, 63, 64]. Others studies have showed poor results and favor operative management in all but low-demand individuals, which is an uncommon scenario when considering pediatric populations [8, 11]. As no definitive criteria was used for classifying partial ACL ruptures in these studies, the disparate results may be due to differences in baseline ACL function after injury.

Operative Management

In pediatric patients with clinical findings of ACL insufficiency, operative management is recommended due to a relatively poor track record of non-operative management in young athletes [5, 6]. In the sole article discussing management of pediatric partial ACL ruptures, complete takedown of the native ligament and subsequent reconstruction was performed in ACL insufficient cases [8]. This technique is also generally endorsed in adult literature, and the outcomes of complete ACL reconstruction for partial tears mirror those for complete tears which is discussed elsewhere [9]. ACL reconstructions for partial tears can be managed postoperatively with the standard protocols used following reconstruction of compete tears.

More recently, some adult studies have advocated a concept of "selective reconstruction" where only the injured portions (i.e., bundles) of the ACL undergo reconstruction. The intact portions of the native ACL are left intact which provides the benefit of proprioceptive fibers and theoretically reduces the diameter of reconstructive bone tunnels. Multiple studies comparing conventional reconstruction to selective reconstruction have showed the two techniques to be similar with regard to knee stability, outcomes scores and survivorship in short- to mid-range follow-up [65–69]. Further studies are clearly needed to better understand the long-term function of these selective reconstructions and their specific applicability to a pediatric population.

Outcomes

The outcomes of ACL reconstruction for partial tears have not been reported in a pediatric population. In the adult literature, standard ACL reconstruction for partial tears has mirrored the postoperative outcomes for complete tears [9]. The results of conventional ACL reconstructions in pediatric patients will be discussed in a later chapter. Augmentation procedures have been shown to have equivocal results to standard reconstructions in adults, but no data is available for review in pediatric patients [65–69].

With regard to non-operative treatment, the study by Kocher et al. remains the only investigation to document outcomes following conservative management of partial ACL ruptures in children [8]. This study's survival analysis documented risk factors for progression of ligamentous instability requiring subsequent reconstruction, including older age (>14 years), posterolateral bundle tear, and tears involving >50% of the ligament (Fig. 9.2). Aside from progression to reconstruction, patients who avoided reconstruction still showed significantly lower

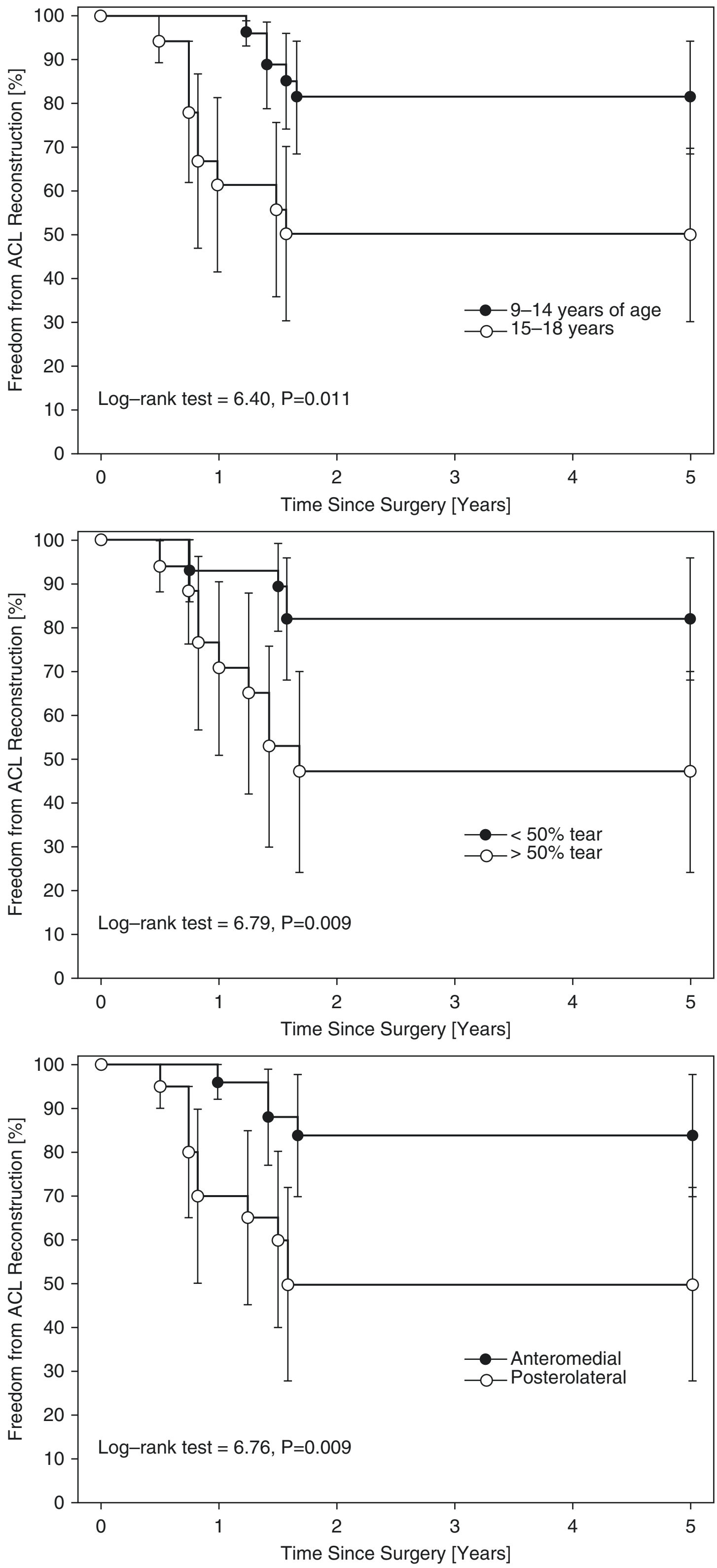

Fig. 9.2 Reprint of Figs. 2–4 from Kocher, M. S., et al. (2002). "Partial tears of the anterior cruciate ligament in children and adolescents." *Am J Sports Med* 30 [5]: 697–703

Lysholm scores, patient satisfaction, Cincinnati sports activity scores, Cincinnati ADL scores, and Cincinnati sports function scores when their tears were large (>50%) or posterolateral. Patients with anteromedial tears or small (<50%) showed very high scores in all domains.

These findings mirror results in the adult literature, which shows a variable degree of success in non-operative management of partial ACL tears. The success of this treatment pathway is most likely due to appropriate diagnosis of adequate clinical stability of the remnant ACL fibers. A nonfunctional ACL that undergoes non-operative management should be expected to follow the trend of a conservatively managed complete rupture. Vavken and Murray reviewed 47 studies focusing on the operative and non-operative management outcomes of ACL injuries in pediatric patients and showed operative reconstruction to have superior outcomes with regard to patient outcomes, future instability, and development of secondary injuries [6]. Studies have shown a time-sensitive effect on delayed ACL reconstruction in pediatric patients in the development of secondary injuries [5, 70]. Lawrence et al. showed that delaying reconstruction >12 weeks was associated with a 4-fold increase in medial meniscal tears, a 5.6-fold increase in medial compartment chondral injury, and an 11.5-fold increase in lateral compartment chondral injury. They also noted a continuous time-dependent relationship between surgical delay and development of medial meniscal or lateral/patellofemoral chondral injuries [5].

Summary

Multiple studies have shown partial thickness ruptures of the ACL to be quite common in pediatric athletes, with rates of partial tears ranging from a quarter to over half of all cases [1, 4, 7, 8]. Despite this acknowledgment, to date only one investigation has focused on the management of partial ACL injuries in a pediatric population [8]. The management and outcome of partial ACL ruptures are highly linked to diagnostic decision-making of treating orthopedic surgeons in advocating non-operative versus operative management. We recommend a multimodal decision-making process incorporating results from patient history, physical examination, imaging, and a low threshold to performing a diagnostic arthroscopy, if indicated. While pediatric athletes with partial ACL ruptures may have improved healing capabilities, compared with adult, persistent ligamentous instability in this active group can lead to significant secondary injuries with concerning adverse effects on lifetime joint health. More high-quality evidence is needed to help guide the diagnosis and management of partial ACL ruptures in pediatric patients.

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10 Surgical Considerations and Treatment Algorithm for ACL Tear

Marios G. Lykissas, Ioannis Gkiatas, and Georgios Kontakis

Introduction

The rate of anterior cruciate ligament (ACL) reconstruction per 100,000 population aged 3–20 years has increased nearly threefold over a 20-year period, with peak incidence in late adolescence [1]. Management of ACL tears in skeletally immature patients remains controversial secondary to a lack in the basic science literature on physeal growth, ACL growth, and response to injury. Clinical studies published on the treatment of this condition have contributed to the confusion by having poor methodology and low level of evidence and combining patients with different levels of skeletal maturity and methods of treatment.

Nonoperative Management

Nonoperative management of ACL tears in children and adolescents is an especially seductive approach. The advantages of delaying surgery include additional psychological maturation of the patient, which facilitates compliance with postoperative rehabilitation, and greater skeletal maturity, which allows for a more familiar traditional surgical procedure. For these two reasons, and in order to eliminate the risk of growth disturbances, many surgeons still advocate a nonoperative approach till the end of child's growth despite the poor results [2–5]. Poor results after conservative treatment of complete ACL tears include recurrent instability episodes, meniscal and articular cartilage damage, and poor satisfaction with sports performance [6]. Poor meniscal condition plus an ACL tear portends osteoarthritis [7, 8].

Many surgeons have held historical concerns that operative treatment may lead to physeal damage, growth arrest, and/or angular deformities, which, in turns, have led patients and surgeons to elect either nonoperative management or to delay ACL reconstruction until growth has been completed. However, because of the recent knowledge that nonoperative treatment and delayed ACL reconstruction are both associated with worse outcomes [4, 9] coupled with the newer surgical techniques, more patients and surgeons are opting for early ACL reconstruction in children and adolescents. It has been showed that in children who return to sports without reconstruction, osteoarthritic changes may be present on radiography in less than 12 years post-injury [6, 10–13].

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Surgical Management

Operative techniques for ACL reconstruction in children can be categorized in the following categories based on the bone-tunnel relationship to the physes: (1) extraphyseal or ACL reconstruction without bone tunnels, (2) all-epiphyseal (or trans-epiphyseal) or Anderson's technique (including all modifications of Anderson technique) [7, 14–16], (3) hybrid techniques (physeal sparing on the femur and transphyseal on the tibia), and (4) transphyseal or drilling across the physis. Soft tissue autograft is favored graft option for children; the types of graft that have been reported include allograft tendon, patellar tendon autograft, bone-tendon-bone (BTB) autograft, quadriceps tendon autograft, or hamstring tendon autograft [17]. Following is the overview of various surgical techniques of ACL reconstruction in skeletally immature patients.

Extraphyseal Techniques

As far as *extraphyseal* surgical technique is concerned, the modified MacIntosh procedure has gained more attention as a combined extra- and intra-articular physeal-sparing ACL reconstruction technique that uses a part of the iliotibial band. The central one-third of the iliotibial band is harvested proximally and left attached to its insertion on Gerdy's tubercle distally. The free end of the pedicled iliotibial graft is brought through the knee joint in the over-the-top position, then under the intrameniscal ligament, and finally sutured to the periosteum anteriorly. The graft is also secured on the distal lateral femoral periosteum and intermuscular septum with sutures.

Long-term data on *extraphyseal* ACL reconstruction found good and excellent Lysholm scores on 52 out of 84 knees at 9.8 years' follow-up; 13 out of 84 reported poor outcomes [18]. This study also included radiographic data on 30 of the 84 patients and reported an average Hospital for Special Surgery (HSS) ACL radiographic score of 20.9. This is a 28-point score which assigns points according to the severity of periarticular and degenerative radiographic changes. The lower the score, the more severe the radiographic changes. Also of note, 54% of these patients had reduced their level of activity since the injury.

Although the iliotibial band is a relatively weak graft and is not placed isometrically on either the tibia or the femur, the functional results appear to be good. More specifically, in a group of 44 patients treated operatively with iliotibial band graft, only two underwent revision surgery. In the remaining 42 patients, the mean International Knee Documentation Committee (IKDC) subjective knee score was 95.7 ± 6.0 points, and the mean Lysholm knee score was 95.7 ± 6.7 points [19]. Though results of the technique are favorable for all skeletally immature patients, most authors use this technique for very young patients, in Tanner stages I or II.

All-Epiphyseal Techniques

The *all-epiphyseal* ACL reconstruction technique utilizes bone tunnels that are confined to the distal femoral and proximal tibial epiphysis, thereby avoiding physeal tissue entirely [17]. Many different all-epiphyseal techniques have been described. The first and most common all-epiphyseal surgical technique was described by Anderson in 2004 [20]. According to Anderson's technique, a bone tunnel is drilled in an outside-in fashion in the distal femoral and proximal tibial epiphysis, and a hamstring autograft is secured with suspensory cortical fixation on the femoral side and a suture over a screw on the tibial side [21].

There are a variety of fixation techniques described for securing the all-epiphyseal graft. A recently described technique utilizes an interference screw to secure the graft on the femur, while the graft is looped around a cortical button which is secured on the tibia (OrthoPediatrics Corp, Warsaw, IN). This technique has the reported advantages of all-epiphyseal fixation, including anatomic ACL footprint restoration and physeal avoidance. Moreover, it employs novel graft fixation methods which may afford enhanced pullout strength in epiphyseal bone; however, there are limited published data available at this time to fully support this. The Cordasco-Green "all-epiphyseal, all-inside" technique modified the technique described by Lawrence et al. by employing cortical button suspensory fixation on both the femur and the tibia. This reconstruction involves inside-out drilling of the proximal tibial and the distal femoral epiphyseal sockets, leaving cortically based bone bridges for securing a quadrupled hamstring autograft with suspensory fixation [3, 16]. This method offers the continued advantages of not crossing the physes with bone tunnels nor tensioning the graft across the physis with sutures, but additionally avoiding the use of screw fixation in softer epiphyseal bone, for which there is a paucity of evidence regarding biomechanical pullout strength.

In 2012 Lykissas et al. [15] described an all-epiphyseal surgical technique where a split tibial tunnel is used. It is a modification of the Anderson's technique of tibial tunnel placement and fixation. Besides minimizing the risk of growth disturbances that an all-epiphyseal technique offers, the split tibial tunnel increases the safety margin by minimizing the tibial epiphysis tunnel sizes, in addition to avoiding damage into the growth plate. The bone bridge between the two tunnels in the proximal tibial epiphysis serves a solid low-profile fixation post and thus avoids any hardware or fixation across the tibial physis.

Hybrid Techniques

Some authors prefer a *partial transphyseal* technique, crossing the proximal tibial physis but sparing the distal femoral physis [17, 22, 23]. The rationale of this technique is that growth disturbances are mostly secondary to eccentric damage to the distal femoral physis rather than the central graft tunnels used for tibial fixation. Furthermore, during skeletal development the tibial physis has less growth and closes more centrally and earlier than the femoral physis.

Transphyseal Techniques

More mature, low-risk, pubescent Tanner stage IV patients are treated with a transphyseal ACL reconstruction using quadruple hamstring grafts fixed with an endobutton proximally and a screw and a post distally. Postpubescent patients in Tanner stage V of development, including males older than 16 years and females older than 14 years of age, may be safely treated with a standard adult ACL reconstruction surgical technique, including bone-tendon grafts and aperture fixation.

Despite the growing number of ACL reconstruction surgeries being performed in the pediatric population, there is no consensus on the optimal surgical technique [24]. In 2011 Kennedy et al. [24] presented an experimental study, where they tried to evaluate the biomechanical results of three pediatric ACL reconstruction physeal-sparing techniques in skeletally immature patients. These techniques were the all-epiphyseal technique, the transphyseal over-the-top technique, and the iliotibial band reconstruction. The results were compared regarding anteroposterior translation, internal rotation, varus angulation, and coupled knee motion. According to the authors, the all-epiphyseal and the transphyseal over-the-top reconstruction were unable to restore anteroposterior and rotational stability at lower flexion angles. The iliotibial reconstruction was able to restore native knee anteroposterior stability at all flexion angles, but it led to a decreased internal and varus rotation when compared with the ACL-intact state, suggesting that this reconstruction technique may overconstrain rotational movements of the knee.

Treatment Algorithm

Several treatment algorithms have been published in the literature. The more conservative approach to management of ACL reconstruction in children uses a selective approach of reconstruction only in symptomatic patients (Fig. 10.1) [2]. With increased recognition of importance of meniscus, some authors recommend treatment of large or

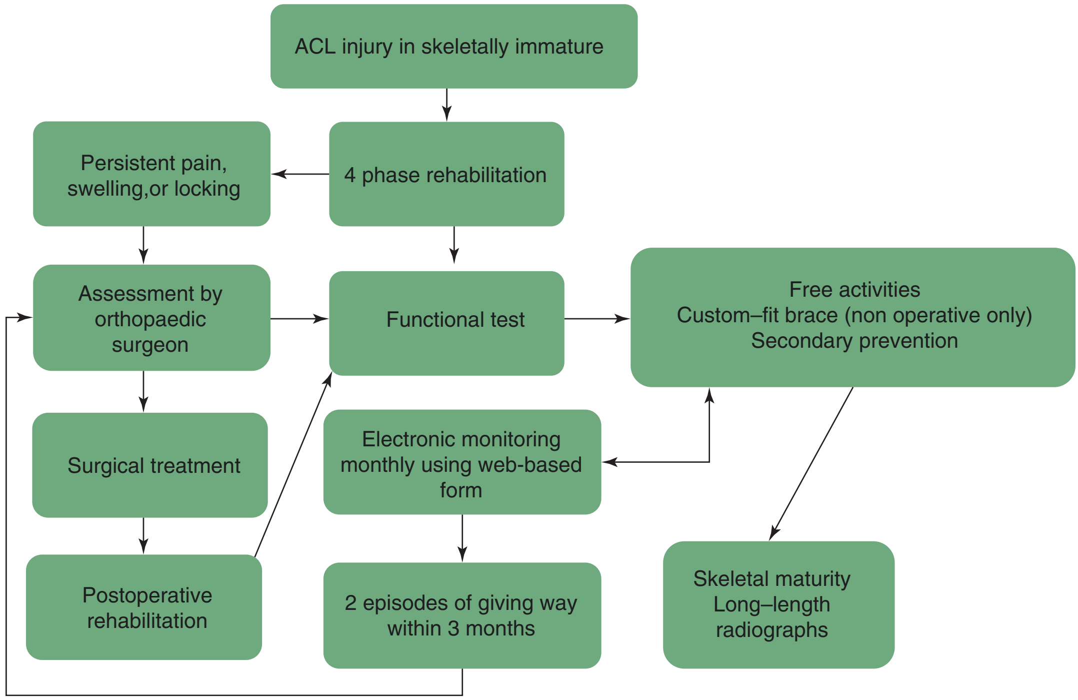

Fig. 10.1 Proposed conservative treatment algorithm for anterior cruciate ligament injury in skeletally immature individuals (Adapted from Management of anterior cruciate ligament injuries in skeletally immature individuals. J Orthop Sports Phys Ther, 2012. 42(3): p. 172–83)

unstable meniscus tears primarily and delaying ACL reconstruction till patient approaches skeletal maturity [4]. Currently, most pediatric sports orthopedic surgeons would prefer to perform ACL reconstruction at the time of injury, irrespective of patient's age or activity level. The type of procedure would depend on several factors including skeletal maturity, growth remaining, Tanner staging, size of the knee, and physician experience and expertise (Figs. 10.2 and 10.3) [3, 25].

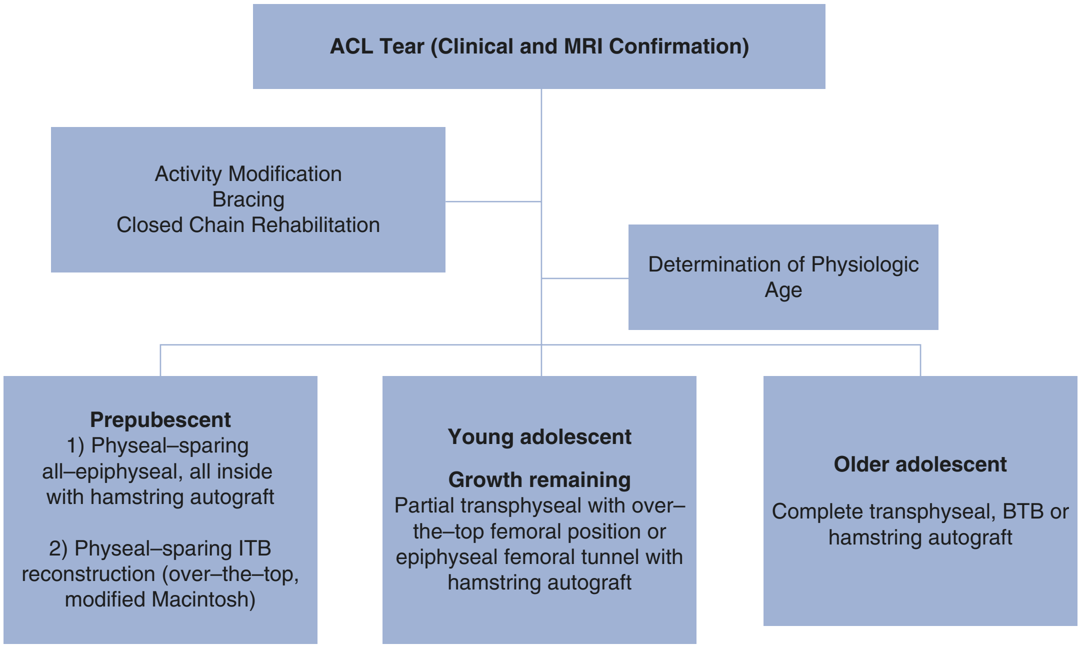

Fig. 10.2 Treatment algorithm devised on the basis of the available data and technical considerations. Surgical decision-making is based on several patient-related variables: clinical instability, associated intra-articular pathology, patient activity level and goals, and skeletal age (Adapted from Reconstruction 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(5): p. e28)

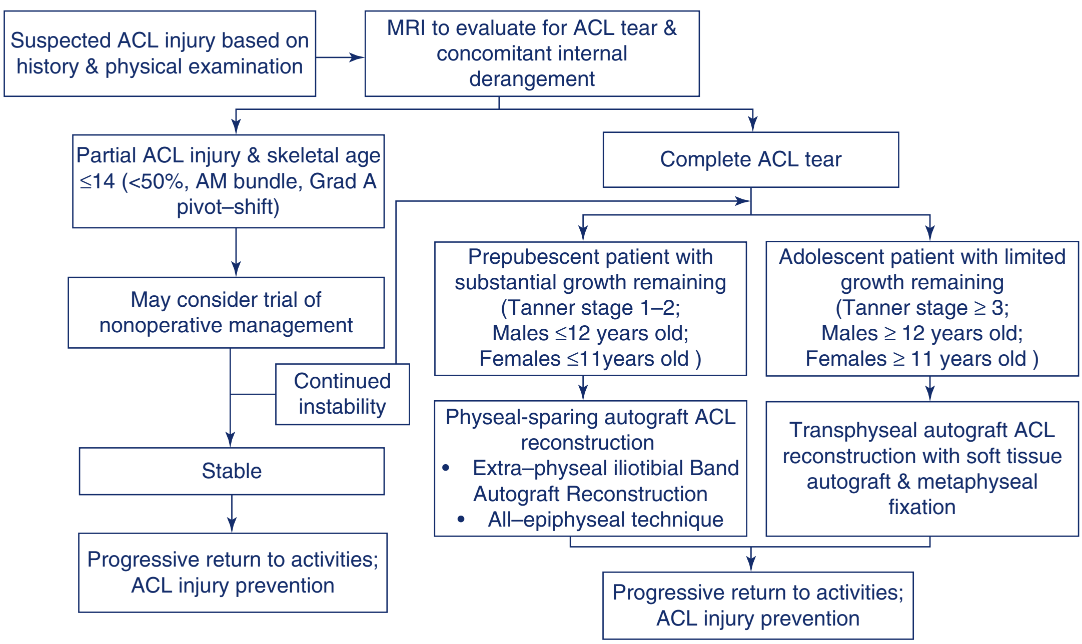

Fig. 10.3 Diagnostic and treatment flowchart for the management of ACL injury in children and adolescents (Adapted from Management of ACL Injuries in Children and Adolescents. J Bone Joint Surg Am, 2017. 99(7): p. 600–612)

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Risk Factors and Practical Considerations During ACL Reconstruction

11

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Introduction

The rate of anterior cruciate ligament (ACL) injuries in younger patients has continued to increase. The treatment rationale and techniques for management of pediatric ACL tears have evolved. Despite improved diagnosis and management of ACL tears in skeletally immature patients, there still continues to be controversies related to it. The current chapter would provide an overview of the risk factors for ACL injury and would discuss the strategies related to assessment of skeletal growth and treatment approach. It would provide practical considerations and decision-making tips during ACL reconstruction in these patients, including graft choices, safe tunnel placement, and fixation techniques. Finally, ACL reconstruction in rare situations would be briefly reviewed.

Risk Factors

Many risk factors have been identified for ACL tears, primarily in females. These risk factors can be broadly categorized as age, anatomic factors, hormonal imbalance, biomechanical factors, and environmental factors [1]. Some risk factors are modifiable while others are not [2]. It is important to identify these risk factors as having multiple risk factors or having significantly excessive value of a particular risk factor could place patients at an exponentially higher risk, not only for an ACL tear, but for graft re-rupture and contralateral ACL tear [2]. Assessment of risk factors could also help in counselling patients and to direct preventive efforts towards modifiable risk factors.

The chapter on epidemiology of ACL tears in young patients in this book is focused on association of age, activities, and injury rates. ACL injury rates have been reported to be the highest during the second decade of life. Besides increased injury rates in this young population, recent data from a large prospective cohort study demonstrated that graft failure rate after ACL reconstruction was highest in the 10–19 year age group; it accounted for 37.5% of all graft failures [3]. The study demonstrated an 8.2% risk of graft failure after ACL reconstruction in this age group which was 2.3 times higher than their peers 10 years older [3]. Shelbourne et al. reported that for patients <18 years age who had ACL reconstruction, there was a 17% risk for re-injury to either knee [4]. There is an inverse relationship between Marx activity score and age, and this may explain the increased rate for injury and re-injury in this age group [5]. Besides increased activity level, there may be other factors

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responsible for increased rates of ACL injury and re-rupture in this age group, including altered neuromuscular coordination, certain risk factors or compliance issues.

Anatomic risk factors that increase ACL strain and injury include increased anterior pelvic tilt, increased femoral anteversion, increased quadriceps angle (Q-angle), decreased intercondylar notch width or intercondylar femoral notch stenosis (FNS), increased posterior tibial slope, decreased roof intercondylar angle (RIA), and excessive ligamentous laxity, amongst others. Female patients tend to exhibit these anatomic characteristics more frequently than male athletes and these differences may account for more injuries in females.

Increased anterior pelvic tilt could lead to increased hip anteversion, internal rotation, and flexion and thus would affect the alignment of the lower limb [6]. Also, increased anterior pelvic tilt would lengthen and effectively weaken the hamstrings and would change the moment arm for the gluteals [6]. The change in limb alignment and decreased hamstring activation could lead to increased ACL tear.

Women have a relatively wider pelvis that could lead to an increased Q-angle [7]. A high static Q-angle is predictive of a high dynamic Q-angle and places the knee under increased valgus stresses, especially during jumping or pivoting activities [6]. During noncontact ACL tears, the ACL is shown to tear in 70 ms [8]. This is the time it takes to reach maximal ligament length in the valgus position before gross genu valgum occurs [9]. The concept of dynamic valgus has been recognized as an important contributor to ACL tear and preventive efforts are geared towards trying to control it.

Femoral notch stenosis is suggested to be a risk factor for noncontact ACL tears by some [2, 10, 11] and refuted by others [12–14]. It is a measure of the intercondylar notch-width index (NWI) or the ratio of the intercondylar notch to the total width of the femur as calculated at the level of the popliteal tendon [10]. A stenotic notch is more common in females. Critical notch stenosis is defined as a NWI ≤ 0.2 [10, 15]. At least one study has shown athletes with stenotic notch to be at increased risk of ACL rupture with an average NWI mean of 0.189 compared to normal NWI of 0.213 ± 0.044 [10].

Posterior tibial slope is the angle between a line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the tibial plateau [1]. The medial and lateral tibial slopes in children has been shown to be approximately 6° and 3.5°, respectively, and approach the adult value of 7–10° with growth [16, 17]. Studies have shown a correlation between increased posterior tibial slope and ACL tear. Dejour and Bonnin reported that 10° increase in the posterior slope of the medial tibial plateau on a weightbearing lateral radiograph was associated with a 6 mm increase in anterior tibial translation in normal and ACL-deficient knees in adults [17]. Increased posterior tibial slope would lead to increased anterior tibial translation, which would then increase the tension in ACL in resting position, predisposing it to injury [1, 18, 19]. This had led to the recommendation of proximal tibial extension osteotomy in adults with ACL deficiency and increased posterior tibial slope and could be the basis for guided growth in children.

The RIA is a measure of the obliquity of the intercondylar notch in relation to the femoral shaft. On lateral radiographs, it is the angle between Blumensaat's line and long axis of femur [20]. The RIA measured 38° in patients with an ACL tear, 44° for those with a tibial spine fracture and 40° in the control group [20]. Patients with tibial spine avulsions had steeper RIAs when compared to control groups and patients with ACL tears [20]. The clinical significance of this is unknown.

Ligamentous laxity would lead to joint hypermobility, i.e., allow for joints to move past their anatomic constraints causing injury. Generalized ligamentous laxity is evaluated per the Beighton 9-point scale evaluating: hyperextension of the elbows, knees, small finger, thumb and ability to place the palm on the floor. Female athletes with greater passive joint motion and generalized joint laxity greater than one standard deviation above the mean have an increased risk for ACL injury

[2, 21]. Every 1.3 mm increase in knee joint translation corresponds with a fourfold increased risk of ACL rupture [22]. Knee hyperextension increases the risk of ACL injury by fivefold [22]. The presence of generalized ligamentous laxity may be associated with other anatomic variations. An evaluation of soccer players with increased laxity compared to their normal counterparts noted decreased knee flexion angles during initial cutting activities with concomitantly diminished hamstring activation [22]. The existence of this delay in hamstring activation along with ligamentous laxity may increase the risk of ACL injury. In patients with hyperextension of knee (15° or more), it is not clear if the goal of ACL reconstruction should be to achieve symmetric hyperextension and risk graft stretching or to achieve full extension (0°) and cause asymmetry between both knees. For these patients, we have routinely fixed the ACL graft at zero degrees of knee extension and have noticed that the knee would gain some hyperextension over period of time.

The effect of fluctuating hormonal levels on knee laxity and ACL injuries in post-menarchal females has been studied [23, 24]. In a systematic review, female athletes sustained more noncontact ACL injuries during pre-ovulatory phase (between menses and ovulation) or first half of their menstrual cycle [25, 26]. There was a significant decrease in ACL injuries in the postovulatory phase (between ovulation and menses) or second half of their menstrual cycle. Oral contraceptives which stabilize these hormonal fluctuations have shown to decrease ACL injury rates in females [27]. It is controversial whether the effects of female sex hormones estrogen, progesterone, and relaxin are directly through hormonal receptors in ACL and thus alteration of ACL mechanical properties, or indirectly through neuromuscular changes [28–30]. There is lack of evidence to recommend ACL preventive efforts towards females during certain phase of menstrual cycle or to recommend oral contraceptives for their protective effect. Young males with noncontact ACL injuries have also shown increasing concentration of testosterone, estradiol and increased ligamentous laxity, compared to controls [31].

The biomechanical profile of an athlete is a complex interaction between the trunk, hip, knee, ankle, and foot. Imbalances in the biomechanical profile could lead to poor neuromuscular control. Such imbalances are manifested during jumping, pivoting, cutting, and deceleration activities and would place the limb in a precarious position of genu valgum, genu recurvatum, and foot pronation that may increase the risk of ACL tear [6]. Also, female athletes are more often "quadriceps dominant" when compared to their male counterpart. This high quadriceps activation compared to hamstring activation in females could lead to increased ACL tear rate in females. Female athletes at high risk for ACL rupture demonstrate increased knee abduction angles, abduction moments, and ground reactive forces during landing [32]. These risk factors and preventive efforts are well described in the chapter on female athlete.

Environmental risk factors include the surface on which athletes compete [1]. Wet and dry playing surfaces can increase the risk of injuries by different mechanisms. Dry, hard surface during summer can lead to increased frictional forces between the foot and the playing surface leading to increased ACL tears. Situations with excessive traction may provide added stability and increased performance but may also increase the risk of ACL ruptures [1, 33, 34]. In a cadaveric study comparing different combinations of natural grass/turf surface and shoes/cleats, the least ACL strain was seen with cleats on natural grass surface [35]. A study of four different cleat designs for football shoes showed that the Edge design with longer irregular cleats on the periphery and smaller pointed cleats positioned interiorly had 3.4 times higher association with ACL tears than non-Edge designs [36]. A review of the Norwegian handball team showed an increase in ACL injuries on artificial floor that had higher documented coefficient of friction [34]. Upgrades in turf football fields have shown to reduce the number of ACL ruptures by 50% when compared to natural grass [1].

Growth Assessment

Chronologic age matched the skeletal age in only one-third of subjects in one study [37]. For each patient of same chronologic age, there may be significant variation in skeletal development and remaining growth (Fig. 11.1). Generally, girls above 14 years of age and boys above 16 years of age could be considered to be skeletally mature and adult-type ACL reconstruction could be performed in these patients. Since chronologic age is often not sufficient for assessing the developmental stage of an individual, skeletal and biologic (physiologic) age needs to be determined.

Skeletal or "bone age" refers to the degree of maturation according to the development of skeletal tissue [38]. There are several methods of determining skeletal age, including evaluation of hand and wrist radiographs, knee radiographs, elbow radiographs, or pelvic radiographs. The most common method of estimating skeletal age is by comparing a posteroanterior radiograph of the left hand and wrist with the age-specific radiographs in the Greulich and Pyle atlas [39]. The chapter on evaluation of growth provides in-depth review and recommendations, including the shorthand method, which can help to determine skeletal age in the clinic without formal bone age assessment using the atlas. To simplify, the appearance of thumb sesamoid marks the beginning of puberty. The authors of the current chapter have used a quick method of skeletal age assessment by evaluation of physis of distal phalanges of thumb and first ray. This is based on study by Sanders et al. on progression of scoliosis [40]. Those with open distal phalangeal physis are considered prepubescent patients who have not yet completed their pubertal growth spurt or have not reached their peak height velocity; those with closing or closed distal phalangeal physis are considered pubescent patients with inconsequential remaining growth.

It is assumed that skeletal age based on hand X-rays would reflect the skeletal age of the body but that may not be true. The status of distal femoral and proximal tibial physis is of more importance and interest during ACL reconstruction. The study by Roche and French on differences between skeletal maturity between knee and hand, showed that on an average, skeletal age

Fig. 11.1 Group of girls aged 11–12 years. It is apparent that despite similar chronologic age, the amount of growth remaining in each girl is variable. Skeletal age and Tanner staging would allow better estimation of remaining growth

based on hand X-rays correlated with skeletal age based on knee X-rays using Pyle and Hoerr atlas [41, 42]. But for an individual patient, there could be a discrepancy of more than 1 year, between these two methods of assessment (Fig. 11.2). There has been discrepancy between the skeletal age based on distal femur physis and skeletal age based on proximal tibial physis. Since knee physeal violation is a significant concern during ACL reconstruction in skeletally immature patients, it is important to evaluate knee radiographs to assess the distal femoral and proximal tibial physeal status.

Physiologic age can be determined by Tanner staging and assessment of secondary sex characteristics [43]. Self-reporting of Tanner stage by patient or parents has been used but has not been very reliable [44]. Similarly Tanner staging by orthopedic surgeons has been unreliable [45]. It is also impractical and problematic to undress these patients in the clinic for assessment of sexual maturation and hence alternatives are sought. Patients are preliminarily staged prior to surgery by questioning them about the onset of menarche or growth of axillary hair; the Tanner staging could be later confirmed during surgery. Evaluation of only axillary and pubic hair may suffice for Tanner staging, though such simplified approach has not been validated.

Prepubescent patients are categorized as Tanner stage 1 and 2 with skeletal age up to 12 years in boys and up to 11 years in girls. Pubescent patients are in Tanner stage 3 and 4 with skeletal age 13–16 years in boys and 12–14 years in girls. Postpubescent skeletally mature patients are Tanner stage 5 with skeletal age >16 years in boys and >14 years in girls. Since growth is a dynamic phenomenon, the approach towards determination of maturity and remaining growth needs to be flexible and strict criteria for such assessment should be avoided. Besides skeletal and biologic age, patient's standing and sitting height as well as serial measurements would increase the accuracy of growth estimation.

Fig. 11.2 Discrepancy of skeletal age based on hand and knee X-rays. Based on left hand X-ray, skeletal age of this 13 years, 4 months old girl was 13.5 years, i.e., very close to skeletal maturity and minimal growth remaining. Based on knee X-rays, skeletal age of the girl was less than 10.5 years (tibial apophysis has yet not fused with tibial shaft) with open distal femoral and proximal tibial physis. The patient had patellar instability and underwent successful growth modulation despite advanced skeletal age based on hand X-rays. Effect of growth modulation suggests that increased physeal damage during ACL reconstruction in this patient could have led to deformity

Practical Considerations During ACL Reconstruction

Details of several different techniques of ACL reconstruction in skeletally immature patients would be discussed in subsequent chapters in this book. The following section would review the controversial decision-making process related to pediatric ACL reconstruction and would provide some practical tips to help with surgical management.

Autograft Choice

The use of soft tissue grafts have shown to reduce the risk of growth disturbances and are preferred over bone-tendon grafts during ACL reconstruction in the skeletally immature patients [46–48]. Bone-tendon grafts are discouraged in younger patients to avoid harvest of bone close to physis and to avoid placement of bone plugs across open physis to minimize growth disturbances. Hamstring tendon graft is the most widely reported graft for ACL reconstruction in children. The outcomes of ACL reconstruction using hamstring graft have been reported for all-epiphyseal ACL reconstruction [49–53]. They are also commonly used for transphyseal ACL reconstruction [54–56].

Use of iliotibial band (ITB) for ACL reconstruction was first described by Macintosh and Darby in 1976 in adults [57]. This technique has been since modified and adopted for ACL reconstruction in younger patients (Tanner Stage 1 and 2) [58, 59]. As no tunnel is drilled, this technique is safer and would avoid growth disturbances from physeal violation, though tensioning of graft across the physis could, in theory, lead to physeal tethering and growth disturbances. The chapter on ACL reconstruction without bone tunnels outlines the details and outcomes of this technique.

Kohl et al. reported on the use of quadriceps tendon autograft without bone plug for transphyseal ACL reconstruction in 15 patients with mean age of 12.8 years [60]. Middle part of the quadriceps tendon, measuring 7–9 mm × 8 cm was used. At a mean follow-up for 4.1 years, no graft ruptures were reported. Of 49 patients treated with a quadriceps tendon autograft with bone plug using transphyseal technique, Mauch et al. described one growth disturbance in a 10.5 year old girl [61]. An all-epiphyseal technique using quadriceps tendon autograft with bone plug has also been described though outcomes have not been reported [62].

Bone-patellar tendon-bone (BTB) autograft could be safely used for ACL reconstruction in patients nearing skeletal maturity and when the physis are closing [63]. However, BTB graft has also been used in patients with open physis. Memeo et al. have reported on BTB autograft in 10 patients with mean age of 14.4 years (range 13–16 years) and mean follow-up of 24.9 months (range, 15–44 months) [64]. All patients were Tanner stage 3 with open physis. Slightly vertical tunnels measuring 7–9 mm were drilled across the proximal tibial and distal femoral physis. The author reported no growth disturbances [64]. Despite few reports of ACLR using BTB in pubescent patients with open physis, one has to be cautious as deleterious effects are possible from harvest of BTB graft and from placement of bone plugs across physis. Soft tissue autograft (compared to BTB) is a safer alternative in general. Bonnard et al. reported the results of ACL reconstruction in skeletally immature patients using periosteum-patellar tendon-periosteum autograft [65].

Allograft, Including Living Donor Allograft

Allograft is a poor choice of graft in the young active patient population and should be discouraged. Multiple studies have reported on increased failure rates after allograft ACLR in younger patients. Engelman et al. performed a retrospective chart review on 73 patients [66]. They noted 15 graft failures, of which 11 were allograft. Analysis from the MOON data showed an alarmingly increased number of ACLR failures when using allograft in young patients [3]. The allograft rupture rate was 37.5% in the 10–19 year age group. As per their model, a 14 year old with

ACLR using allograft had a 22% risk of re-rupture compared to 6.6% chance of re-rupture for ACLR using autograft [3]. Overall, the risk of graft failure has been reported to be 4.4–7.7 times higher for allograft in the young and active patient population when compared to autograft techniques [3, 66, 67]. Pallis et al. studied a cohort of US Military Academy recruits with an ACL reconstruction prior to matriculation [67]. One hundred twenty patients with 122 ACL reconstructions were followed. The grafts used were 61 BTB autografts, 45 HT autografts, and 16 allografts. Of the 16 allografts, 7 (44%) failed which was 7.7 times higher than their autograft counterparts. Thus allograft ALCR should be avoided for ACLR in younger patients unless in a revision or multi-ligament reconstruction setting.

Goddard et al. reported on 32 children with mean age of 13 years, who underwent transphyseal ACL reconstruction using living donor (parental) hamstring tendon allografts. Excellent subjective and clinical outcomes were reported with 93% return to strenuous activities. Two children sustained ACL graft rupture within 2 years after surgery [68]. Hui et al. reported on 14 prepubertal patients who received living donor (parental) hamstring tendon allograft during transphyseal ACL reconstruction. At minimum 2 years follow-up, there were no graft re-ruptures and all patients had returned to strenuous activities [69].

Hamstring Tendon Graft Diameter

It is controversial whether small diameter autograft would be appropriate for patient's size or would increase the risk for subsequent graft failure. Weight less than 50 kg, height less than 140 cm, thigh circumference less than 37 cm, and a body mass index less than 18 are factors associated with a quadrupled hamstring graft diameter less than 7 mm [70, 71]. In adults, 8 mm is considered to be the minimum required diameter for ACLR. Grafts smaller than 8 mm in diameter are at a 6.8 times greater risk of failure and every 0.5 mm increase in diameter from 7 to 9 mm decreases the likelihood of graft rupture by 0.82 [72–74]. The minimum or optimal graft diameter for ACL reconstruction in children is not established yet.

Guzzanti et al. reported on eight patients with mean age of 11.2 years and Tanner Stage I [49]. All patients underwent physeal sparing ACL reconstruction using hamstring tendon autograft and 6 mm tunnel in the tibial epiphysis [49]. All patients were able to return to full activities without any growth disturbances or graft failures. Anderson reported on 12 patients with mean age of 12.9 years (Tanner stages I-III), who underwent all-epiphyseal ACL reconstruction using quadrupled hamstring autograft. The minimum diameter of the graft in the report was 6 mm [53]. At a mean 4.1 year follow-up there were no graft re-ruptures.

Bollen et al. reported on the fate of quadrupled hamstring graft used for transphyseal ACL reconstruction in five patients (3 Tanner I, 2 Tanner II) at mean of 34.6 months [75]. The diameter of the quadrupled graft (6–7.5 mm) did not change despite 42% average increase in length. Most of the gain in length was on the femoral side. The study indicates neogenesis of the graft and not mere stretching of the graft, as stretching would likely decrease the diameter as length increases. The findings of this study were refuted by Astur et al., who reported decrease in the diameter of quadrupled hamstring graft by average 25.3% and postulated that to be the reason for higher graft rupture rate in children [76].

In 103 patients who underwent all-epiphyseal ACL reconstruction using predominantly hamstring autograft, there was no difference in graft rupture rates between those with graft diameters of ≥8 mm and those with diameters <8 mm [77]. In this large series, one patient had a 6 mm graft, 16 patients had 7 mm graft, 15 patients had 7.5 mm graft, and rest had graft diameter of ≥8 mm. The authors preferred to tailor the graft size to individual patient without a minimum or optimal graft size. It appears from literature review that less than 8 mm diameter graft is acceptable for all-epiphyseal ACL reconstruction which is typically performed in prepubescent patients [53]. It is not known if less than 8 mm diameter graft would be optimal for transphyseal ACL reconstruction which is typically performed in pubescent patients.

If the harvested graft diameter is <8 mm, and ≥8 mm graft diameter is desirable, then few options exist. Augmentation of autograft with an allograft (Hybrid graft) is one option, but it is controversial. Jacobs et al. reported hamstring graft augmentation with allograft in patients whose graft size was less than 8 mm and were able to achieve a graft size of nearly 10 mm [78]. It reduced the graft failure rate from 28.3 to 11.9%. In contrast, Pennock et al. demonstrated that augmented grafts with a final size 8.9 mm had a re-rupture rate of 30% when compared to 5% re-rupture rate with nonaugmented autografts of 6.4 mm diameter [79]. It is not known if augmentation of autograft with an allograft can lead to an immunologic reaction, graft absorption, or can affect tendon-bone healing. Another technique for increasing graft diameter is by increasing the number of folds to make a 5 or 6 strand hamstring graft, provided adequate graft length is present [80, 81].

Graft Preparation and Fixation

For hamstring graft preparation, Anderson recommended both ends of the hamstring tendon graft to be sutured together rather than suturing each end of the graft separately to minimize the size of the graft and therefore the size of the required tunnel [53, 82]. Along with pretensioning of the graft to remove creep prior to implantation, Cruz et al. recommended circumferential compression of the graft using a standard cylindrical sizing block [83]. In a laboratory study using hamstring tendon allograft, the authors were able to decrease the diameter of the graft from mean of 8.28 mm at baseline to 7.38 mm after tensioning and compression. Since the collagen content of the graft does not change, a compressed graft is desirable as it would require a smaller size tunnel for pediatric ACL reconstruction.

For the all-epiphyseal ACL reconstruction, Guzzanti et al. reported their technique of keeping the hamstring grafts attached to the tibia and rerouting the detached proximal end of the graft through an epiphyseal tibial tunnel [49]. This would obviate any fixation in the tibial tunnel but the graft is tensioned across the proximal tibial physis. Anderson described similar metaphyseal fixation distal to the proximal tibial physis using screw and post [53]. For ITB extra-physeal technique, the tibial fixation is performed by suturing the graft to the periosteum on the anterior aspect of tibia and below the level of tibial physis [58]. Patients are subsequently immobilized to allow for healing of the graft. Edwards et al. studied the effect of tensioned (80 N) iliotibial band graft across open growth plates in canine model [84]. They found a substantial rate of distal femoral valgus deformity and proximal tibial varus deformity despite no evidence of a bony bar. Thus, there are concerns with fixation across (not through) the physis, including tethering of the physis, compression on the periochondrial ring, and growth disturbances according to the Heuter-Volkmann principle, but clinical outcomes have not shown any significant growth disturbances [82, 84, 85].

During all-epiphyseal ACL reconstruction, there are concerns about the use of interference screw in the tibial epiphysis, which include tunnel dilatation and injury to either the physis or the articular surface. Interference screw do require a certain minimum tibial tunnel size. Twenty millimeters of minimum tibial tunnel has been suggested [86]. Current methods of tibial tunnel fixation include suspensory fixation, split tibial tunnels with interposed bone bridge (Fig. 11.3), and metaphyseal fixation across the tibial physis [87, 88].

For femoral fixation during all-epiphyseal technique, the most common methods used are suspensory fixation or interference screw [53, 87]. When outside-in epiphyseal tunnels are drilled, the suspensory device may need an extension or washer to prevent the device from slipping into the tunnel [53]. There is possibility of irritation of the hardware by overlying iliotibial band. Kohl et al. used femoral metaphyseal screw as a post to tie the graft in 15 skeletally immature patients and reported one case of progressive valgus [60].

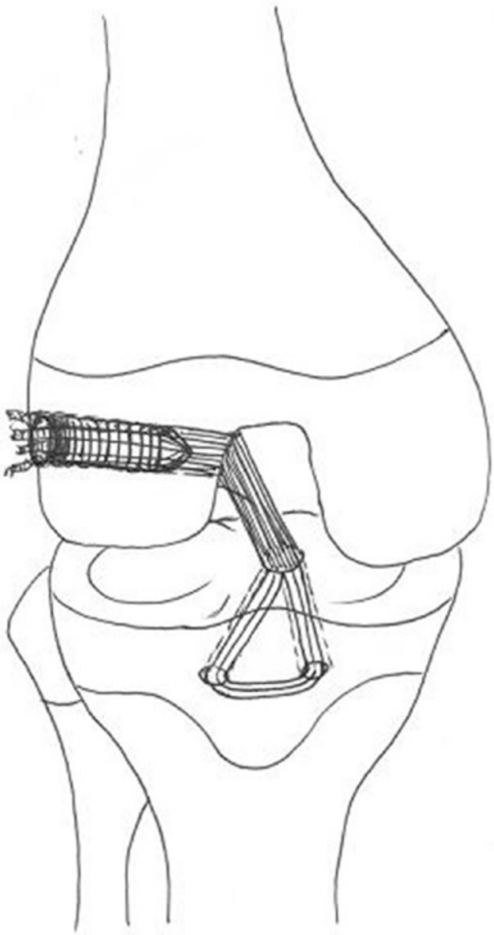

Fig. 11.3 All-epiphyseal ACL reconstruction using split tibial tunnels and bone bridge would avoid hardware in tibial epiphysis and would help minimize size of tibial tunnels

Transphyseal Tunnel Size and Orientation

Meller et al. performed transphyseal ACL reconstruction in 4-month-old skeletally immature sheep and found no angular deformity or leg-length discrepancies [89]. The surgery was performed using several key principles of transphyseal technique that are recommended to avoid growth disturbances, i.e., the tibial tuberosity was spared to prevent genu recurvatum, thermal damage to the physis was avoided, small transphyseal drill holes were made in the center of the growth plate, soft tissue graft was used, graft fixation was achieved away from the physis, and the graft was moderately pretensioned before fixation.

Animal studies have shown that for transphyseal ACLR, the prevalence of physeal arrest increases when physeal damage from tunnel drilling involves >7% of the total physeal volume [90]. Kercher et al. performed MRI-based computational study and noted that graft radius (drill size) was the most critical parameter affecting the volume of physeal injury [91]. Based on computer modeling, Shea et al. demonstrated that increasing the drill diameter from 6 to 9 mm would increase the percentage of physeal volume removed from 1.6 to 3.8% for the tibial physis and 2.4 to 5.4% for the femoral physis [92].

Besides the tunnel diameter, the orientation and location of the tunnel is an important determinant of physeal injury. For tibial transphyseal drilling, tunnels that start more medial, distal, and with a steeper angle of inclination reduced the amount of tibial physeal and apophyseal violation compared to tunnels that start more lateral, proximal, and with a shallow angle of inclination [93]. Increasing tunnel drill angle from 45° to 70° would decrease the physeal volume percent injury from 4.1 to 3.1%. The average angle to maintain a distance of 20 mm from the proximal tibial physis was 65° (range, 40–85°) [91].

For femoral transphyseal drilling, tunnels drilled through the anteromedial portal would violate the femoral physis more lateral and more obliquely creating a larger percentage of physeal damage, than those drilled using the trans-tibial technique [94, 95] (Fig. 11.4). Tunnel through the anteromedial portal, however, could be placed more vertical and perpendicular to the physis if desired [69, 96]. Outside-in transphyseal drilling of the femoral tunnel produces more damage to the femoral physis than trans-tibial drilling (4.9% vs. 2.1%), as the outside-in transphyseal tunnels are placed at a more oblique angle (72.8° vs. 32.1°) [51].

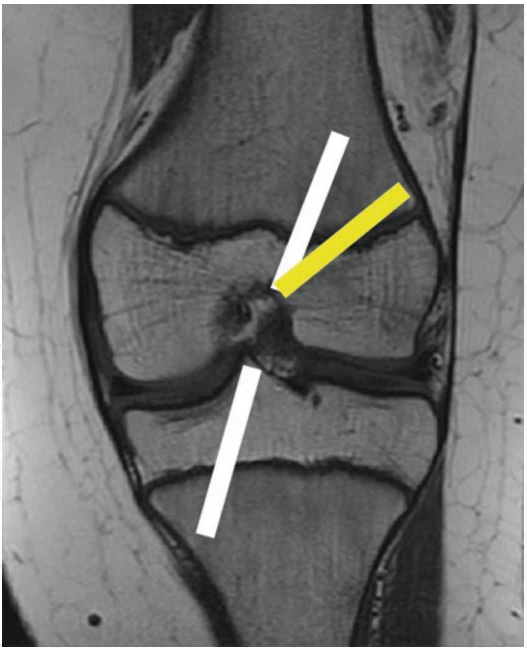

Fig. 11.4 The amount of physis removed during transtibial femoral tunnel (*white*) is less compared to oblique femoral tunnel through anteromedial portal (*yellow*)

Fig. 11.5 The size of tibial epiphysis is an important consideration during all-epiphyseal ACL reconstruction. The maximum oblique length (*black line*) is more important than vertical height (*black arrow line*). The "safe" tunnel length (*dashed line*) is along the ideal tunnel track, which is less in length and angle compared to maximum oblique length. The oblique tibial height (*dotted arrow line*) may be a better preoperative measurement to decide on safe tunnel diameter, though normative values have not been studied

Prepubertal Patient: To Drill or Not to Drill

Transphyseal ACL reconstruction has been reported to be safe in prepubertal patients (Tanner I and II) [69, 96, 97]. However, most surgeons would prefer to avoid drilling through the physis in this age group. The two widely accepted and safer surgical options are the extraphyseal technique (over-the-top on femur and anterior to tibia without drilling tunnels) and all-epiphyseal ACL reconstruction (tunnels with in femoral and tibial epiphysis) [53, 58]. The extraphyseal technique is safe from physeal injury standpoint as no tunnels are drilled, but the graft is in a nonanatomic position. The all-epiphyseal technique is more anatomic but there is concern about physeal injury. In the absence of comparative clinical study, which technique should be considered?

One of the limiting factors for the all-epiphyseal technique is the size/height of the tibial epiphysis [98]. In order to establish a tibial tunnel, there probably needs to be a threshold under which drilling through tibial epiphysis is neither safe nor feasible. Normative data suggests that the height of the tibial epiphysis is 15–16 mm in adolescents [98, 99]. The maximum oblique depth (along the distal aspect of epiphyseal tibial tunnel) was ~30 mm, occurring at a mean angle of 50° regardless of age or sex [99]. Davis et al. simulated a "safe" tibial tunnel placement which was about 5 mm proximal to the maximum oblique depth; it measured 19 mm in younger patients and 21 mm in older patients (Fig. 11.5). According to Anderson, the more important factor is the height of the epiphysis relative to the size of the tunnel that is drilled; smaller the child, smaller the size of tibial epiphysis but there would be corresponding decrease in the size of harvested hamstring graft which would require smaller tunnel to be drilled [82].

We recommend the extraphyseal technique in the very young child (skeletal age ≤10 years) as

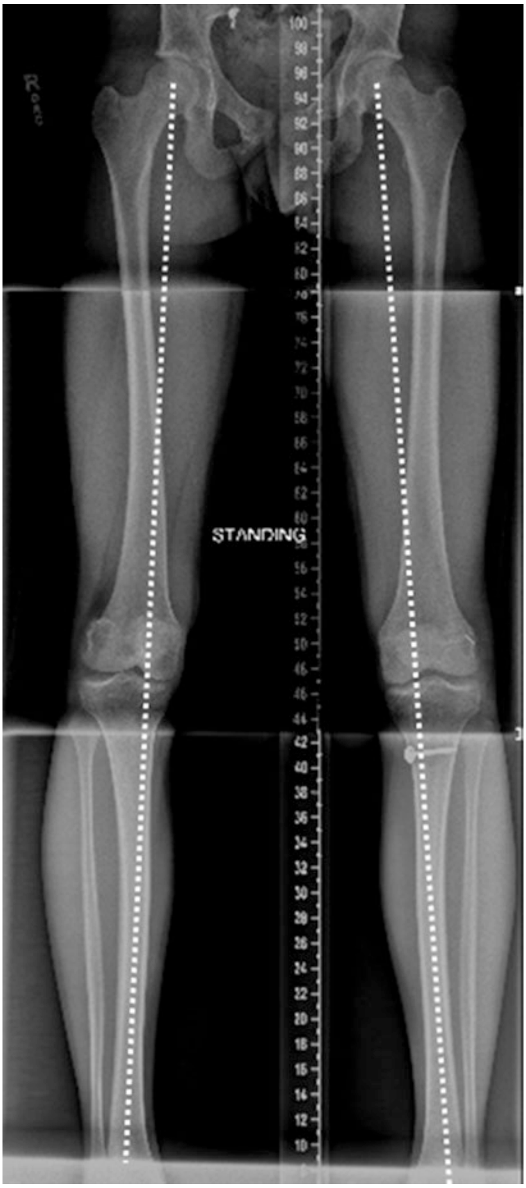

Fig. 11.6 Full length X-ray of a patient who underwent right sided ACL reconstruction using extraphyseal ITB technique at age 10 years. Two years later, he sustained left sided ACL tear and underwent all-epiphyseal ACL reconstruction. At skeletal maturity, there is no limb length discrepancy or deformity and both knees had excellent results

the small tibial epiphysis may not permit safe and adequate tibial tunnel placement. For children >10 years age, an all-epiphyseal technique would be used (Fig. 11.6).

Double Bundle (DB) Pediatric ACL Reconstruction

It has been recognized that young age is a risk factor for ACL tear and ACL graft rupture after reconstruction [3, 100]. The increased rate of failure of pediatric ACL reconstruction may be secondary to increased activities, decreased compliance, and/or altered neuromuscular control. There has been interest in trying to reduce the rate of ACL failure. In adults, DB ACL reconstruction has shown to better restore anterior and rotational stability compared to single bundle ACL reconstruction, and may help to decrease ACL graft failure rates [101]. This principle could be applied to pediatric ACL reconstruction (Fig. 11.7). Salzmann et al. reported a case of a 14 year old female who underwent DB partial transphyseal ACL reconstruction using hamstring tendons, transphyseal tibial tunnels, epiphyseal femoral tunnels, and interference screw fixation in all four tunnels [102]. Siebold et al. compared 16 skeletally immature patients with DB ACL reconstruction with 17 skeletally immature patients with single-bundle ACL reconstruction [103]. There were no differences in the subjective scores though rotational stability was better restored with DB ACL reconstruction and patients were more satisfied with it. There was a significantly higher rate (25.7%) of graft re-rupture for single-bundle ACL reconstruction, compared to 14.3% re-rupture rate after DB ACL reconstruction. Using computer modeling of knee MRI, Shea et al. recommended a cautious approach during DB transphyseal ACL reconstruction. The combined physeal damage from 9 mm transphyseal anteromedial and posterolateral tunnel placement was 6.5%, which approached the threshold of 7% to prevent growth disturbances [104].

Special Circumstances

Indications for ACL reconstruction have broadened as techniques have become more sophisticated and medical management of systemic

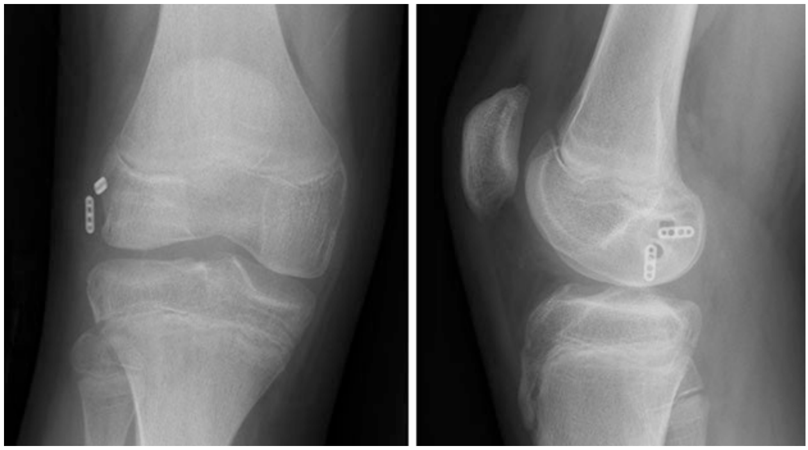

Fig. 11.7 Double-bundle all-epiphyseal ACL reconstruction is an option, though clinical results to support it are lacking

diseases have improved. ACL reconstruction has been reported in a patient with athetoid cerebral palsy for knee instability 2 years after a traumatic injury [105]. Due to involuntary movements, the postoperative protocol was modified to include 3 weeks of casting in extension followed by 3 months in a functional ACL brace to prevent hyperextension [105]. At 13 month follow-up the patient underwent a second look arthroscopy that showed satisfactory positioning and functioning of the graft. The patient had negative pivot shift and Lachman tests.

ACL reconstruction in a patient with Osteogenesis Imperfecta and recurrent knee instability has been reported [106]. A 9 mm tibialis anterior allograft was used during surgery and fixed with interference screws with femoral tunnel back up fixation using a post due to weak fixation. Postoperatively the patient was strict non-weight bearing for 2 weeks, partial weight bearing for 2 weeks and progress to full weight bearing after 4 weeks. Follow-up MRI at 14 months demonstrated 20% dilation of the tibial tunnel. By the 27 month follow-up, the patient had returned to full activities [106].

ACL tears have been reported in patients with skeletal dysplasia, though rarely. Achondroplasia is the most common skeletal dysplasia. Patients with achondroplasia tend to have increased genu recurvatum and increased anterior tibial slope [107]. This anterior tibial slope may protect the ACL from anterior translational forces. There is a low prevalence of ACL tears in patients with achondroplasia (0.7%) when compared to general population [107].

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12 ACL Reconstruction Without Bone Tunnels

Peter D. Fabricant and Mininder S. Kocher

Introduction

Tears of the anterior cruciate ligament (ACL) were once considered rare in skeletally immature athletes; however, they are now observed with increasing frequency. As mentioned previously in this text, a dramatic rise in youth competitive athletic activity and year-round training and competition, along with increased awareness of ACL injuries in children, has led to a commensurate increase in the frequency of ACL tears in the skeletally immature. A recent epidemiological analysis of a New York State administrative database revealed that the rate of ACL reconstruction in children under age 20 had increased nearly threefold over a 20-year period from 1990 to 2009 and indicated that adolescents and teenagers represent the largest per capita demographic of ACL reconstructions [1].

While, historically, nonoperative management until skeletal maturity followed by traditional ACL reconstruction was a popular treatment strategy, recent understanding of the risks of nonoperative treatment and surgical delay has supported a trend toward early operative treatment [2–7]. In prepubescent patients, unique anatomy and considerable remaining skeletal growth make physeal-respecting ACL reconstruction challenging. This is significantly more difficult in the smallest knees with congenital ACL absence.

Herein we discuss the indications, surgical technique, aftercare, and clinical outcomes after ACL reconstruction without bone tunnels, using an iliotibial band autograft technique. Although a thorough understanding of ACL developmental anatomy, clinical and radiographic evaluation of children with ACL injuries, assessment of skeletal maturity, and postoperative rehabilitation are vital for the orthopedic surgeon caring for children with ACL injuries, these topics are covered elsewhere in this text and will be highlighted here only for circumstances unique to this procedure.

Historical and Clinical Rationale

Performing ACL reconstruction without bone tunnels is an ideal technique for prepubescent children. The technique described here was first performed by Dr. Lyle Micheli (Fig. 12.1) as a modification of an extra-articular tenodesis performed by Dr. David MacIntosh. In MacIntosh's original procedure, the iliotibial band was harvested proximally and left attached to Gerdy's tubercle distally. It was routed proximally around

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Fig. 12.1 Modified MacIntosh IT band ACL reconstruction

the lateral collateral ligament and sutured to itself, forming an extra-articular tenodesis [8]. Micheli's modification was borne out of necessity for the smallest knees of children with congenitally absent ACLs. Originally conceived as a temporary procedure to provide stability until skeletal maturity, lasting stability made revision unnecessary. The indications were then expanded to include prepubescent children with acquired ACL injury [9, 10].

The iliotibial band combined extra- and intra-articular reconstruction has several advantages, including complete avoidance of the physes, improving the ease of revision surgery (no previous tunnels and all other autograft sources remain intact), and providing an additional extra-articular reconstruction limb analogous to the anterolateral ligament [9, 11–13]. Currently, the technique is indicated as a primary or revision ACL reconstruction for prepubescent children (Tanner stages 1–2; skeletal age ≤11 years old in females, ≤12 years old in males). While some opponents of this technique cite its "nonanatomic" configuration, biomechanics studies have shown restoration of kinematic constraint [14] and good clinical outcomes with low revision rates at a mean of 5.3 years postoperatively [9].

Clinical Evaluation and Surgical Preparation

Children are evaluated clinically and radiographically for ACL tears and concomitant injury as outlined previously throughout this text. A thorough evaluation of bony alignment, skeletal maturity, and Tanner staging is performed. A course of pre-reconstruction physical therapy is prescribed focusing on reducing pain, swelling, and effusion, regaining normal gait mechanics, and maximizing quadriceps and hamstring strength preoperatively. This delay of approximately 4 weeks helps to minimize postoperative arthrofibrosis [15]. In the event of an urgent meniscal (e.g., locked bucket-handle tear) or osteochondral injury with loose body, the reconstructive surgery can either be staged or performed earlier after appropriate counseling of the risks, benefits, and requirements involved in either approach.

Surgical Technique

A combined general anesthetic with regional blockade is performed after consultation with the anesthesiologist, which consists of either a fascia iliaca block or a combination of femoral and lateral femoral cutaneous nerve block. Depending on surgeon, anesthesiologist, and family preference, an indwelling catheter may be left in place overnight to provide sustained analgesia.

After an examination under anesthesia, a non-sterile tourniquet may be placed high on the thigh, but is not inflated until after graft harvest to facilitate iliotibial (IT) band access. Surgery begins with IT band harvest through a longitudinal-oblique 4.5 cm incision from the lateral joint line (a point equidistant from Gerdy's tubercle and the lateral epicondyle) to the superior border of the IT band. A long, broad Cobb elevator is used to elevate the subcutaneous tissue off the superficial surface of the IT band a minimum of 15 cm up the thigh. The anterior and posterior borders of the IT band are identified. Anteriorly, the IT band is confluent with the fascia of the vastus lateralis. The transition point is noted where the dense and opaque IT band tissue transitions to a more transparent vastus fascia. Posteriorly, the IT band blends into the posterior intermuscular septum. Once these borders are identified, the IT band is incised near either border leaving a few millimeters of intact IT band on either side. The cuts are continued proximally with curved meniscotomes for a distance of at least 15 cm. The graft is truncated proximally with a curved meniscotome or an open-ended tendon harvester with cutting mechanism. If similar instruments are unavailable, a counter incision may be made proximally to detach the graft. After harvest, the free end is tubularized with a nonabsorbable suture. The graft is further freed distally from the lateral joint capsule but leaving it attached to Gerdy's tubercle (Fig. 12.2a, b). The graft is then placed back in the wound to prevent desiccation during arthroscopy.

Diagnostic arthroscopy is performed through standard anterolateral and anteromedial portals, and any meniscal or chondral work is performed at this point. The medial portal is widened, and a large curved clamp is introduced through the medial portal and into the over-the-top position. Widening the medial portal allows for easier clamp spreading and minimizes the chances of traumatic and irregular enlargement of the portal. The clamp is placed through the soft tissue remnants at the posterior aspect of the over-the-top position to allow for a sling, pushed through the posterolateral capsule of the knee and into the IT band defect on the lateral knee. The clamp is opened and closed several times to dilate the passageway and allow for easy graft passage. The suture attached to the free end of the graft is placed in the clamps and brought back into the knee. The graft is typically parked in the over-the-top position, and the sutures are brought out the medial portal (Fig. 12.3a, b).

Next, a longitudinal incision is made medial to the tibial tubercle and distal to the tibial epiphysis near the superior border of the pes anserinus tendon insertion. Dissection is carried down to but not through the periosteum, and then blunt dissection is directly proximal with a curved clamp up into the knee underneath the intermeniscal ligament. This passageway is then dilated to aid with tibial preparation and graft passage. A curved "rat-tail" rasp is used to create a groove in the tibial ACL footprint in order to create an exposed bony bed to facilitate intra-articular healing of the graft as well as to posteriorize the tibial footprint to a more anatomic position that

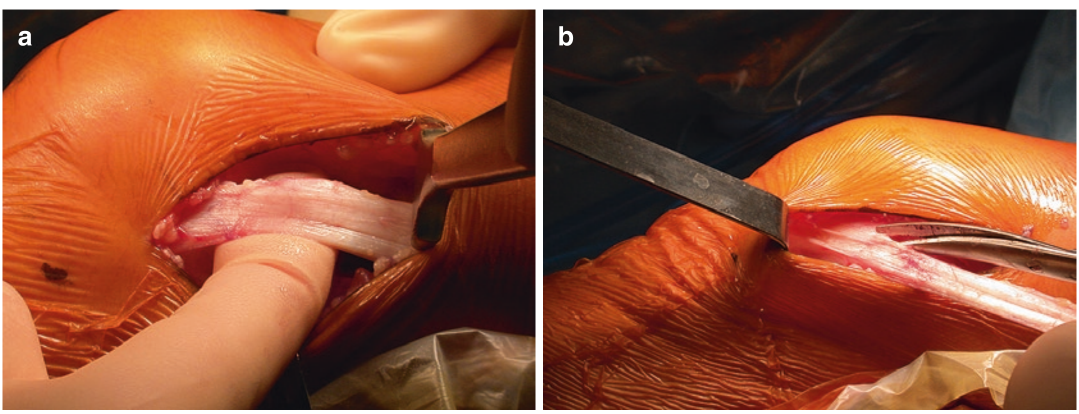

Fig. 12.2 IT band graft harvest. Isolation of the midportion of the IT band (**a**) is followed by proximal detachment and dissection distally to Gerdy's tubercle (**b**). The graft is then tubularized proximally with sutures that are used to pass the graft

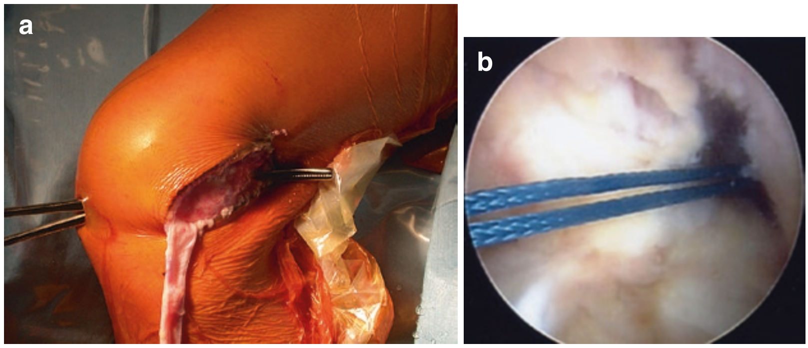

Fig. 12.3 IT band graft passage is performed by using a curved clamp in the over-the-top position (**a**). The sutures are then passed intra-articularly (**b**)

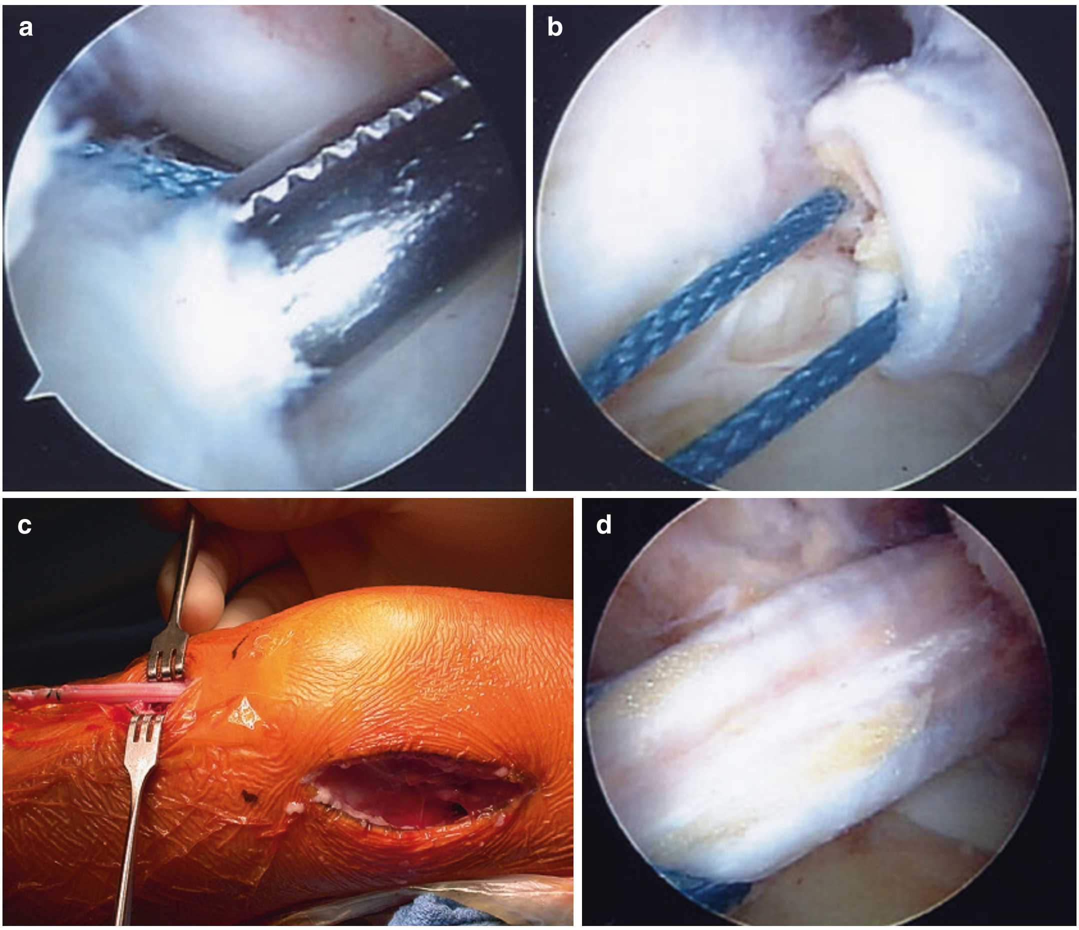

Fig. 12.4 IT band graft passage to final position. A tonsil clamp is used to grasp the passing sutures underneath the intermeniscal ligament (**a**), and the graft is pulled out the tibial incision (**b**, **c**), resulting in positioning of the graft in its anatomic position (**d**)

minimizes the chance of impingement in extension. The clamp is then reintroduced in the knee, and the intra-articular sutures are grasped and brought out through the tibial incision, advancing the graft to its final intra-articular position (Fig. 12.4a–d). With tension on the graft, the knee is flexed and extended to confirm impingement-free range of motion.

The arthroscope is removed, and the knee is allowed to rest in 90° of relaxed flexion with neutral foot rotation in order to prevent over-constraining the knee [14]. With tension on the

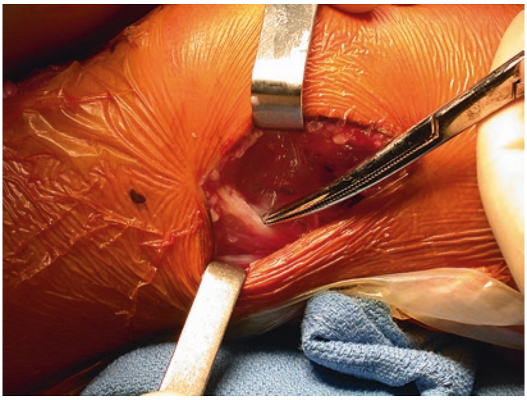

Fig. 12.5 With tension on the graft, the graft is sewn into the periosteum of the lateral femoral condyle and the intermuscular septum (identified here with clamp) with a heavy nonabsorbable suture using at least three figure-of-eight stitches to achieve an extra-articular tenodesis

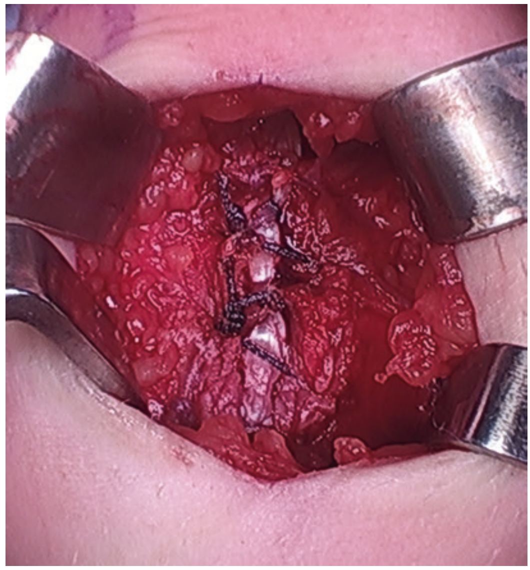

Fig. 12.6 Tibial fixation is performed using three or more sutures between the graft and adjacent periosteal flaps. Once all sutures are placed, they are tied sequentially with firm tension on the graft and a posterior drawer on the tibia

graft, the graft is sewn into the periosteum of the lateral femoral condyle and the intermuscular septum (Fig. 12.5) with a heavy nonabsorbable suture using at least three figure-of-eight stitches to achieve an extra-articular tenodesis.

After completion of the tenodesis, the leg is placed in extension. The periosteum in the tibial incision is incised and elevated with a Cobb elevator. The bone is decorticated with a burr. Sutures are then placed through the periosteal flaps and graft but not tied. At least three sutures should be placed. Once all sutures are placed, they are tied sequentially with firm tension on the graft and a posterior drawer on the tibia (Fig. 12.6). The knee is examined to confirm a negative Lachman exam. The graft can be reexamined arthroscopically, if desired.

Rehabilitation

Currently, few youth-specific ACL rehabilitation protocols have been described, and many have been designed based on a combination of the adult literature and clinical expertise [16–20]. Although postoperative rehabilitation is covered elsewhere in this text, the features unique to this technique are worth highlighting. Specifically, patients who undergo this procedure are maintained with touchdown weight bearing (20% body weight) for 6 weeks postoperatively with range of motion limited to 0–30° for 2 weeks followed by 0–90° through week 6. This allows for adequate protection of the implant-free periosteal graft fixation. After 6 weeks, rehabilitation is similar to other protocols and consists of regaining full range of motion, working on closed chain strengthening, with straight-line jogging initiated 10 weeks postoperatively. Running and agility training is started at 12 weeks and progressed toward sport-specific training and jump landing. Patients are evaluated with an ACL return to play (RTP) assessment at 6 months including range of motion, strength, thigh girth, balance, and functional testing. Any identified deficits are targeted for improvement. Return to play is gradual, sport-dependent, and initiated at 6–9 months depending on RTP assessment. Full return to competition is therefore expected around 10 to 12 months postoperatively. Patients wear a hinged knee brace postoperatively until week 6 when quadriceps control returns, at which point they are converted to functional ACL brace for use during exercise and sports out to 2 years postoperatively. Two years after surgery, bracing becomes optional but is encouraged for these younger prepubescent patients, particularly those who compete in high-risk sports.

Surgical Outcomes

This technique has been shown to be safe and effective. The senior author reported outcomes after ACL reconstruction using IT band autograft in 44 patients (mean chronologic age 10.3 years; range, 3–14 years) with minimum 2-year follow-up (mean 5.3-year follow-up) [9]. Re-tear rate was 4.5%; in the remaining patients, the International Knee Documentation Committee (IKDC) subjective knee score was 96.7 ± 6.0, and the Lysholm knee score was 95.7 ± 6.7. No growth disturbances were observed either clinically or radiographically. These results have been maintained in the longer term as well with a subsequent study of 237 patients (mean chronologic age 11.2 years; range, 5–15 years) at an average of 6.2 years postoperatively showing a 7% revision rate, 2% arthrofibrosis rate, <0.5% rate of septic arthritis, and no limb length or angular deformities. Pedi-IKDC and Lysholm scores averaged 84 and 93 points, respectively [21]. Clinical success has been replicated in other institutions as well: 22 knees at an average follow-up of 3.0 years had mean Pedi-IKDC and Lysholm scores of 96.5 and 95 points, respectively, with high mean patient satisfaction, no limb length or angular deformities, and three knees (14%) requiring revision ACL surgery [22]. A representative sagittal MRI illustrating the position of the healed graft is shown in (Fig. 12.7).

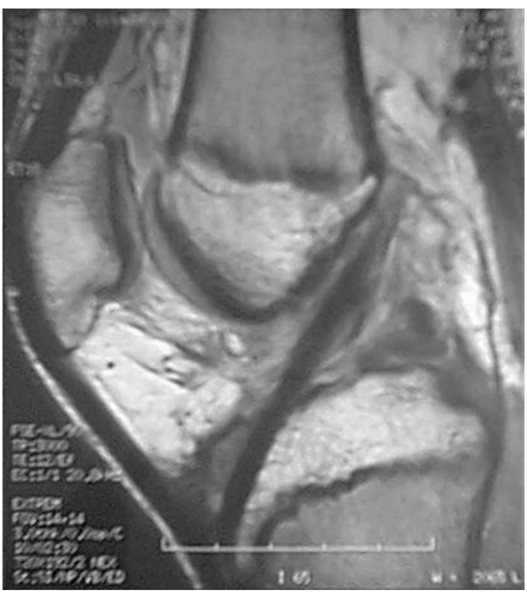

Fig. 12.7 Sagittal MRI showing position of healed ITB ACL graft

Conclusion

While ACL tears were historically considered a rare injury in skeletally immature athletes, they are now observed with increasing frequency due to a dramatic rise in youth competitive athletic activity and year-round training and competition. Recent epidemiological data has shown that the greatest number of ACL reconstructions per capita is being performed in adolescents, including skeletally immature patients. In light of the increasing frequency and awareness of ACL injuries in children, diagnostic and treatment strategies have evolved and now cater to the unique anatomy of the skeletally immature patient. Current literature supports the trend toward early operative treatment to restore knee stability and prevent progressive meniscal and/or chondral damage. In the skeletally immature, prepubescent patient (Tanner stages 1–2; skeletal age ≤11 years old in females, ≤12 years old in males), the iliotibial band ACL reconstruction provides a safe, effective option for ACL reconstruction without the need for bone tunnels or surgical implants.

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13 ACL Reconstruction Using Epiphyseal Tunnels

Allen F. Anderson and Christian N. Anderson

Introduction

Tears of the anterior cruciate ligament in pediatric patients have been reported with increasing frequency [1]. Werner et al. [2] reported a 19% increase in ACL tears in patients 10–14 years old from 2007 to 2011. The management decisions for pediatric patients with ACL tears should be made in the context of the harms and efficacy of the different methods of treatment.

Historically ACL tears in skeletally immature patients were treated nonoperatively with functional bracing, physical therapy, and activity modification. Despite the potential advantages of greater psychological and skeletal maturation, the older literature provided weak evidence that nonoperative treatment may cause long-term knee impairment [3–6]. More recently, studies with levels 2 and 3 evidence have found that nonoperative treatment or delayed reconstruction was associated with meniscal tears, chondral injuries, and sports-related disability [7–10].

An increased rate of ACL reconstruction in pediatric patients has occurred in the last 20 years [11]. This change in management preferences from nonoperative to surgical reconstruction results from a greater awareness that additional meniscal and chondral injuries are caused by nonoperative treatment or delayed surgical reconstruction [5, 7–9, 12–14] and improvement in surgical techniques [13–17].

Vavken and Murray [14], in a systematic review of 47 studies, found that nonoperative treatment resulted in poor clinical outcomes and a higher incidence of meniscal and chondral injuries. They concluded that surgical stabilization should be considered the preferred method of treatment and nonoperative treatment should only be considered as a last resort. Ramski et al. [13], in a meta-analysis, found six studies ($n = 217$) that compared operative to nonoperative treatment and five studies ($n = 253$) that compared early to delayed surgery. Posttreatment instability occurred in 13% of the operative and 75% of the nonoperative cohort, medial meniscus tears were 12-fold more likely in the nonoperative cohort, and return to sports was 86% in the operative and 0% in the nonoperative cohort. Both of these studies concluded that multiple trends favored early surgery. Similarly, Dunn et al. [16], in another meta-analysis, found that the odds of meniscal tears were 12-fold higher and instability was 33-fold higher in the nonoperative cohort.

Although there is now compelling evidence that nonoperative treatment is associated with meniscal and chondral injuries and sports-related disability, the decision to perform surgery depends on the risk and efficacy of surgical reconstruction. Frosch et al. [18], in a meta-analysis of 55 studies including 935 patients who

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had either physeal-sparing, partial physeal sparing, or transphyseal reconstruction, found that the risk of leg-length discrepancy or angular deformity after surgical reconstruction was 1.8%. In a systematic review of 31 studies (n = 479), Vavken and Murray [14] found that three patients developed angular deformity and two patients had leg-length discrepancies.

The options for surgical reconstruction in skeletally immature patients include transphyseal, physeal-sparing, and hybrid techniques. Most studies demonstrate favorable results using these techniques, with good patient-reported outcome scores, objective measures, and low complication rates [14, 15, 19, 20].

Our algorithm for determining the appropriate surgical technique involves risk stratifying patients based on skeletal maturity. Boys with a bone age of less than 13 years and girls with a bone age of less than 12 years have significant knee growth remaining [21] and, consequently, are placed in a high-risk category. Boys with bone ages of 13–15 years and girls with bone ages of 12–13 years are placed in an intermediate-risk category because they have at least 1–2 cm of knee growth remaining [21]. The effects of physeal growth arrest in patients classified as high and intermediate risk would be severe [21]. Consequently, we do not recommend transphyseal drilling in high-risk patients (boys with bone age <13 years and girls <12 years) or younger intermediate-risk patients (boys with bone age 13–14 years and girls 12–13 years). Boys with a bone age of greater than 15 years and girls with a bone age of greater than 13 years are classified as low risk because they have 1 cm or less of knee growth remaining [21] and iatrogenic physeal damage would likely result in no significant growth disturbance.

In 2003, Anderson [15] described an anatomic outside-in all-epiphyseal reconstruction that followed the generally accepted principles of ACL reconstruction in adults but avoided both the tibial and femoral physis. In a biomechanical study by Kennedy et al. [22], this technique was shown to partially restore rotatory and anteroposterior laxity of the knee, whereas the iliotibial band technique over constrained these movements. However, Sena et al. [17] demonstrated the all-epiphyseal technique was more effective than the iliotibial band technique in restoring knee kinematics during pivot-shift testing.

This physeal-sparing technique theoretically decreased the risk of growth disturbance by avoiding damage to the physes. Therefore, for high-risk patients, we recommend an outside-in all-epiphyseal reconstruction with hamstring autograft, using suspensory fixation on the tibial side and shielded screw fixation on the femoral side. Younger patient in the intermediate group also may be treated with an outside-in all-epiphyseal reconstruction (boys with bone age 13–14 years and girls 12–13 years). Older patients in the intermediate group (boys with a bone age of 14–15 years and girls of 13 years) may be treated safely with a transphyseal reconstruction.

The all-epiphyseal technique has yielded good results, with a low risk of complications and revision rate of 5%. However, from a series of 76 outside-in all-epiphyseal procedures, four had failure of the femoral suture loop (5%), and in another series of all-inside all-epiphyseal reconstructions using the Arthrex TightRope, 2 of 20 had suture loop failure. In five of these cases, the cortical button migrated into the knee joint with no failure of the graft or intraarticular damage. These buttons were very difficult to remove arthroscopically. In order to achieve an all-epiphyseal femoral tunnel that fits sufficiently distal to the physis to avoid physeal injury, the starting point on the lateral femoral cortex must be placed within the joint space. In this prominent position on the lateral femoral condyle, the anterior and posterior motion of the iliotibial band during knee flexion and extension may cause cyclic motion of the cortical button leading to abrasion and subsequent failure of the suture loop. This complication may be even more common as two-thirds of these cases were diagnosed during routine postoperative follow-up or for evaluation of unrelated minor injuries.

In order to avoid this complication, we have subsequently modified our approach by using all-epiphyseal graft fixation (OrthoPediatrics, Warsaw, IN). The modified outside-in technique uses suspensory fixation on the tibial side and shielded screw fixation on the femoral side that prevents the physis from being damaged by the interference screw.

Surgical Technique

Outside-In All-Epiphyseal Anterior Cruciate Ligament Reconstruction

Place the injured leg in an arthroscopic leg holder, and flex the hip to 20° to facilitate visualization of the knee in the lateral plane using fluoroscopy. Position the C-arm on the side of the table opposite the injured leg, and place the monitor at the head of the table on the same side as the injured knee. Before the leg is prepared and draped, visualize the tibial and femoral physes in both anteroposterior and lateral planes. Then, rotate the C-arm 30° externally to visualize the extension of the tibial physis into the tibial tubercle on the lateral view of the tibia.

Make an oblique incision in Langer's lines 3–4 cm long; dissect the semitendinosus and gracilis tendons free. Then, transect the tendons at the musculotendinous junction using a standard tendon stripper and detach them distally. Next, double the tendons and place a no. 2 FiberWire suture (Arthrex, Naples, FL) in the tendon ends using a locking whipstitch. Place the doubled tendons on the back table under 4.5 kg of tension using the GraftMaster device (Acufex, Smith & Nephew, Andover, MA). Although some authors recommend using a tendon of at least 8 mm in diameter, in our experience, the double tendons are sufficient. The tendons are not tripled to increase size unless they have been damaged during harvesting. Insert the arthroscope into the anterolateral portal, and insert the probe through the anteromedial portal. Perform an intra-articular examination in a standard manner. Remove the debris from the intercondylar notch so the anatomic footprint of the ACL on the femur can be visualized. At this point in the procedure, repair any tears of the menisci.

Place an arthroscope in the anteromedial portal and the ACL drill guide in the anterolateral portal. Place the tip of the guide at the center of the footprint of the ACL on the femur. Elevate the handle of the guide 35–40° anteriorly so the drill hole does not damage the lateral collateral ligament, anterior lateral ligament, or popliteus tendon attachment (Fig. 13.1). Make a 2 cm incision and split the iliotibial band at this point. Visualize the position of the drill guide and guide wire with the C-arm in the anteroposterior plane, and then advance the guide wire across the femoral epiphysis. Using the arthroscope, visualize entry of the guide wire into the intercondylar notch. The proper entry point is at the center of the anatomic footprint of the ACL on the femur. With the femoral guide wire in place, insert a second guide wire into the anteromedial aspect of the tibia, passing through the epiphysis, with the aid of the drill guide (Fig. 13.2). From a direct lateral position, externally rotate the C-arm approximately 30° to reveal the physis extending into the tibial tubercle. Lift the handle of the drill guide so the pin clears the anterior portion of the tibial physis. Then, drill the guide wire into the tibial epiphysis using real-time fluoroscopic imaging. Ensure the pin enters the joint just anterior to the free edge of the lateral meniscus and in the footprint of the ACL on the tibia.

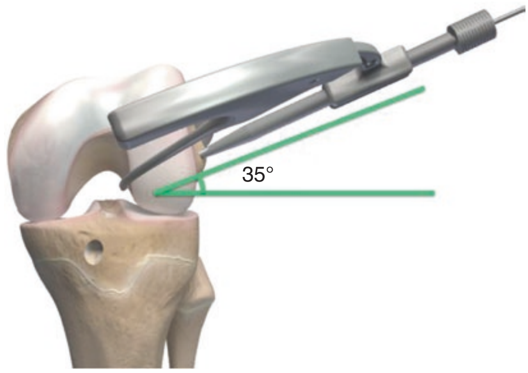

Fig. 13.1 The femoral guide. The handle of the guide should be elevated approximately 35–40° to avoid damaging the lateral collateral ligament and popliteus tendon during reaming (Copyright 2013 OrthoPediatrics Corp., with permission)

Before proceeding, confirm that both guide wires are in the correct position. Measure the diameter of the quadruple hamstring graft using tendon sizers; these grafts typically range from

Fig. 13.2 The tibial guide. The handle of the guide is positioned medial to the tibial tubercle to allow the guide wire to be advanced through the anteromedial epiphysis (Copyright 2013 OrthoPediatrics Corp., with permission)

6 to 8 mm in diameter. Because a tight fit is essential, use the smallest reamer possible to ream over the guide wires. Chamfer the edge of the femoral hole intra-articularly. After drilling the tibial and femoral holes, it is necessary to insert the OrthoPediatrics ShieldLoc sleeve into the femoral hole. Insert the counterbore reamer into the femoral hole until it bottoms out on the lateral femoral cortex (Fig. 13.3). During this step, the counterbore is inserted to a depth of 8 mm and increases the diameter of the femoral hole by 2 mm. The small amount of bone removal occurs rapidly. Retract the iliotibial band and carefully remove the soft tissue immediately around the hole to allow for clear placement of the ShieldLoc sleeve. The appropriately sized ShieldLoc sleeve is screwed on to the insertion device (Fig. 13.4a) and then gently tapped into the femoral tunnel (Fig. 13.4b). The fluted fins on the outside of the ShieldLoc sleeve prevent the device from backing

Fig. 13.3 The counterbore reamer (Copyright 2013 OrthoPediatrics Corp., with permission)

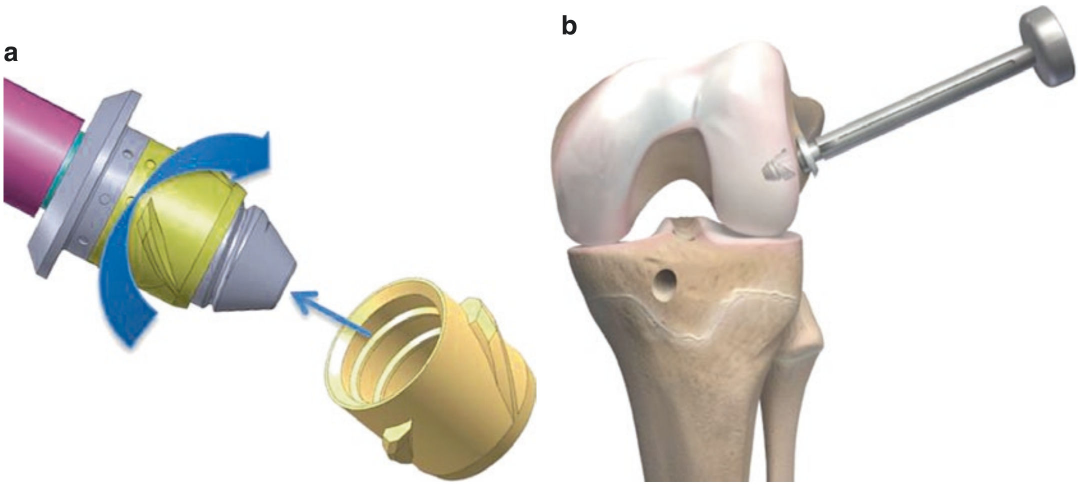

Fig. 13.4 The ShieldLoc sleeve is screwed on the insertion device (**a**) and tapped into the femoral tunnel (**b**) (Copyright 2013 OrthoPediatrics Corp., with permission)

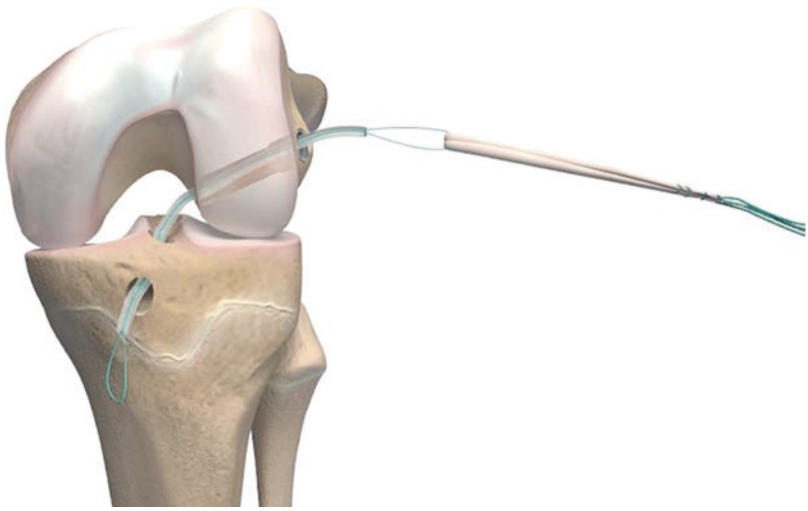

Fig. 13.5 The Graft Passer loop is used to shuttle the graft through the femoral tunnel into the tibial tunnel (Copyright 2013 OrthoPediatrics Corp., with permission)

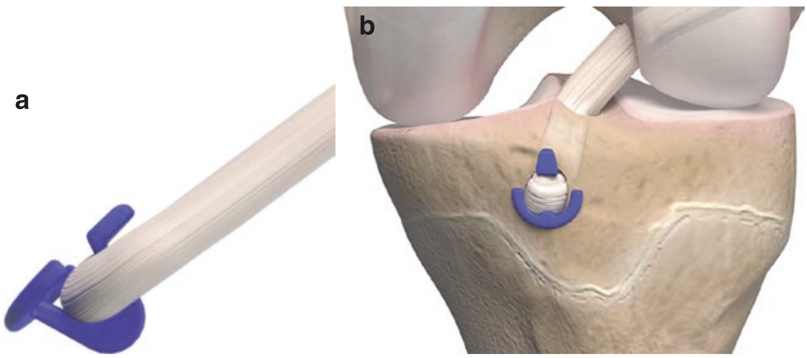

Fig. 13.6 (**a**) The ArmorLink device is grasped with a hemostat and passed around the loops formed from doubling both the semitendinosus and gracilis tendons. (**b**) The free strands of the graft exiting the femoral tunnel are then pulled laterally to seat the ArmorLink on the tibial cortex (Copyright 2013 OrthoPediatrics Corp., with permission)

out of the femoral tunnel while removing the insertion device. The ShieldLoc sleeve is designed to protect the physis from radial pressure caused by the insertion of the interference screw. After the ShieldLoc sleeve has been inserted, place the Graft Passer from the Disposable Kit through the femoral tunnel, and with an arthroscopic grasper, pull the Graft Passer loop out of the tibial tunnel (Fig. 13.5). Place one end of each graft through the Graft Passer loop on the femoral side. Then pull the tibial end of the Graft Passer, bringing the graft through the femoral tunnel into the tibial tunnel. Gently pull 1–2 cm of the graft loop outside of the anterior tibial cortex to allow installation of the ArmorLink implant. With the use of hemostat, pass the ArmorLink around the tendons (Fig. 13.6a). Pull on the free strands of the graft coming out of the femoral tunnel in order to seat the ArmorLink on the tibial cortex (Fig. 13.6b).

The ArmorLink may be positioned in any orientation. Observe the ShieldLoc when pulling the free strands of the graft to make sure the ShieldLoc sleeve does not catch on the sutures in the free ends of the graft and become displaced. If the ShieldLoc sleeve moves when pulling the tendons through, then stabilize the ShieldLoc sleeve with a hemostat to prevent displacement. With the knee in approximately 20–30° of flexion, apply tension with the graft tensioner, and insert the screw of the ShieldLoc (Fig. 13.7). Evaluate the graft for intercondylar notch impingement (Fig. 13.8a, b), and then close the wound in a standard fashion. Postoperative X-rays of a 9-year-old male show the position of the femoral drill hole and the ArmorLink implant.

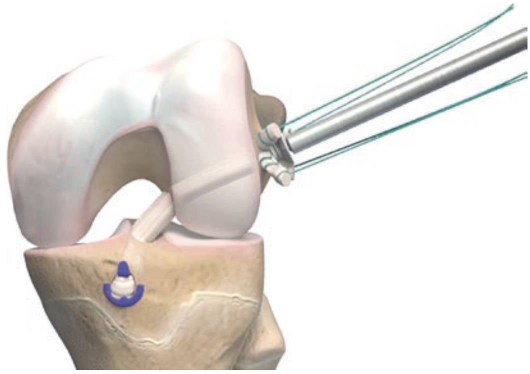

Fig. 13.7 The graft is then tensioned with the knee at 20–30° of flexion, and the interference screw is then inserted into the ShieldLoc sleeve. The free ends of the semitendinosus and gracilis are trimmed after satisfactory stability is confirmed (Copyright 2013 OrthoPediatrics Corp., with permission)

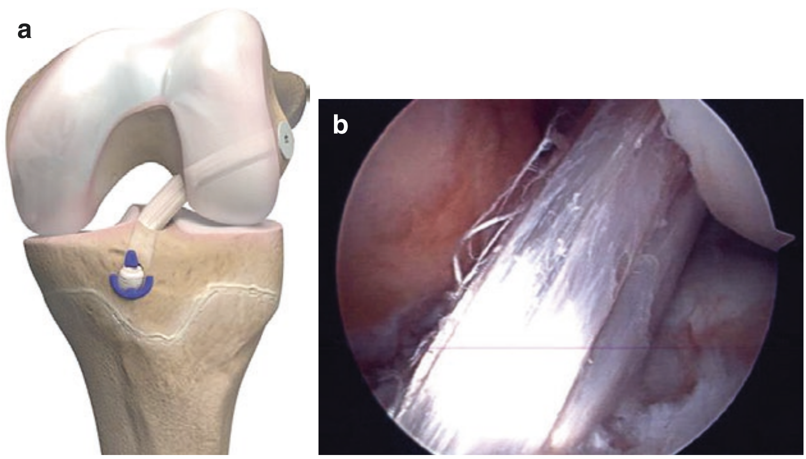

Fig. 13.8 (**a**, **b**) The knee is then extended and the graft is evaluated for impingement in the intercondylar notch (Copyright 2013 OrthoPediatrics Corp., with permission)

Postoperative Rehabilitation for Transepiphyseal or All-Epiphyseal Anterior Cruciate Ligament Reconstruction

Postoperatively, the leg is placed in a long-leg hinged knee brace locked in extension. Rehabilitation following the transepiphyseal ACL reconstruction procedure has three phases. Phase I begins when the patient awakens from surgery. Encourage the patient to perform straight-leg raises and to contract the quadriceps muscles. Use cryotherapy for 5–10 min each hour. The day after surgery, the patient performs range-of-motion exercises and hamstring stretches in a prone position. Patients without meniscal repairs may ambulate with crutches and partial weight bearing for 4 weeks. For patients who required meniscal repair, only toe-touch weight bearing is allowed for the first 6 weeks. The 1-week postsurgical goal is to have a range of motion of 0° of extension to 90° of flexion (Fig. 13.9).

Phase II of rehabilitation is the strengthening phase that may last from 2 to 11 weeks. During this phase, patients perform active range-of-motion exercises and patellar mobilization and undergo electrical muscle stimulation. Patients should work at a comfortable pace. At postsurgical week 2, the patient is fitted with a functional knee brace and is encouraged to bear weight. Exercises should be introduced in order of increasing difficulty, including hamstring stretches, quadriceps muscle stretches and strengthening, proprioception exercises, and functional strengthening. Finally, strengthening exercises may be performed in a pool. The goal is for the operative knee to have the same range of motion as the normal knee by postsurgical week 6.

Fig. 13.9 Postoperative AP and lateral X-rays of a 9-year-old male show the position of the ArmorLink implant and the femoral drill hole

The goal of the final rehabilitation phase is to regain full function of the knee. This phase lasts from 12 to 20 weeks. Rehabilitation activities during this phase include functional strengthening exercises, straight-line jogging, plyometric exercises, sport cord exercises for jogging, lateral movement, and foot agility exercises. Between postsurgical weeks 16 and 20, patients may resume functional activities (full-speed running) while wearing the brace. At postsurgical week 32, patients may return to full participation in sports. Patients are followed with clinical evaluation and scanograms are performed at skeletal maturity.

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14

Review of Different Surgical Techniques for All-Epiphyseal Anterior Cruciate Ligament Reconstruction

Lionel E. Lazaro, Junho Ahn, Frank A. Cordasco, and Daniel W. Green

Introduction

Given the strength of the cruciate ligaments over the immature epiphysis, intrasubstance tears of the anterior cruciate ligament (ACL) were once viewed as uncommon in pediatric patients [1]. However, current literature indicates a significant increase in the incidence of ACL injuries and reconstruction in the immature patient [2, 3]. This increase in incidence is thought to be secondary to a dramatic increase in the numbers of children who participate in competitive athletics year round. Additionally, an increase in the level of competition and early sports specialization are suspected to be contributing factors as well. A higher index of suspicion and a lower threshold for diagnostic investigation of pediatric ACL injury [4] have subsequently increased. In 2014, Dodwell et al. [5] reported a significant increase in the rate of ACL reconstruction from 17.6 in 1990 to 50.9 in 2009 per 100,000 population aged 3–20 years in New York State. Moreover, the Scandinavian registry revealed an incidence of ACL reconstruction in 76 per 100,000 girls and 47 per 100,000 boys between the ages of 10 and 19 years [6].

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Tears of the ACL account for a large number of sport-related injuries in the immature athletes [7, 8]. Historically, the perceived risk of physeal injury in this population had led to treatment recommendations that included initial nonoperative treatment followed by delayed reconstruction once they achieve skeletal maturity [8]. However, this treatment has fallen out of favor because of the potential effect of additional meniscus and chondral damage secondary to the instability present in the ACL-deficient knee. Lawrence et al. [9] reported an increase in both irreparable medial meniscus tear and chondral injury of the lateral tibia-femoral compartment when reconstruction was delayed >12 weeks after the initial injury. A systematic review of 48 studies on clinical outcome following surgical and nonsurgical treatment of ACL injury concluded that surgical treatment resulted in superior clinical outcomes [10]. Kocher et al. [11] reported that 33% of pediatric patients with partial ACL tear initially treated nonoperatively required delayed reconstruction to address the residual instability. Additionally, McCarroll et al. [12] reported that 50% of pediatric patients treated nonoperatively did not return to athletic activity and there was a high rate of discontinuation of athletic activity of choice.

Due to poor outcomes following nonoperative treatment and concern for additional intra-articular damage because of the instability present in an ACL-deficient knee, ACL reconstruction in the immature athlete is usually

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recommended [8–10, 13]. However, the recognized risk of growth disturbance with the use of conventional ACL reconstruction techniques, routinely used in the adult patient, has led to the development of several physeal-sparing techniques for ACL reconstruction in the immature athlete. These surgical techniques can be classified into four groups: (1) extraphyseal, (2) partial transphyseal, (3) complete transphyseal, and (4) all-epiphyseal. We believe that these various techniques can have specific roles given the wide range of skeletal growth in the immature athletes [1].

All-Epiphyseal ACL Reconstruction Techniques

We recommend all-epiphyseal ACL reconstruction techniques (Table 14.1) for immature athletes with more than 3 years of growth remaining. The advantage of an epiphyseal ACL reconstruction is that it restores the anatomic foot print of the ACL without crossing the physeal plate [1, 14, 15]. In addition, it restores the biomechanics of the knee joint decreasing the posterior joint contact stress relative to the ACL-deficient knee [16–18].

Classic Anderson Techniques

This technique, first described in 2003, uses two incisions and creates outside-in bone tunnels completely within the tibial and femoral epiphysis (Fig. 14.1). The graft of choice is a quadruple hamstring autograft. Anteroposterior and lateral views using C-arm fluoroscopy are used to assess guide wire and tunnel placement in relation to the femoral and tibia physes. The graft is first secured at the femur using suspensory cortical fixation with an EndoButton. The tibial fixation is then performed tying sutures over a post in the tibial metaphysis. The reported mean International Knee Documentation Committee (IKDC) score is 97% with no growth disturbances at a mean follow-up of 4.1 years (patients followed to skeletal maturity) [14, 19].

Table 14.1 All-epiphyseal ACL reconstruction

Technique	Anderson technique	Modified Anderson	Ganley-Lawrence all-epiphyseal technique with retroscrews	Green-Cordasco all-inside technique
Number of patients	12	–	3	23
Ages	13.3 ± 1.4 years	–	10–12 years	12.6
Preparation of allograft	Quadrupled	Quadrupled	Quadrupled	Quadrupled
Pretension	10 lb	10 lb	15 lb	20 lb for 5 min
Visualization	C-arm fluoroscopy	C-arm fluoroscopy	O-arm with 3D reconstruction	Mini C-arm fluoroscopy
Graft type	Hamstring autograft (gracilis and semitendinosus)	Hamstring autograft (gracilis and semitendinosus)	Hamstring autograft (gracilis and semitendinosus)	Hamstring autograft (semitendinosus)
Graft size	6–8 mm	6–8 mm	20 mm length	55–65 mm length (GraftLink), 7–8 mm
Bone tunnels/sockets	Bone tunnels	Bone tunnels	Bone tunnels	Bone sockets
Fixation in femur	Suspensory	Interference screws	Interference screws	Suspensory fixation
Fixation in tibia	Tie over a metaphyseal post	Suspensory fixation	Interference screws	Suspensory fixation

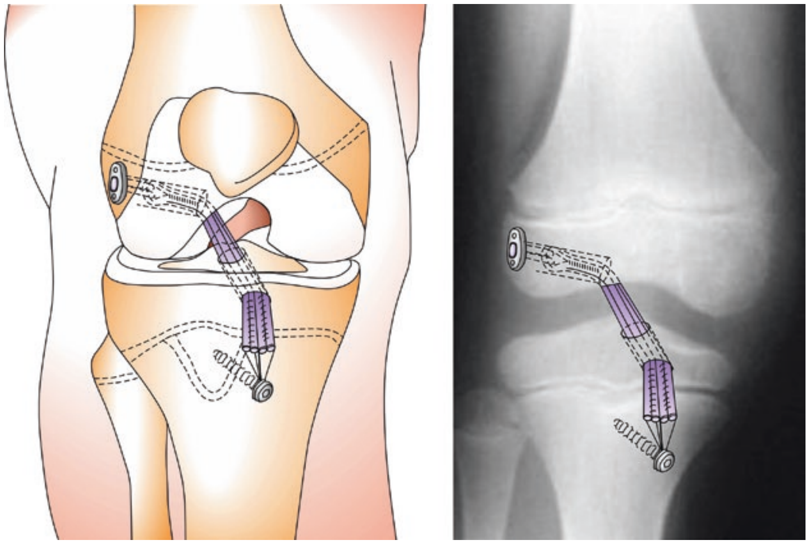

Fig. 14.1 Classic Anderson technique

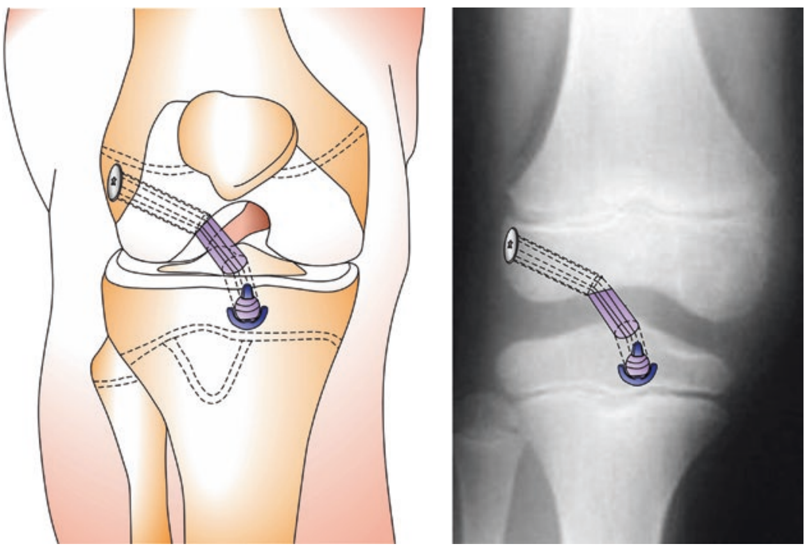

Fig. 14.2 Modified Anderson technique

Modified Anderson Technique

This technique uses different fixation devices at both the lateral femoral epiphysis and the anterior tibial epiphysis (OrthoPediatrics implants, Warsaw, IN). Instead of the tibial screw used for fixation of the autograft, a novel suspensory ArmorLink™ is utilized. This device has been designed to keep the fixation at the level of the epiphysis and to avoid crossing the physis with the fixation. This method eliminates the theoretical risk of growth disturbances due to the tethering of the tibial post located in the metaphysis distal to the physeal plate. At the femoral side, the EndoButton is replaced with a ShieldLoc™ ring/screw system (Fig. 14.2).

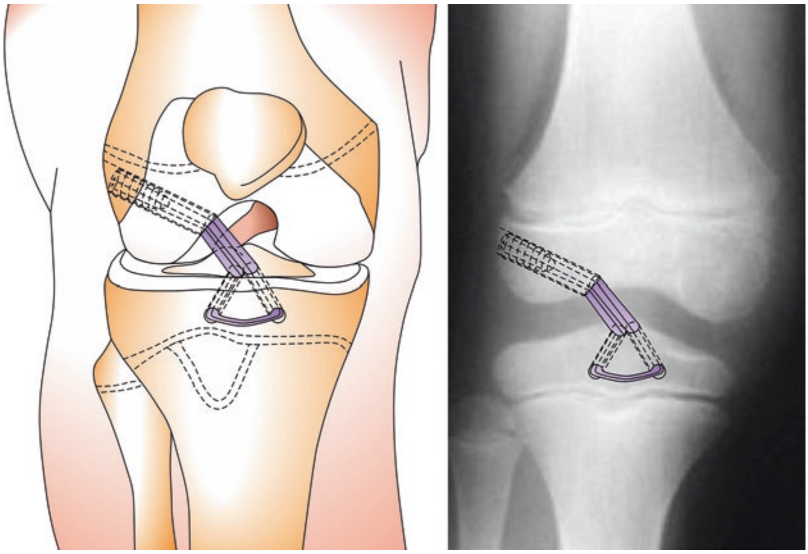

Fig. 14.3 Lykissas wall technique

Graft preparation, guide wire insertion, C-arm fluoroscopy visualization, tibial and femoral bone outside-in tunnel drilling, and arthroscopic evaluation are all performed in the manner as previously described in the classic Anderson technique [14]. However, the OrthoPediatrics set has all the tools necessary to perform the modified technique. After the bone tunnels have been drilled, a counterbore reamer is drilled into the lateral portion of the lateral femoral condyle tunnel to a depth of 8 mm. This creates an additional 2 mm increase in the diameter of the tunnel. An appropriately sized ShieldLoc™ sleeve is inserted laterally into the tunnel in the lateral femoral condyle using a ShieldLoc™ insertion device with light tapping. Then, the guide sutures attached to the graft are passed through the tibial tunnel followed by the femoral tunnel and finally out the lateral femoral condyle. The distal portion of the graft is suspended outside of the anterior tibial cortex by looping the graft around the ArmorLink device using a hemostat. The sutures on the free end of the graft are then gently pulled to create tension on the distal portion of graft so that the ArmorLink device sits on the tibial cortex. It is not necessary for the rotational orientation of the ArmorLink™ device to be in any particular position, as long as it is sitting flush with the anterior cortex. After the graft has been pulled through the ShieldLoc sleeve, the knee is placed in 20–30° flexion, and the graft is then tensioned with the graft tensioner. An interference screw is inserted to anchor the graft proximally.

Lykissas et al. [20] reported a technical modification to this technique. He described a split tibial tunnel within the epiphysis that functions as a low-profile fixation post (Fig. 14.3). Because half of the graft passes through each split tibial tunnel, the size of the tunnel is smaller, thereby increasing the safety margin.

Ganley-Lawrence All-Epiphyseal and All-Inside Transepiphyseal Technique

In 2010, Lawrence and Ganley introduced an all-epiphyseal technique with retroscrews for ACL reconstruction in skeletally immature patients (Fig. 14.4) [15]. By avoiding any fixation, tunnels, or placing grafts through the open physes, this technique theoretically diminishes the risk of growth abnormalities that could result from disruption of the physes. In the original report, three prepubescent boys in Tanner stage I and II of

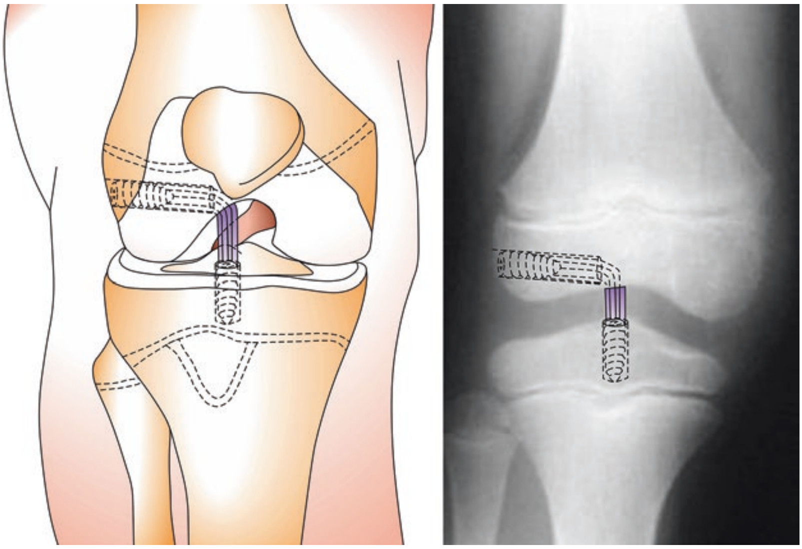

Fig. 14.4 Ganley-Lawrence technique

bone development underwent ACL reconstruction with this technique. After a mean follow-up of 5.7 years after surgery, no angular or growth discrepancies were noted on radiographic examination [15].

Graft preparation, knee position, and arthroscopic evaluation are performed in the same manner as the previously described techniques. The remaining torn ACL is removed and any meniscal tears are addressed. The outside-in femoral guide, set at 95°, is inserted into the anteromedial portal made earlier for arthroscopic examination and set on the medial portion of the lateral femoral condyle within the intercondylar notch. A small incision is made over the lateral aspect of the lateral femoral condyle, and the tissue is dissected to the bone. The outside-in femoral guide is then used to insert a guide wire parallel to the distal femoral physis in the epiphysis until it reaches the intercondylar notch out of the ACL footprint on the femur. After the wire has been placed, a RetroDrill is used to create the all-epiphyseal tibial tunnel. The cannulated guide pin for the drill is used to prevent complete drilling through the anterior tibial cortex. The tibial tunnel should be approximately 17 mm in depth from the joint space. Using an O-arm, intraoperative CT scans are done to confirm that the positions of the femoral guide wire and tibial tunnel are at a safe distance from the physes. The femoral tunnel is created using a standard reamer in an outside-to-inside fashion from the lateral femoral condyle to the intercondylar notch. The femoral tunnel is examined arthroscopically to ensure that the distal femoral physis has not been damaged.

The quadrupled hamstring autograft is prepared in the same manner as described in previous techniques and should be approximately 20 mm in length. The prepared graft is wrapped in damp gauze and pretensioned to 15 pounds. For graft insertion, a FiberStick suture is passed up the guide pin used for the RetroDrill into the articular space and then out the femoral tunnel. The suture is then used to pass the graft and a nitinol wire through the femoral tunnel and to the tibial tunnel. The proximal end of the nitinol wire is then brought out of the anteromedial portal. The graft is tightly pulled through the tibial tunnel and is secured using a RetroScrew screwdriver passed over the nitinol wire while the graft is held under tension. The knee is cycled repeatedly through flexion and extension. Finally, the femoral portion of the graft is secured using an interference tenodesis screw while tension is applied with the graft tensioner. The incisions are closed using standard methods. A locked knee brace is used to keep the joint in maximum extension.

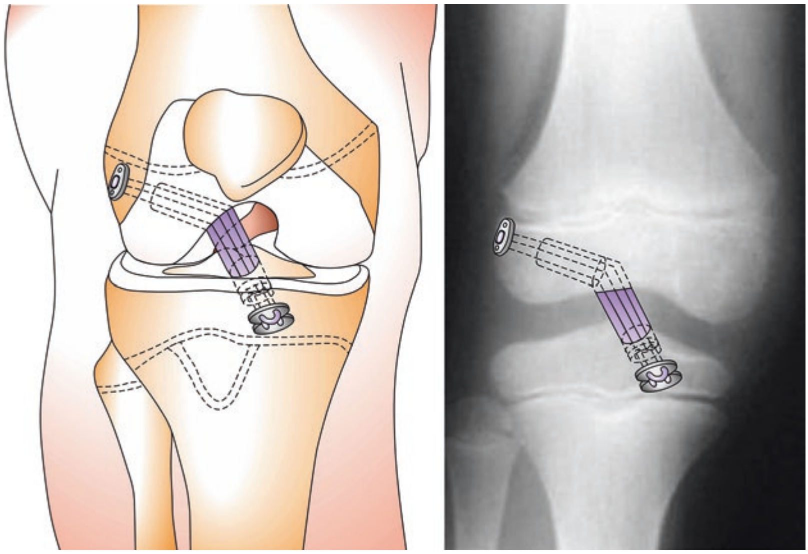

Fig. 14.5 Cordasco-Green technique

Cordasco-Green All-Epiphyseal and All-Inside Transepiphyseal Technique

This technique is another example of an all-epiphyseal technique for ACL reconstruction [4, 21]. However, unlike the other techniques, both ends of the graft are fixed with buttons rather than tenodesis screws, and bone sockets are used instead of tunnels (Fig. 14.5). Through the use of buttons, the graft can be secured without placing screws in the softer non-cortical bone; hence the cortical bone is left intact on both the femoral and tibial locations. In addition to this feature, the use of buttons instead of tenodesis screws may potentially provide greater contact of the graft to the surrounding bone improving the environment for tissue incorporation [31]. The improved graft-to-bone healing potentially allows a shorter recovery from surgery and faster return to activity [22]. As with the other all-epiphyseal techniques for ACL reconstruction, the Cordasco-Green technique may be used in patients who are prepubescent. Twenty-three patients with a mean age of 12.6 years who underwent ACL reconstructive surgery were assessed for growth abnormalities after a mean follow-up of 18.5 months using hip-to-ankle anteroposterior radiographs and MRI [23]. No cases of growth arrest, angular deformities, or significant leg length discrepancies were observed. The 2-year clinical outcomes in this group of 23 athletes revealed that 91% return to sport and two athletes are required a second surgery. Cruz et al. [8] evaluated 103 patients, with a mean follow-up of 21 months, who underwent all-epiphyseal ACL reconstruction (either Ganley-Lawrence or Cordasco-Green reconstruction techniques). They reported an overall complication rate of 16.5%, where re-rupture accounted for 10.7%.

The injured knee is positioned in 60° flexion and the hip is externally rotated. The autologous hamstring graft is prepared first using the semitendinosus tendon. The tendon is prepared using the GraftLink technique. The final dimensions of the graft should be approximately 55–65 mm in length and 8–10 mm thick. The graft is then placed in pretension under 20 pounds for 5 min. Arthroscopic evaluation of the knee joint is performed, and after the intercondylar notch is prepared, the femoral guide is inserted through the anterolateral portal. A pediatric ACL guide and mini C-arm fluoroscopy are used to confirm that the wire is parallel and distal to the femoral physis as the guide wire enters the notch. Arthroscopic visualization at the intercondylar notch confirms that the guide wire is appropriately positioned through the femoral footprint of the ACL.

A FlipCutter is drilled through the drill sleeve from the lateral portion of the lateral femoral condyle outside to inside until it reaches the intercondylar notch. The drill position is confirmed with C-arm fluoroscopy. The drill sleeve is gently inserted 7 mm into the lateral femur using a mallet to create a bridge between the end of the tunnel and the lateral cortex of the lateral femoral condyle. The FlipCutter blade is flipped and the socket is reamed retrograde to approximately 25 mm. The FlipCutter is removed and a FiberStick suture is passed into the newly created socket and retrieved through the anteromedial portal. The tibial socket is created in a similar fashion. The tibial footprint of the ACL is prepared, and a tibial ACL guide which is set to 30–40° is inserted into the anteromedial portal over the tibial footprint. The position of the guide is assessed through mini C-arm fluoroscopy. The drill sleeve on the tibial ACL guide is inserted into the cortex of the tibia using a mallet. The FlipCutter is placed in the drill sleeve and used to drill through the tibial epiphysis into the articular space. Moving retrograde, the FlipCutter is deployed to ream the tibial socket. The socket should be approximately 15 mm in depth and should leave a bony bridge between the end of the socket and the cortex of at least 7 mm. A second FiberStick suture is inserted into the tibial socket from the anterior aspect of the tibia into the articular space. The suture is then retrieved through the anterolateral portal to facilitate subsequent graft passage.

Once both sockets have been made, the graft is inserted into the anteromedial portal using the first FiberStick suture and brought out to the lateral femoral condyle where the reverse tightening button is flipped over the lateral epiphyseal cortex. The graft is partially tensioned to advance the graft into the femoral socket. Using the previously placed tibial FiberStick suture, the tibial portion of the graft is passed through the tibial socket, and the GraftLink suture is shuttled thru the tibial socket and out the tibial drill hole. Fixation of the tibial end of the graft is achieved by placing a TightRope ABS button on the GraftLink loop attached to the graft. The graft is tensioned with the flexed knee 20° at the femoral end followed by the tibial end. The knee is cycled through flexion and extension numerous times and is evaluated using the Lachman anterior drawer test and the pivot-shift test. The knee is cycled to address creep and final tensioning is performed. The sutures are backed up with knots on both the femoral and tibial sides. The incisions are closed through standard methods, and a locked knee brace is placed to keep the knee in extension.

Complications

Graft Failure

Following ACL reconstruction, the pediatric patient has a higher activity level. This puts the ACL graft under greater stress and makes it more susceptible to reinjury. Cruz et al. [8] reported 10.7% of re-rupture following several different techniques and graft choice of all-epiphyseal ACL reconstruction. Koch et al. [24] reported 16.7% re-rupture following reconstruction as describe by Anderson [14]. Forsch et al. [25] in his meta-analysis reported 4.8% re-rupture following index ACL reconstruction in children and adolescents. The re-rupture rate is greater in pediatric patients when compared to older adolescent and adult patients [24, 26]. Re-rupture rate in younger patients may be higher because of their higher level of activity and elevated functional demands [8].

Growth Disturbance

As these surgical techniques are developed, careful evaluation of the distal femoral and proximal tibial physes must be performed to assess the risk of growth disturbance. One important consideration in patients with an open physis is the effect of the epiphyseal instrumentation to create either the tunnels or sockets and secure the graft. Lawrence et al. [27] reported a premature closure of the lateral distal femoral physis resulting in valgus deformity following revision ACL reconstruction using epiphyseal tunnel. He suggested that drilling near the physis can result in thermal injury, altered vascularity, and abnormal mechanical forces that negatively affect the growth plate. Previous animal studies reported that physeal injury of >7% of the distal physis and >4% of the tibial physis can result in growth disturbance [23, 28–30]. Nawabi et al. [23] utilized specific MRI sequences to evaluate for physeal injury following all-inside, physeal-sparing ACL reconstruction in skeletally immature patients. They reported that 67% of the patient suffered a small tibial physeal disturbance (2.1% of total physeal area) and no disturbance was noted on the femoral side. They reported no growth disturbance at 18.5 months follow-up. Koch et al. [24] reported no growth arrest in his cohort of 12 patients that underwent epiphyseal ACL reconstruction. Cruz et al. [8] reported only one patient (<1%) with growth disturbance in 109 pediatric patients that underwent all-epiphyseal ACL reconstruction.

Koch et al. [24] did report leg-length discrepancy in 17% of patients, by means of overgrowth. Although not completely understood, growth stimulation or overgrowth has been attributed to increased vascularity in the distal femoral shaft as well as an increase in cell division within the physis following periosteal disruption [31]. Similar to growth arrest, overgrowth is a potential complication of ACL reconstruction that may lead to angular deformity and limb-length discrepancy. However, overgrowth is a complication that is associated with younger patients [32, 33].

Growth disturbance is a major concern when surgically treating pediatric patients with ACL injury. Preoperative and postoperative long-leg radiographs to adequately assess overtime for any growth disturbance and/or change in alignment following ACL reconstruction are recommended as standard of care.

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15

Femoral Physeal Sparing/ Transphyseal Tibial (Hybrid) Technique for ACL Reconstruction in Skeletally Immature Athletes

Matthew D. Milewski and Carl W. Nissen

Introduction

As the number of ACL injuries diagnosed in adolescent athletes has increased substantially in the last decade, multiple different approaches have been described for ACL reconstruction in these patients. A lot of interest and literature has been devoted to ACL reconstruction in the youngest populations, particularly prepubescent athletes, and techniques such as the Micheli–Kocher iliotibial band combined intra-articular extra-articular reconstruction and the Anderson or Ganley–Lawrence all-epiphyseal technique are excellent options for children in this youngest population of patients sustaining ACL injuries [1–4]. While the highest rates of ACL injury occur in patients between 15 and 17 years of age, the next highest rate of ACL injury occurs in patients between 12 and 14 years of age [5]. This population is of particular interest in regard to skeletal maturity. Some of patients in this age group with ACL injuries might be near skeletal maturity, particularly the females, while others in this age group might still have 3–4 years of skeletal growth. Therefore, different surgical treatment options may be necessary in this population in order to take advantage of the benefits of individual techniques. In particular, a femoral physeal sparing epiphyseal drilling technique combined with a transphyseal tibial drilling technique, or hybrid technique, might be most appropriate for skeletally immature athletes that are within or around 2 years from skeletal maturity.

Rationale for Surgical Treatment

Traditional treatment of ACL injuries in a near skeletally mature group was a "wait until skeletal maturity" approach so that traditional adult ACL reconstruction techniques could be used. This allowed surgeons to minimize any concerns about physeal risk and also to use traditional ACL reconstruction techniques that would not be physeal sparing and might include bone plugs such as with a bone-patellar-bone autograft. Patients and their families would be asked to either use activity modification and/or bracing during this period of waiting for their reconstruction. However, multiple authors have shown the risks of nonoperative or delayed surgical treatment in skeletally immature patients include progressive meniscal and chondral injury [6–10].

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In particular, Lawrence et al. has shown that as little as a 3 month delay in surgical treatment of the ACL deficient knee in a skeletally immature patient can result in a significant increase in meniscal and chondral pathology [9]. Therefore, in patients and families where activity modification will be difficult or impossible, it has been recommended to consider ACL reconstruction in these skeletally immature patients.

History and Physical Exam

Adolescent athletes who have sustained a knee injury that is concerning for an ACL injury will often describe either direct trauma, i.e., were hit from side or impacted the knee on the ground or another player, or indirect trauma, i.e., noncontact injury from a planting, pivoting, cutting mechanism. They will often report an immediate knee effusion and difficulty with ambulation acutely when the ACL has been torn. A sideline examination will often reveal an asymmetric anterior drawer test and a positive Lachman's exam without a firm endpoint. In this young population, this exam can be difficult in the coming days due to swelling, pain, and anxiety and therefore the acute, on the field, exam is important. A full ligamentous exam and meniscal signs should be done to assess for other associated knee injuries. A better assessment of the ACL integrity can often be done in the office once the patient's hemarthrosis/effusion has decreased, range of motion improved, and pain/anxiety has subsided.

Assessment of Skeletal Maturity

Once the diagnosis of an ACL injury has been confirmed in a skeletally immature patient based on physical exam and MRI imaging, an assessment of skeletal maturity is essential to determining the risk of each of the ACL reconstruction techniques. Tanner staging is widely used among pediatricians and correlates height, weight, height velocity, and weight velocity with physiologic signs of development [11]. However, this type of staging has been less accepted in orthopedic and sports medicine clinics. Radiographic determination of skeletal maturity is much more commonly used. Bone age as determined by a left hand radiograph using the Greulich and Pyle atlas is commonly used. A short hand version for bone age determination has been recently developed [12].

Various treatment algorithms have been developed for determining which ACL reconstruction technique is appropriate in a skeletally immature patient. Milewski et al. presented one version based on skeletal age as determined by bone age [13]. For those patients found to be symptomatic from their ACL deficiency, there were five different options. For the youngest patients aged 6 or younger, the Micheli–Kocher intra-articular, extra-articular reconstruction was most appropriate. For the next youngest patients with a bone age of 8, the modified Anderson all-epiphyseal reconstruction technique was recommended. For patients with a bone age of 10, the Ganley–Lawrence all-epiphyseal docking procedure was felt to be most appropriate. For patients with a bone age of 12, a modified "hybrid" all-epiphyseal femoral tunnel with a transphyseal tibial tunnel procedure was recommended and will be discussed further below. For patients with a bone age of 14 and that were approaching skeletal maturity, transphyseal femoral and tibial reconstruction with soft tissue only across the physis was recommended. Therefore, for the patients with a bone age of 12, and generally at least 2 years of skeletal growth remaining but usually not more than 3–4 years of growth remaining, the hybrid reconstruction technique can be used in adolescent athletes who have sustained an ACL tear (Figs. 15.1 and 15.2).

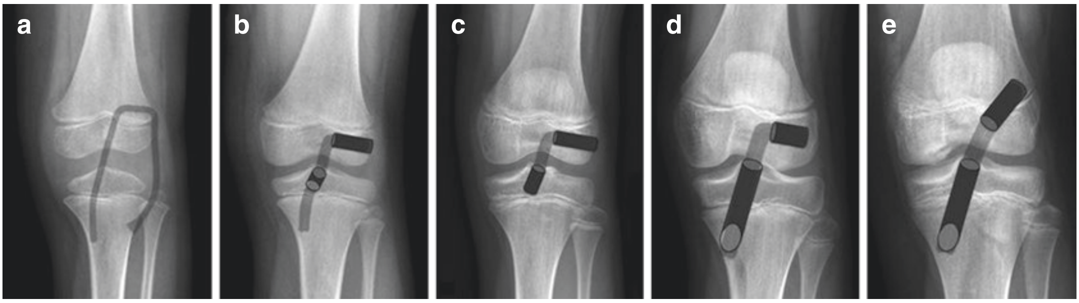

Fig. 15.1 Radiographs revealing representative images of patients with bone ages of 6–14. (**a**) Bone age of 6: Micheli–Kocher intra-articular extra-articular procedure. (**b**) Bone age of 8: Anderson all-epiphyseal procedure, which has been modified. (**c**) Bone age of 10: Ganley–Lawrence all-epiphyseal docking procedure. (**d**) Bone age of 12: Hybrid all-epiphyseal femoral transphyseal tibial procedure. (**e**) Bone age of 14: Transphyseal femoral and tibial reconstruction with soft tissue only at the level of the physis. Reprinted with permission: Milewski et al. Clinics in Sports Med. 2011

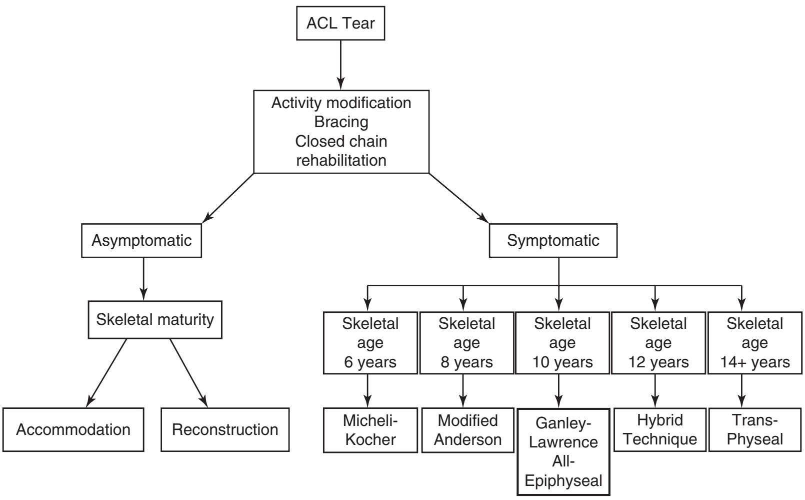

Fig. 15.2 Treatment algorithm for patients with a ruptured ACL. After a trial of activity modification, bracing, and closed-chain rehabilitation, symptomatic patients are candidates for surgical reconstruction. Prepubescent patients are at greatest risk for growth disturbances, and physeal-sparing techniques such as an all-epiphyseal or combined intra-articular and extra-articular reconstruction are employed. Soft tissue transphyseal reconstruction is performed on older/postpubescent patients. Reprinted with permission: Milewski et al. Clinics in Sports Med. 2011

Rationale for Hybrid Reconstruction

Several series have shown that transphyseal ACL reconstruction using soft tissue grafts, usually hamstring autograft, in postpubescent adolescents is safe with no angular deformities or leg length discrepancies and excellent outcomes [14–16]. However, there is concern that transtibial drilling techniques may produce a vertical graft orientation and place less of the graft in the central aspect of the femoral footprint than accessory medial portal drilling techniques [17].

Fig. 15.3 The amount and location of femoral physis effected using different operative techniques. (**a**) The location of a vertically orientated tunnel, which affects less of the femoral physis but is typically outside of the native ACL footprint. (**b**) The location of a classic anatomic accessory medial portal, or outside in technique, that places the tunnel anatomically in the ACL footprint but affects a large portion of the distal femoral physis. (**c**) The location of a femoral tunnel, which is in the anatomic center of the ACL footprint within the epiphysis in a trajectory that avoids the femoral physis. Reprinted with permission: Milewski et al. Clinics in Sports Med. 2011

Independent femoral tunnel drilling can be done with either accessory medial portal drilling, 2 incision outside-in drilling, or outside-in drilling using a retrograde drilling technique [17, 18]. Unfortunately, these techniques, when used in the typical adult manner, will produce a very oblique tunnel through the lateral physis of the distal femur that potentially damages a larger portion of the physis and also potentially the perichondral ring. However, the retrograde inside-out drilling can also be done safely with proper intraoperative imaging guidance to avoid the physis (Fig. 15.3).

Transphyseal tibial drilling is thought to be safer than trans-femoral physeal drilling in these skeletally immature patients for several reasons. First, the tunnel is more central and can be modified to be more vertical. Placing the tunnel more vertical in the tibia allows the tunnel to be more central in the tibial physis and to be more circular and therefore create a smaller hole in the physis. In addition, the tibial proximal physis produces less longitudinal growth than the distal femoral physis and therefore is less risky for producing a leg length discrepancy. By drilling through the physis, more graft is able to be placed on the tibia side and this allows for the potential for more ingrowth and also for a variety of distal fixation techniques. It is the authors' opinion that this technique is also less technically demanding than an all-inside reconstruction technique especially for surgeons who are familiar with traditional drilling techniques.

Hybrid Reconstruction in the Literature

Hybrid reconstruction has been described previously in the literature with good results although the previous hybrid technique involved an "over-the-top" femoral position of the graft. The "over-the-top" femoral position allows the femoral physis to be completely avoided but does place the graft in a nonanatomic position. Lipscomb and Anderson reported on 24 skeletally immature patients with a mean age of 13 that underwent a hybrid ACL reconstruction using hamstring autograft, "over-the-top" femoral position and a transphyseal tibial tunnel [19]. Eighty-three percent of patients returned to preoperative activity levels and one patient had a leg length discrepancy of 2 cm with a mean follow-up of 35 months. Andrews et al. studied eight adolescent patients (mean age of 13.5) who had undergone hybrid reconstruction with fascia lata or Achilles allograft with an "over-the-top" femoral fixation and had 87.5% good to excellent results with no growth disturbances at mean follow-up of 58 months [20]. Lo et al. reported on five patients (mean age 12.9 years) using a hybrid reconstruction technique with an over-the-top femoral placement of a soft tissue autograft and transtibial drilling [21]. They utilized 6 mm or smaller tunnels on the tibia and had no evidence of limb length discrepancies at mean follow-up of 7.4 years.

Author's Technique for Hybrid ACL Physeal Sparing Reconstruction

The author prefers the use of a hybrid ACL reconstruction technique using a femoral physeal sparing retro-drilling technique with a transtibial transphyseal technique for young athletes around a bone age of 12 with at least 2 years of growth remaining. Once preoperative family discussion, preoperative imaging, and subjective outcome measures have been completed, outpatient arthroscopic surgery is scheduled. A discussion about preoperative nerve block(s) including their risks is also included.

The lead author (MDM) prefers a flat OR table utilizing an arthroscopy post for assistance with medial compartment visualization. Alternatively, the senior author (CWN) prefers an arthroscopy leg holder with a dropped foot of the bed. The flat OR table set up allows for more traditional fluoroscopic views. It also allows for easier figure-4 positioning if a lateral meniscus repair is necessary. Its disadvantage includes a more difficult access for posteromedial approaches if a medial meniscal repair is required. The lead author utilizes a Spider arthroscopic holder (Smith & Nephew, Andover, Mass.) in standard ACL reconstructions where hyperflexion is needed during accessory medial portal drilling. However, hyperflexion is not needed during femoral physeal sparing retro-drilling. A thigh tourniquet is applied prior to post or leg holder placement. An examination under anesthesia and compared to the contralateral knee is essential to correctly understand the knee's ligamentous integrity.

Diagnostic arthroscopy is done first in a standard fashion. Examination should include the patellofemoral compartment, both medial and lateral gutters, medial and lateral compartments, intracondylar notch, and possibly the posteromedial and posterolateral recesses. Anteromedial portal is made under direct visualization. If meniscal or chondral pathology is found, then its treatment is carried out first prior to ACL reconstruction. The author prefers inside-out meniscal repair using 2-0″ Fiberwire meniscal repair needles (Arthrex, Naples, Florida) for most meniscal tears. All-inside repair with 360° Fast-Fix meniscal repair devices (Smith & Nephew, Andover, Mass.) are sometimes utilized for smaller tears.

Once the ACL tear has been confirmed arthroscopically and associated pathology treated, ACL remnants are debrided and a notchplasty may be done depending on the narrowness of the intracondylar notch. Soft tissue grafts are used universally for physeal sparing ACL reconstruction techniques. A quadrupled gracilis and semitendinosis is usually utilized for this technique. Alternatively a quadrupled single tendon semitendinosis graft can also be used (Fig. 15.4). A small amount of tissue may be left on the femoral ACL footprint to assist in placing the femoral tunnel in the center of the native footprint. The arthroscope can be switched to the anteromedial portal for the femoral tunnel drilling. The Flipcutter pediatric ACL femoral guide (Arthrex, Naples, Florida) is utilized at a setting of about 90°. The targeting guide is directed to the center of the ACL femoral footprint. Increasing attention is now paid to the lateral starting point. The percutaneous lateral starting point should be below the femoral physis but also avoid iatrogenic injury to the femoral insertion sites for the LCL and popliteus. There is

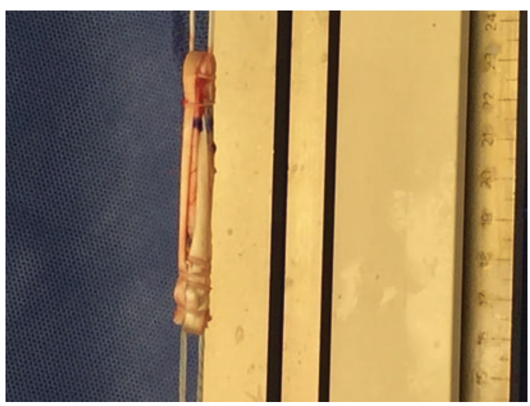

Fig. 15.4 Quadrupled semitendinosis graft with gracilis doubled over the top with sutures in both ends and has been prepared for adjustable loop button fixation on both the femur and tibia

a very small area posterior to their insertions that also avoids iatrogenic injury to the posterior femoral articular cartilage. Therefore, the author prefers a lateral starting point anterior to the LCL and popliteus insertion. This is usually in line with the mid aspect of the femoral shaft on a perfect lateral of the distal femur on the fluoroscopic view. This still allows for a posterior intra-articular exit point in the center of the ACL footprint. A smaller 2.4 mm guide pin is drilled first and checked on the AP fluoroscopic view to make sure the tunnel will be below the distal femoral lateral physis (Fig. 15.5). Once this is confirmed, the pin is replaced through the drill guide with the appropriate sized Flipcutter for the autologous hamstring autograft (Fig. 15.6). Once the retro-drill has been fully inserted into the notch, it is then deployed and then retro-drilled for a tunnel of at least 20 mm. This can be drilled all the way to the lateral epiphysis cortex. A suture is placed through the tunnel after the drill has been removed for later graft passage.

Once the femoral tunnel is completed, attention is turned towards the tibial tunnel. A standard ACL guide can be used and aimed towards the center of the ACL tibial footprint. For this technique, the angle of the guide is increased to 70° and moved more centrally with the drill starting point through the anteromedial incision used for hamstring harvest. By moving the starting

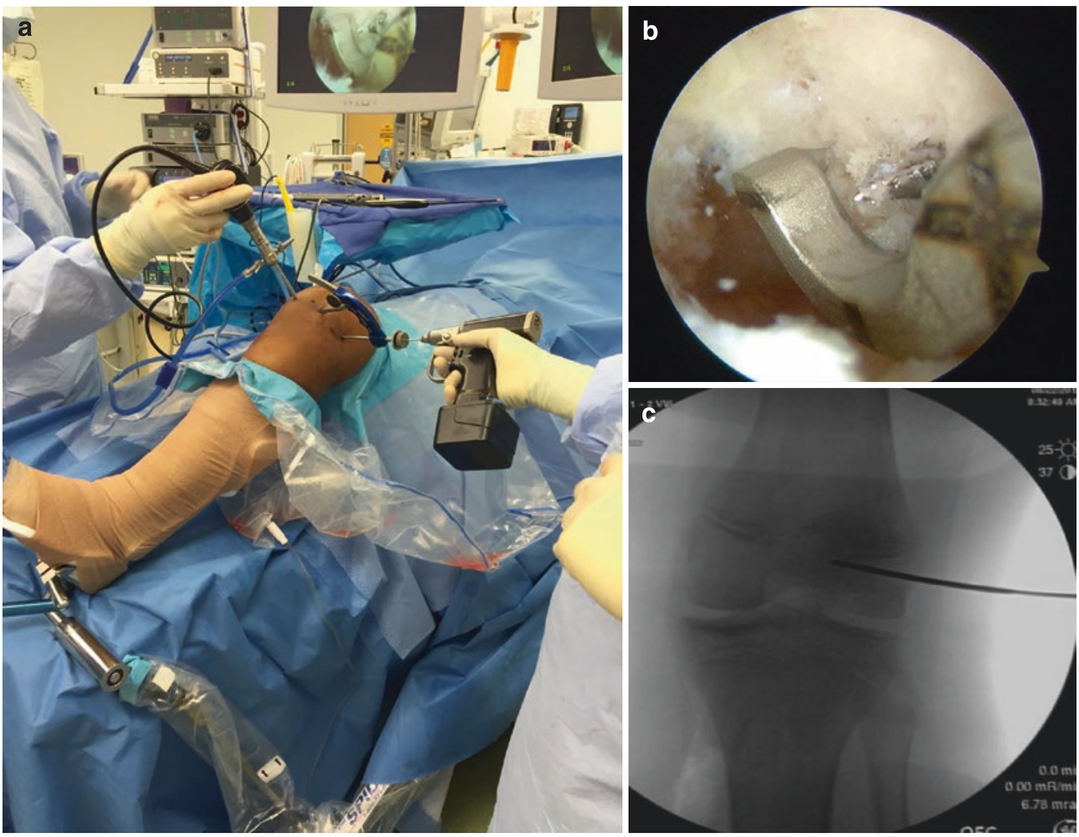

Fig. 15.5 Arthroscopic all-epiphyseal ACL tunnel drilling. (**a**) Flat bed and arthroscopy post set up is used here with a Spider arthroscopy leg holder (Smith & Nephew, Andover, Mass.) 30° arthroscope is used through the anteromedial portal here. The Arthrex pediatric femoral guide (Naples, Fl) is used here through the anterolateral portal and set to 90°. The 2.4 mm guide pin is drilled first. (**b**) Arthroscopic view through the anteromedial portal of the pin placement in the ACL femoral footprint. (**c**) Fluoroscopic view confirming a location below the femoral physis

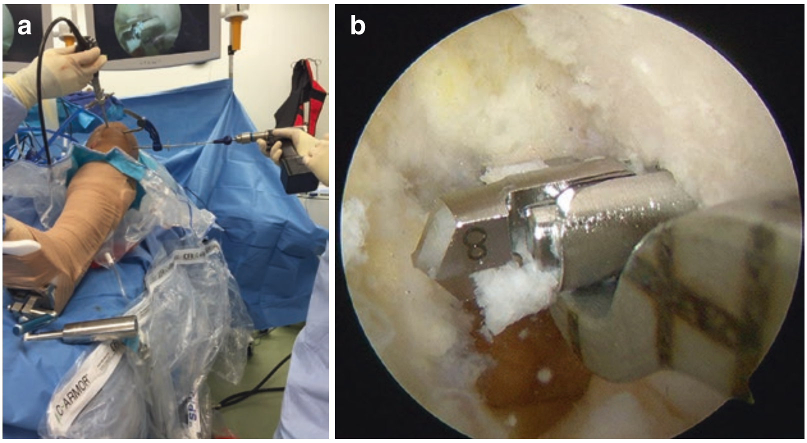

Fig. 15.6 Arthroscopic all-epiphyseal retro-drilling femoral ACL tunnel drilling using the Arthrex Flipcutter 8 mm drill. (**a**) Flat bed and arthroscopy post set up is used here with a Spider arthroscopy leg holder (Smith & Nephew, Andover, Mass.) 30° arthroscope is used through the anteromedial portal here. The Arthrex pediatric femoral guide (Naples, Fl) is used here through the anterolateral portal and set to 90°. (**b**) Arthroscopic view through the anteromedial portal of the drill placement in the ACL femoral footprint

point distally and more centrally, it reduces the physeal injury by producing a more circular tunnel through the tibial physis. Suture is then passed from the femoral tunnel through the tibial tunnel. It is useful to use a depth gauge in the tibial tunnel at this time. Fluoroscopy is used to help measure the distance from the physis to the anteromedial aperture. This can be useful in determining if a minimum amount of space is available for screw fixation such that the screw wouldn't cross the physis. If the distance is too small or the surgeon prefers distal fixation, then either cortical button, screw and post or staple fixation can be used distally as needed in the tibial metaphysis. Once the graft is placed and the femoral button deployed, slack is taken out of the adjustable loop until the graft is firmly pulled into the femoral socket. It is useful to mark the graft at a distance equal to the tunnel length to confirm the graft is fully seated. Tibial fixation is completed at this time with the knee in near full extension. The author prefers to cycle the knee multiple times in between tensioning the adjustable loop devices to reduce any creep in the loop systems.

Postoperative rehabilitation includes an emphasis on early range of motion. Once good quadriceps control is established, crutches and bracing can be discontinued. Advancing to running is generally delayed until around 3 months and only if the patient demonstrates improving quadriceps strength as demonstrated by less than a 30% deficit on isometric strength testing. Plyometrics and hop testing training can begin in months 3–6 and must be completed before a return to play assessment. We use a comprehensive return to play assessment that includes clinical parameters (no pain, no swelling, symmetric range of motion), subjective outcomes (pediatric IKDC), symmetric quadriceps and hamstring strength (<10% deficit on isometric and isokinetic strength testing), and multiple hop testing (as evaluated by sports-trained physical therapist with an assessment of distance, symmetry, and form). Clearance is done at its earliest at around 6 months postoperatively. Average return to play in the author's adolescent athletic population is around 9 months. It is suggested that the patients are followed clinically and radiographically until skeletal maturity to assess for any potential growth abnormality including leg length discrepancy or angular deformity (Fig. 15.7). The sooner any potential growth issue is identified, the sooner potential growth modulation treatment options can be done if the growth abnormality is felt to be potentially clinically significant.

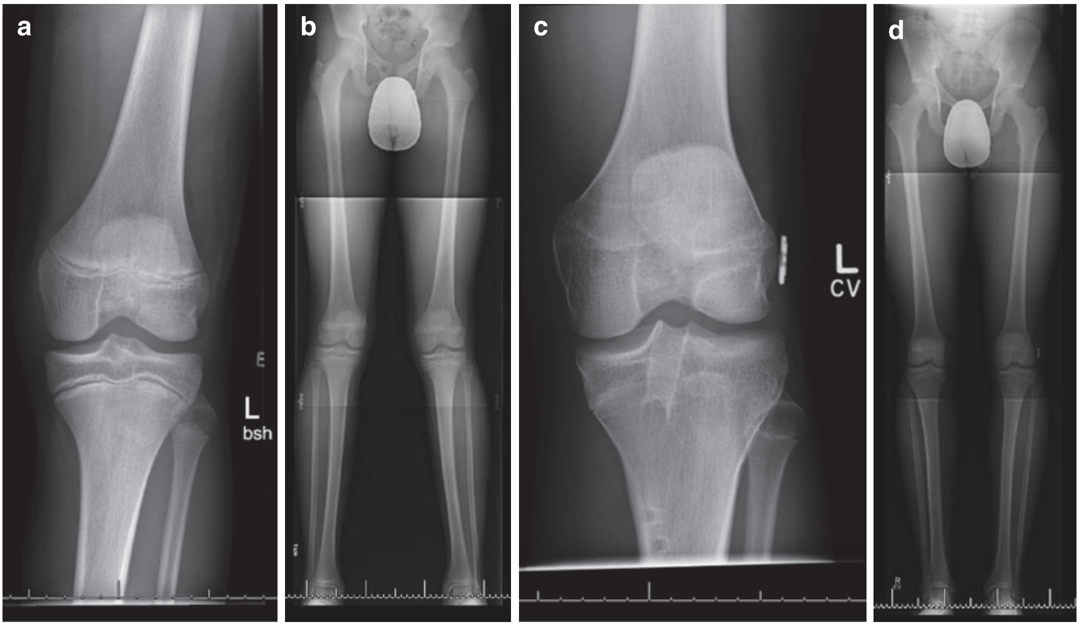

Fig. 15.7 13.3 yo male with bone age of 13.6 sustained left ACL and lateral meniscal tears. Initial radiographs including AP (**a**) and standing lower extremity alignment films (**b**) are included. He underwent left knee ACL reconstruction with a hybrid femoral physeal sparing technique with hamstring autograft and lateral meniscal repair using inside-out vertical mattress sutures. He returned to sports including football 8 months after his surgery. He returned to clinic for routine follow-up at 2 years and 8 months postoperatively and had returned to full football without issue or instability. No clinical leg length discrepancy was noted. Radiographs at most recent follow-up are included here including AP (**c**) and standing lower extremity alignment films (**d**)

Conclusion

As ACL injuries in adolescent athletes continue to increase, so do the techniques for reconstruction. A physeal sparing femoral tunnel placement with a transphyseal tibial tunnel, a hybrid ACL reconstruction technique can be used in skeletally immature patients with 2 years of growth remaining. It allows for a more anatomic femoral tunnel location within the footprint and minimizes potential physeal injury to the femoral physis. A vertical transphyseal tibial tunnel minimizes physeal injury and maximizes graft within the tibial tunnel. Future studies will be needed to examine the long-term effects of these procedures and compare their functional outcomes with other techniques for skeletally immature athletes.

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16 Transphyseal ACL Reconstruction in Skeletally Immature Patients

Crystal A. Perkins, S. Clifton Willimon, and Michael T. Busch

Introduction

Anterior cruciate ligament (ACL) injuries in skeletally immature children with significant growth remaining present a challenge to orthopedic surgeons. The evolution of year-round single sport young athletes and increasing competitive demands has resulted in a significant rise in the incidence of ACL injuries in skeletally immature patients. The total number of ACL reconstructions performed from 1994 to 2006 increased in all age groups, but most significantly in patients younger than 15 years of age who experienced an increase of 425% [1]. Consequently, there is a growing incidence of ACL injuries in prepubescent and pubescent athletes that have appreciable growth remaining.

Management of ACL Injuries

Studies of ACL injuries in skeletally immature patients suggest a trend toward operative management in order to increase stability, improve function, and avoid poor outcomes associated with further injury. Reinjury often results in irreversible meniscal and articular cartilage damage [2–5]. Although nonoperative treatment may have a role in very specific circumstances, a growing number of youths with ACL injuries should be considered for reconstruction. McCarroll described the results of transphyseal ACL reconstructions in skeletally immature children compared to a nonoperatively treated cohort [6]. Sixty junior high school or younger athletes with arthroscopically documented ACL tears underwent intra-articular reconstruction with tibial and femoral bone tunnels and autogenous bone-patellar tendon-bone graft at an average age of 14.2 years (range 13–17). Thirty-eight children within this cohort were initially deemed to be too skeletally immature for immediate reconstruction (physes "wide open", no adolescent growth spurt, patient 10–15 cm shorter than older siblings or parents, Tanner 1–2) and were treated nonoperatively until closer to skeletal maturity. All patients with delayed surgical intervention reported persistent instability and/or meniscal tears during the period of nonoperative management. The other 22 patients in the cohort underwent reconstruction at the time of initial injury. Assessment of outcomes of the cohort (delayed and immediate reconstructions) demonstrated that 90% returned to pre-injury sports, none reported instability, and there were no growth disturbances or angular deformities at a minimum 2 year follow-up (average 4.2 years). This landmark article influenced many to be more likely to reconstruct skeletally immature patients.

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It also popularized the transphyseal technique in this patient population.

The vast majority of ACL tears in skeletally immature athletes occur in adolescents with limited growth remaining. This allows for traditional transphyseal reconstructions with very little concern for growth disturbance. One has to be careful, however, about extrapolating favorable results from these nearly skeletally mature adolescents to prepubertal children. A thorough understanding of the pediatric knee, including physeal and ligamentous anatomy and growth remaining, are critical when selecting and performing reconstructive procedures. With careful patient selection and attention to technical details, transphyseal ACL reconstruction is a sound and viable treatment for most skeletally immature children. Physeal sparing reconstructions are another option for skeletally immature children with an ACL tear. However, critics of these techniques question their ability to replicate normal anatomy and restore normal knee kinematics [7].

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 youths who have 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 and identifying individuals at particular risk for complications, understanding and minimizing the risks of traditional transphyseal ACL reconstruction based upon basic science and clinical series, comparing the transphyseal technique to other alternatives such as all-epiphyseal or physeal sparing reconstructions, reviewing functional outcomes of transphyseal ACL reconstructions and minimizing graft failures, and monitoring patients after surgery for potential growth disturbances.

Assessment of Growth Remaining

The distal femoral physis contributes 70% of femoral growth (12 mm/year) and the proximal tibial physis contributes 60% of tibial growth (6 mm/year). Peak height velocity precedes menarche in girls and the development of axillary and pubic hair in boys [8]. During this time, physeal injury is theoretically most detrimental to longitudinal growth. 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. Chronological age and the presence of an open physis on radiographs are notoriously inaccurate, yet many of the early studies on ACL reconstructions in youths include only these parameters to describe the population of patients being analyzed. Drawing conclusions from these articles is therefore precarious. Tanner staging is based upon dividing secondary sexual characteristics into one of five groups [9]. These stages parallel the adolescent growth spurt and subsequent closure of the physes. Unfortunately, they do not seem to be accurate, as a study of experienced physicians performing these assessments has shown them not to be reliable or reproducible [10]. Social reasons also make physicians hesitant to put themselves in the position of making these assessments. Self-reported assessment tools completed by either children themselves or parents have been developed, but also found to be unreliable [11]. Finally, Tanner staging has not been documented to predict the growth remaining specifically at the distal femoral and proximal tibial physes.

In an attempt to determine at what age it is feasible to drill through the physis, 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 1–2, bone age <12 years in boys and <11 years in girls), pubescent (Tanner 3–4, bone age 13–16 years in boys and 12–14 years in girls), or older adolescents (Tanner 5, bone age >16 years in boys and >14 years in girls). Based on bone age, prepubescent patients are treated with physeal sparing reconstructions, adolescent patients with transphyseal reconstructions with soft tissue grafts, and older adolescents with adult-type ACL reconstructions with either soft tissue or bone-patellar tendon grafts [12].

Bone age utilizes a posterior-anterior radiograph of the left hand and wrist, which is then compared to standard examples in the Greulich-Pyle atlas [13]. These standards were based upon observations from a largely white northern European population in Boston during the 1940s, which raises questions about the applicability to more ethnically diverse populations and different nutritional standards as compared to modern times [14]. While 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 Greulich-Pyle data set and assessment [15].

Guzzanti introduced the concept of growth remaining and proposed categorizing children into three groups based on their risk for growth disturbance (high, intermediate, and low) and their respective Tanner stages and bone age [16]. High-risk were preadolescents that had lower extremity growth potential of greater than 7 cm and included Tanner stage 1 children with bone age in females less than 11 years and males less than 12 years. The intermediate group had lower extremity growth potential of 5–7 cm and included Tanner stages 2 and 3 and bone age in females 11–13 years and males 12–15 years. Lastly, 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 intermediate risk and followed to skeletal maturity (24–108 months) resulted in no significant limb length discrepancies. MRI studies in all patients 1 and 2 years post-op showed no evidence of physeal bars. While this is encouraging data, the numbers are small.

Basic Science of Transphyseal ACL Reconstruction

Numerous animal studies have helped to define the anatomy of the physis and its response to trauma. As early as 1959, Campbell described growth retardation that resulted from a single large hole drilled through the physes of dogs. Complete growth arrest resulted when cortical bone was placed across these transphyseal tunnels [17]. The use of soft tissue grafts in skeletally immature dogs has been demonstrated to prevent physeal bar formation that otherwise occurs with open tunnels or those with a bone-based graft [18]. This demonstrates the risk of using grafts that contain bone blocks. Done properly, however, both achilles allografts and bone-patellar tendon-bone autografts have been shown in separate studies to yield excellent outcomes without limb length discrepancies or angular deformities in patients with open physes [19, 20].

Tunnel size can also impact the physis. Transphyseal tunnels violating 7–9% of the cross-sectional area of the physis in rabbits resulted in a permanent growth disturbance, whereas smaller defects of 3–4% did not [21, 22].

Excessive tension of a soft tissue graft across a physis can also alter growth. Edwards evaluated the effects of tensioned connective tissue grafts placed across 4 mm tunnels drilled through the physes of 12 skeletally immature beagles. Tensioning of the graft to 80 Newtons, a force considered supra-physiologic, resulted in significant valgus deformity of the distal femur and varus deformity of the proximal tibia of the treated limbs, a finding which confirms the Heuter-Volkmann principal [23].

Together, these animal studies suggest that appropriately tensioned soft tissue grafts placed in transphyseal tunnels across less than 5% of the cross-sectional area of the physis prevent formation of physeal bars, and that tethering may explain occasional angular deformities of the proximal tibia [24].

Radiograph-based computer models have tried to evaluate tunnel characteristics across open physes. Kercher obtained 3D models of the physes from patients with an ACL tear on MRI. By mapping 8 mm tunnels, he calculated violation of 2.4% of the distal femoral and 2.5% of the proximal tibial physes. The volume percent removed decreased linearly with increasing age [25]. Yoo found similar results with an MRI study in skeletally immature patients who had recently undergone ACL reconstruction [26]. Bone tunnels were found to violate 2.6% of proximal tibial and 2.3% of distal femoral physes. Five of these 43 patients had a focal bone bridge visible on MRI without clinically perceptible deformity. Utilizing a similar 3D modeling technique, Shea found that increasing tibial tunnel drill angle from 45 to 70° from the horizontal decreases volume removed from 4.1 to 3.1%, a 0.2% decrease in physeal volume damage for every 5° decrease in tunnel obliquity [27]. 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.

Risk of Growth Disturbances from Transphyseal ACL Reconstruction

Kocher's survey of the Herodicus Society and ACL study group was published in 2002 and aimed to describe cases of growth disturbances resulting from ACL reconstruction in skeletally immature children [28]. Among 140 surgeons, there were 15 growth disturbances reported, with 12 of these occurring after transphyseal reconstructions. These included seven patients with distal femoral valgus and a bony bar. Of these, three had hardware crossing the distal femoral physes and four had patellar tendon bone plugs crossing the physes. 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 three patients developed recurvatum associated with staples across the tibial tubercle and multiple sutures into the periosteum of the tibia.

Shiflett published a report on four skeletally immature patients (ages at surgery 13.5–14.8 years) with growth arrest following transphyseal ACL reconstruction with hamstring autograft [24]. Two patients had 8–10 degrees of tibial recurvatum with closure of the tibial apophysis in both cases. An additional two patients had 6–9 degrees of genu valgum. All patients were asymptomatic and three had growth modulation procedures to treat their angular deformities. The authors hypothesize that the deformities were a result of excessive tensioning of the graft across the physis secondary to a growth spurt immediately following reconstruction. Despite the use of soft tissue grafts with theoretically limited injury to the physes, this 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.

Clinical Outcomes of Transphyseal ACL Reconstruction

Numerous authors have described favorable outcomes associated with transphyseal ACL reconstruction in skeletally immature patients with no significant length or angular deformities [2, 29–34]. However, the applicability of these studies to skeletally immature children with significant growth remaining is limited due to the wide age range of these study groups, heterogeneous methods of assessing skeletal maturity (or growth remaining), and lack of follow-up to skeletal maturity. One example of this is Kohl's study of skeletally immature patients whose ages ranged from 6 to 18 years. The follow-up averaged 4 years, but we don't know if the youngest patients were followed to skeletal maturity [32]. Clearly growth considerations of a 6 year old are far different than an older adolescent. Failure to follow patients to skeletal maturity also gives a false sense of assurance. Multiple meta-analyses have been published but these include both transphyseal and physeal sparing ACL reconstructions in their analyses, again limiting our ability to make definitive conclusions regarding the safety of transphyseal reconstruction [35–39].

Documenting both bone age and Tanner stage, Kocher described his results of transphyseal ACL reconstructions with hamstring autograft in a retrospective series of 61 knees in 59 pubescent adolescents. Average skeletal age was 14.4 years (range 12–15.5) and self-reported Tanner stage was 3 in all patients except two (Tanner stage 4). At an average follow-up of

3.6 years, mean limb growth was 8.2 cm, and there were no angular deformities or limb length discrepancies. All patients returned to pre-injury athletics. There were two late graft ruptures resulting from sports injury and both underwent revision reconstruction [40]. This supports the safety and efficacy of ACL reconstruction in the mid-range group of skeletally immature patients, but again we have to be careful about extrapolating that to the younger patients (Tanner 1 and 2 or those with relatively large amounts of growth ahead).

Larson et al. [41] reported on one of the largest series of operatively treated Tanner 1 and 2 ACL injuries. Twenty-seven patients (13 males and 14 females) with an average age of 13.9 years (range 9–16 years) underwent transphyseal ACL reconstruction. Tanner stages included 1 (5 patients), 2 (18 patients), and 3 (7 patients). All females were premenarchal, no males had started shaving, and none reported to have had an adolescent growth spurt. At 48-month follow-up (range 24–84 months), there were five graft ruptures requiring revision, four of which occurred in patients with an anterior tibialis allograft. Clinically, all patients had less than 1 cm side to side limb length differences. This study shows good outcomes and low risk of growth disturbance in pubescent patients undergoing transphyseal ACL reconstructions, but again, we have the inaccuracy of Tanner staging and difficulty in translating this to growth remaining. Furthermore, it raises questions about the use of allografts in younger patients, a concern that has been expressed by prior authors [42].

In 2006, McIntosh published the results of transphyseal ACL reconstruction with hamstring autografts in skeletally immature males less than 15 years and females less than 14 years with follow-up to skeletal maturity [43]. Among the 16 patients, 15 had a limb length discrepancy less than 10 mm at final follow-up (average 6.2 mm, range 2–10 mm), which was considered to be clinically insignificant. One patient's operative leg measured 15 mm longer than the nonoperative leg. There were no angular deformities. This raises the possibility of increased growth stimulus from surgery in certain circumstances.

The following three studies highlight the best available evidence for safety of transphyseal ACL reconstructions in prepubescent patients, with results that support continued physiologic growth without angular deformity of the limb. However, these are small series with subjective assessments of skeletal maturity and follow-up that does not extend to skeletal maturity in all patients, making it difficult to form definitive conclusions.

Seventeen children with an average age of 12.1 years (range 9.5–14 years) underwent transphyseal ACL reconstruction with hamstring autograft and were included in a retrospective review by Liddle et al. [44]. Tanner staging was determined to be 1 or 2 based on intraoperative assessment by the surgeon. Graft fixation consisted of a cortical suspensory button on the femur and screw with washer on the tibia to avoid injury to the physes. Sixteen patients reported an excellent outcome at an average follow-up of 44 months (range 25–100 months) and there was a single graft rupture. One patient had a 5-degree valgus deformity postoperatively and there were no physeal abnormalities or limb length inequalities.

Streich described 16 prepubescent patients with an average age of 11 years (range 9–12 years) with 70-month follow-up (range 41–85 months) [45]. Patients underwent transphyseal reconstructions with hamstring autograft. Total average lower extremity growth at final follow-up was 20 cm (range 14–37 cm) and there were no angular deformities or clinically significant limb length discrepancies (defined as greater than 15 mm). Follow-up is not described for each individual patient, so it is unclear whether this extended to skeletal maturity in all patients.

Most recently, Falciglia published his series of 33 "intermediate risk" skeletally immature partial transphyseal ACL reconstructions. Risk group stratification was based on an endocrinologist's assessment of Tanner stage and bone age and proposed growth potential. Intermediate risk children were Tanner stages 2 and 3 with bone ages of 11–12 years in girls and 12–14 years in boys and remaining growth potential of the lower extremity of 5–7 cm. Based on preoperative CT, their planned femoral tunnels violated less than 7% of the cross-sectional area of the physis. The average patient age was 12.4 years (range 10–14.2 years) and average bone age of 12.6 years (range 10–14 years). Patients were stratified into two groups for analysis: group A (12 patients) with minimum follow-up of 10 years (average 13 years 7 months) and group B (21 patients) with follow-up to skeletal maturity (average 6 years 3 months). There were no limb length differences or angular deformities in either group and overall height increase was 12.6 cm for patients in group A and 13.2 cm in group B. There were 2 graft ruptures and average IKDC score was 91.8 [46].

Author's Preferred Approach

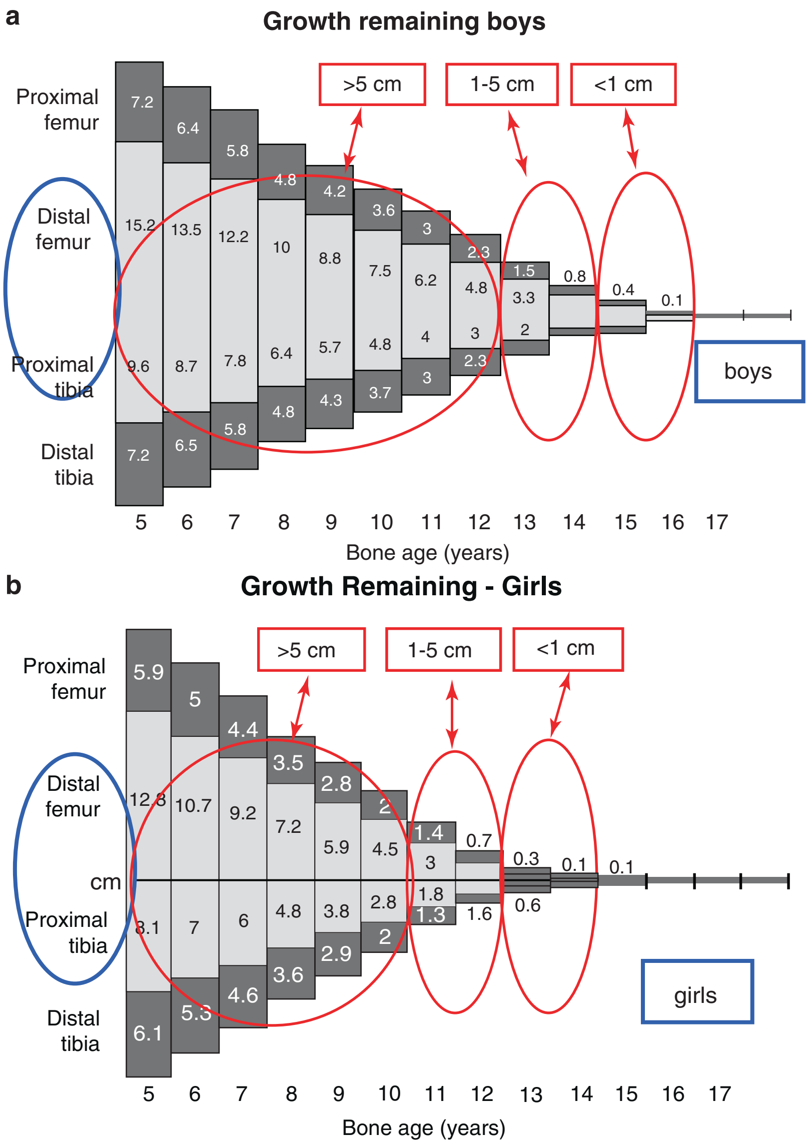
Although the majority of young active patients are best treated with surgical stabilization, there is a limited role for nonoperative treatment. Similar to the management of partial ACL injuries, significant activity restrictions seem to be the core component of reducing the risk of further injuries due to pivot shift events [47]. Most prepubescent children are not ideal candidates due to activity levels and compliance issues, which place them at high risk for potentially irreversible further injuries. Nonoperative care is occasionally recommended for our very young patient with three or more years of growth ahead. In our opinion, families still deserve to know all of their options as well as the associated risks and rewards. By delaying surgical stabilization for up to a few years, the reduced risk of growth disturbance may be preferable in certain circumstances.

Dimeglio has formatted his data on growth remaining into a graphical format that facilitates the prediction of growth remaining from the physes of the knee [48] (Fig. 16.1a, b). While similar to the three groups described by Guzzanti, we feel that the Dimeglio charts directly relate bone age to growth remaining, whereas Tanner staging is imperfect and not directly related to growth remaining. Using this data, we have divided children undergoing ACL reconstruction into three treatment groups that arguably have clinical implications (Fig. 16.1c).

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 boys with a bone age of 15 or 16 years and girls with a bone age of 13 or 14 years. For them, we feel a transphyseal reconstruction is always safe. The keys to understanding this group are several. Since there is so little growth risk, the family can be advised of these remote risks, but should not be unduly caused to worry. There are probably few if any special technique precautions necessary. While the physes should not be totally disregarded, all conventional ACL techniques and grafts are probably reasonable options. Specifically, grafts that include bone blocks such as patellar tendon grafts, quadriceps grafts (with an optional patellar bone block), and Achilles tendon allografts are options. These patients, with less than 1 cm of growth remaining around the knee, are followed clinically for at least 9 months and discharged once radiographs show that their physes surrounding the knee have closed. Alignment is followed clinically and long radiographs for limb alignment are not routinely obtained. The bigger issues that must be discussed with the child and family relate to the importance of proper rehabilitation and reinjury rates in adolescents.

For those patients with 1–5 cm of growth remaining, who have definite risk of developing an appreciable growth disturbance, several strategies come into play. These are typically boys with a bone age of 13 or 14 years and girls with a bone age of 11 or 12 years. For them, a thoughtfully performed "physeal-respecting" reconstruction is a viable option, and is our usual recommendation. Preoperatively, a bone age is obtained and documented. In many cases, we

Fig. 16.1 Dimeglio growth remaining charts for boys (**a**) and girls (**b**). Authors preferred ACL reconstruction technique (**c**) is based on these growth remaining charts



c

Growth Based Surgical Strategy

Growth cm	Girls	Boys	Rx.
<1	13+	15+	Standard procedure
1-5	11-12	13-14	Trans-physeal
>5	≤ 10	≤ 12	Physeal Sparing

obtain a full-length bilateral lower extremity radiograph to document alignment. Occasionally, we identify an existing deformity, typically genu valgum. If significant, this could be a risk factor for the original ACL injury and perhaps a risk factor for subsequent graft injury. Correction with hemi-epiphyseal tethering (often referred to as guided growth) can be considered.

Tunnel sizes are based on graft size, with an average of 7.5–8.5 mm in the preadolescent population. There is mixed literature regarding optimal graft size, but if patients are approaching adult body habitus, we strive for a minimum of 8 mm. If the quadrupled autograft is too small, it can be folded an additional time (if adequate length) or supplemented with allograft. Graft fixation is performed on the femur using cortical suspensory fixation (through a femoral tunnel drilled by a flipcutter through a separate incision) and a solid biocomposite 23 mm interference screw placed distal to the physis on the tibia. Fixation placement is verified with fluoroscopy. Fixation can be supplemented with a staple, post and washer, or anchor distally as deemed necessary (Fig. 16.2).

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 exam 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.

For patients with more than 5 cm of growth remaining, who have a definite risk of developing a meaningful growth disturbance, we feel that additional options should be considered. This patient group typically includes boys with a bone age of 12 years or less and girls with a bone age of 10 years or less. For this youngest age group, we feel the literature has fairly little data on the risks and safety of transphyseal ACL reconstruction, so we typically recommend a physeal sparing procedure. In our hands, this is most commonly the iliotibial band reconstruction modified by Micheli [49] and published by Micheli, Kocher, and others [50, 51]. We have been very happy with the relatively good graft survival rates and no apparent growth disturbances. These knees seem to remain stable over time, and this has not been a "temporizing procedure" as some have labeled it. All epiphyseal reconstructions are growing in popularity for these very young patients as well, but it will take some time to sort out all the issues and outcomes for this relatively rare group of patients [52–54].

To minimize the risk of growth disturbance when transphyseal reconstruction is selected, tunnels should be small and central in the physis. Preference for graft selection is gracilis and semitendinosus autograft with supplemental soft tissue allograft when autograft alone is insufficient. Metaphyseal fixation should be utilized to avoid hardware at the level of the closing physis. Excessive graft tension and damage to the tibial tubercle and perichondral tissue should be avoided. A structured rehabilitation program with experienced physical therapists is important to ensure optimal outcomes. Return to unrestricted cutting and pivoting sports is routinely no sooner than 9 months and requires symmetric core, hip, and lower limb strength and proprioception. Establishing clear patient and family expectations regarding restrictions and estimated return to play is critical to successful outcomes and maximizing compliance. Patients with significant growth remaining warrant close postoperative follow-up until skeletal maturity, with both clinical and radiographic exams to identify linear and angular growth disturbances.

Fig. 16.2 (**a**–**f**) A 14-year-old male sustained a left knee injury playing baseball. Knee radiographs (**a**, **b**) show a skeletally immature individual. Bone age is 13.5 years (**c**). MRI shows complete rupture of the ACL (**d**). The author's preferred transphyseal technique includes cortical suspensory fixation on the femur and interference screw fixation distal to the physis on the tibia (**e**, **f**)

Conclusions

The increasing incidence of anterior cruciate ligament injuries in skeletally immature children demands careful attention by orthopedic surgeons. In addition to chronologic age, assessment of skeletal age is helpful to select the appropriate reconstruction technique. Boys with a bone age of 15 years or older and girls of 13 years and older are ideal candidates for transphyseal ACL reconstructions, as there is minimal risk of growth disturbance. A few considerations exist regarding growth assessment and follow-up, but perhaps the most important thing is not unnecessarily worrying the patient and family about potential growth disturbances.

Based on 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, proper technique, and appropriate follow-up. Children with substantial growth remaining (skeletal age boys 12 years or less and girls 10 years or less) appear to be at risk for more significant deformities. In this group, there is relatively little clinical documentation of the risks and safety of transphyseal ACL reconstruction, so we generally recommend physeal-sparing techniques for these younger patients.

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17 Treatment of Concomitant Pathology During ACL Reconstruction

Taylor Jackson and Theodore J. Ganley

Abbreviations

ACI	Autologous chondrocyte implantation
ACL	Anterior cruciate ligament
ACL reconstruction	Anterior cruciate ligament reconstruction
BMI	Body Mass Index
IKDC	International Knee Documentation Committee
KOOS	Knee Injury and Osteoarthritis Outcome Score
MCL	Medial collateral ligament
MRI	Magnetic resonance imaging
OAT	Osteochondral autologous transfer
OATM	Osteochondral autologous transfer/mosaicplasty
PCL	Posterior cruciate ligament
ROM	Range of motion

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Introduction to Concomitant Pathology in ACL Injuries

Growing numbers of ACL reconstructions in children are being performed each year, and these have led to an increase in the number of concomitant injuries and related procedures [1]. This increase is most pronounced in the 10–14-year-old age group [1]. Additional injuries should be investigated with a high index of suspicion as they occur frequently and are often repairable [2]. In pediatric ACL injuries, concomitant pathology occurs in 56% of injuries, and 21% and 3% patients will have two or three additional injuries, respectively [3]. The most common concomitant injuries are meniscal injuries, additional ligamentous injuries, particularly the medial collateral ligament, and chondral injuries [3–5]. Meniscal injuries are the largest culprit, as 32% of the additional injuries are medial meniscal injuries, while 35% are lateral meniscal injuries [3].

Concomitant injuries may occur at the time of the original insult to the knee or can be the result of progressive damage to the knee due to abnormal joint mechanics or intra-articular derangements [2, 6, 7]. The most famous example of acute injuries is the "Unhappy Triad" consisting of MCL, ACL, and medial meniscus pathology, which was originally described by Campbell in 1936 and later by O'Donoghue [8, 9]. However, more recent work tells a different story [8]. In fact, lateral meniscus injuries are actually more common with acute ACL tear, while medial

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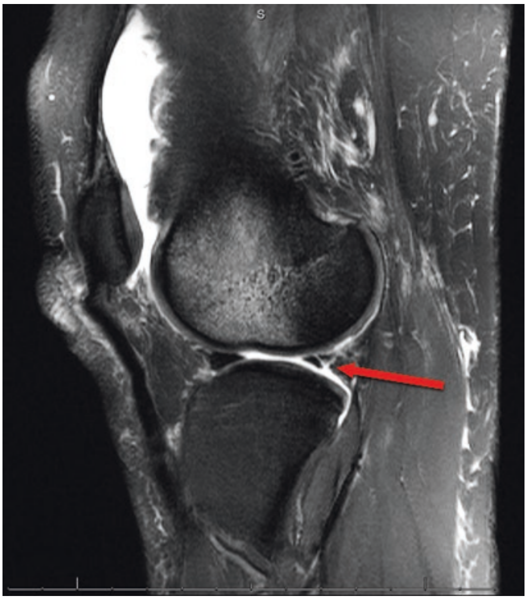

Fig. 17.1 Sagittal view of a knee T2 weighted MRI image depicts a concomitant posterior horn lateral meniscus tear (*red arrow*) in a pediatric patient with a combined ACL/MCL injury. Published with kind permission of © Theodore J. Ganley 2017. All Rights Reserved

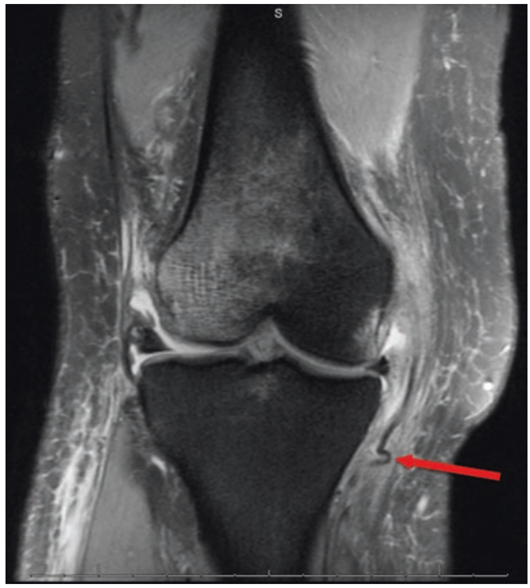

Fig. 17.2 Coronal view of a knee T2 weighted MRI demonstrates a full-thickness MCL tear in a pediatric patient with combined ACL/MCL/lateral meniscus tear injured knee. (Red Arrow indicates loss of the normal shape of the MCL). Published with kind permission of © Theodore J. Ganley 2017. All Rights Reserved

meniscal injuries are more common with chronic ACL injuries [8, 10, 11]. Figures 17.1 and 17.2 demonstrate a lateral meniscus tear and a MCL tear, respectively, in a pediatric patient with a full-thickness ACL rupture.

The natural history of ACL tears treated conservatively in children is the development of progressive instability and reduced function [1, 12, 13]. Patients treated conservatively have a high burden of degenerative changes, further meniscal damage, and osteochondral injury [13]. Young patients undergoing ACL reconstruction more than 12 weeks after the injury are more likely to sustain irreparable meniscal injuries and have a higher incidence of chondral injuries [14–17].

Treatment approach depends on the type of injury and patient characteristics. Depending on the type and location of an injury, it can be left alone with no treatment, treated conservatively with immobilization or bracing, or repaired at the time of ACL reconstruction [1, 2, 4, 13, 18–20]. When evaluating a patient, it is important to keep in mind certain risk factors for additional injuries. Of note, while females are more likely to sustain ACL injuries, they are less likely to have concomitant intra-articular injuries compared to their male peers [7].

Timing ACL Reconstruction

ACL injuries in the pediatric population are not emergencies and rarely necessitate immediate surgical management [5]. However, patients and families should be counseled on the eventual need for surgery, as conservative management with bracing or activity modification rarely prevents progressive intra-articular damage [2, 5, 13]. This is particularly true for younger athletes and very active patients who are less likely to be compliant with activity modification [2]. A prospective study of skeletally immature patients treated nonoperatively for ACL reconstruction, with an average follow-up of 3.8 years, demonstrated that 32% eventually needed surgical reconstruction of the ACL and 19.5% required meniscal surgeries [21].

There is no consensus on the perfect timing of ACL repair to prevent associated injuries, and the decision to treat must be made on an individual basis, in discussion with the patient and his/her family while taking into consideration the pros and cons of delayed treatment [2, 16, 22]. Benefits of waiting include allowing closure of the growth plates and the development of a more mature patient for rehabilitation [19]. Skeletal maturity can be assessed physiologically by bone age and tanner stage and treatment may be delayed if the patient is approaching skeletally maturity [8, 23]. However, from the standpoint of concomitant pathology, the disadvantages of waiting include risk for further instability and subsequent damage, particularly to the meniscus and articular cartilage [10, 15–17, 19, 24].

The trend is towards early reconstruction and stabilization of concurrent ligamentous, meniscal, and chondral injuries in an effort to prevent further injuries [20]. Early reconstruction is recommended even in skeletally immature, especially if it will be more than 1 year until skeletal maturity is reached [14, 20, 25]. A physeal sparing technique can be used in these skeletally immature patients and has been shown to have good functional outcomes with low revision rates with minimal risk for growth disturbance [23]. However, in certain circumstances, such as concomitant MCL injury, the ACL reconstruction can be delayed until the concomitant injury is treated [4].

Meniscal Injuries

Approximately 40–60% of ACL injuries will have an associated injury of either meniscus [11, 21, 26]. While management of concomitant meniscal injuries is similar to isolated tears, they do not necessarily behave in the same way. In fact, combined injures tend to have better outcomes [26, 27]. Risk factors for meniscal injuries include adolescent age, male gender, type of sporting activity, higher BMI, and delayed ACL reconstruction [1, 3, 10, 16, 17, 19]. Patients with additional meniscal injuries have similar mechanisms of injury compared to isolated ACL tears, usually noncontact sporting activities such as pivoting and jumping [7].

Gender is also an important risk modifier for concomitant injuries, as males and females tend to have distinct injury patterns [5, 7, 25]. Though females are at higher risk for ACL injuries in general, they are at lower risk for sustaining concomitant intra-articular injuries [7]. A review of high school athletes revealed that compared to their male counterparts, female soccer players sustained fewer medial meniscal tears and female basketball players sustained fewer lateral meniscal and chondral injuries [7]. The reason for these differences between males and females is unknown but speculated to be due to differences in strength, size, weight, force generation, muscle recruitment, joint alignment, or differences in the resilience of either the ACL or meniscus [7]. There were no reported differences in the mechanisms of injury, history of popping, joint swelling, or return to play between males and females [7]. Males were more likely to sustain medial and lateral meniscal tears and undergo meniscectomy [25]. A higher rate of meniscectomy is perhaps explained by the fact that boys were more likely to have delayed treatment [25].

Evaluating for meniscal injuries should be undertaken early and with a high index of suspicion given the high incidence of repairable injuries and the fact that many can be found early in the patient's course [2]. In a case series of patients with ACL injuries, an arthrogram was performed in 10 out of 12 skeletally immature patients with acute ACL tears and 10.7 days after the injury on average. These arthrograms revealed 10 meniscal tears in 7 patients. Subsequent arthroscopy confirmed 8 tears in 6 patients [2]. An important finding for stratifying risk for meniscal injuries is bone bruises, which are very common and occur in over 80% of acute ACL injuries [28–30]. The evidence of bone bruise on MRI is another important consideration as femoral size of a bone bruise has been correlated with a higher likelihood of sustaining meniscal injuries [28]. In addition, the presence of bone bruise in the posteromedial aspect of the tibial plateau may be a sign pointing towards meniscal root avulsion, which may otherwise go undiagnosed [31]. Once brought to the operating room, it is important to search thoroughly for a meniscal tear, as up to 40% of medial meniscal lesions may occur on the posterior horn, which is difficult to view from a standard approach. These lesions may be either "ramp lesions" which are not easily viewed on MRI or with normal inspection, or "hidden lesions," which are only apparent after debridement or motorized shaving [32]. Undiscovered lesions may result in higher rates of treatment failure [32].

Treating Concomitant Meniscal Pathology

The three treatment options for meniscal injuries are to leave the tear in situ, meniscectomy, and meniscal repair [33]. Meniscectomy is performed most often during ACL reconstruction, at a rate of two to three times as often as repair [26]. As many as 65% of concomitant meniscal injuries are trimmed, compared to 26% that are repaired and 9% left in situ [26]. Between 2007 and 2011, there was a rising incidence of meniscal pathology treatment in pediatric patients [1]. The incidence of meniscal repair increased by 54.8% and the incidence of meniscectomy increased by 37.7% [1].

Patient characteristics are important factors to consider when deciding the best treatment option [18]. Nonoperative management of meniscal injuries during ACL reconstruction is unlikely to be successful in younger patients, especially young athletes, who are unwilling to comply with activity modification [1, 13]. Younger patients with ACL injury are less likely to have tears left in situ and are more likely to undergo partial meniscectomy or meniscus repair compared to older patients [1]. A review of a national database of pediatric ACL reconstructions found that nearly half of all patients undergoing ACL reconstruction also underwent a concomitant meniscectomy and a quarter underwent meniscal repair [1]. Though meniscectomy is more common, there is a trend towards meniscal repair in younger patients due to a higher success rate compared to adults and the desire to reduce the risk of subsequent osteoarthritis [1, 34]. This is reflected in the fact that the rates of meniscectomy increase with advancing age (38.8% in 10–14-year-olds vs. 52.% in 20–45-year-olds) and the rates of meniscal repair decrease with increasing age (27.6% in 10–14-year-olds vs. 16.2% in 20–45-year-olds) [1].

Meniscal Tears Left In Situ

Certain types of meniscal tears can be left in situ during ACL reconstruction. Leaving tears alone is usually more appropriate for lateral meniscal tears [3, 10]. This is reasonable considering lateral meniscal tears are more common in the acute setting, and the incidence does not significantly increase as time to treatment increases [10, 19, 25]. Medial meniscal injuries, on the other hand, are more common in the chronic setting and are more likely to require treatment [10, 19]. Certain tear characteristics that are associated with being left in situ include partial tears, location of the tears, orientation, and tear type [33]. A prospective, multicenter study demonstrated that lateral meniscus tears, partial tears, tears in the peripheral one-third of the meniscus, and longitudinal tears were more likely to be left in situ compared to oblique, complex, or radial tears [33]. In addition, every additional 1 mm in length of a tear decreased the likelihood of a tear being left in situ by 22% [33]. No bucket handle tears were left in situ. For the medial meniscus, the only two factors associated with being left in situ were length, with each 1 mm increase in tear length decreasing the likelihood of being left in situ by 28%, and partial tears, which were more likely to be left in situ than complete tears [33].

A systematic review of meniscal tears left in situ found that medial meniscal tears left in situ required a secondary procedure at a rate of between 0 and 33% and that patients reported significant pain in an average of 14.8% of cases [35]. On the other hand, lateral tears developed either subsequent pain or need for an operation at a much lower rate of 4.8% of cases on average [35]. In addition, lateral meniscal tears left in situ tend to have an improved prognosis compared to attempted treatment [36]. A large multicenter study reported good outcomes for meniscal tears left in situ, with 97.8% and 94.4% of lateral and medial meniscal tears, respectively, requiring no additional surgery at 6 years follow-up [33]. However, the pediatric population may fare worse than older patients, as the average age of those needing additional surgeries in this cohort was 18.6 years compared to 25.1 years for those who needed no additional surgery [33].

Partial and Total Meniscectomy

The most common treatment for meniscal injuries is meniscectomy [1, 26]. In a review of a national ACL injury registry, it was found that the youngest age group of 10–14-year-olds had the most pronounced increase in meniscectomy, although this group retains the lowest rates of meniscectomy overall [1]. The reason for this increase is multifactorial and perhaps related to the increased intensity of athletics and earlier specialization [1, 13, 37]. While it is generally ideal to preserve the meniscus, this is not always possible. Not all tear types are amenable to repair and leaving certain tears in situ may lead to high failure rates, particularly in medial tears or lateral tears larger than 10 mm [33]. Meniscal injuries associated with chronic ACL deficiency are more likely to be irreparable and require meniscectomy [11]. As the time from injury increases, the complexity of the tears tends to increase, making the lesion harder to repair, and these are more likely to be treated with meniscectomy [11]. Complex tears have been associated with a higher rate of failure following repair and therefore are often better managed with meniscectomy [27]. The amount of meniscus trimmed can have an impact on future outcomes [36]. Counterintuitively, small medial resections (<33%) had poor outcomes, whereas large medial and lateral meniscal resections (>50%) actually had better outcomes compared to patients without meniscal pathology in a 6-year follow-up study after ACL reconstruction [36].

Meniscal Repair

The meniscus protects the knee from injury by acting to reduce contact pressure in the knee [18]. Every attempt should be made to preserve the meniscus when possible, as meniscectomy is associated with an increased risk and acceleration of osteoarthritis [26, 34, 35, 38]. Repair of stable peripheral tears may always be indicated for medial meniscal injuries since there is low risk for complications [35]. Studies of patients at the time of revision ACL surgery have shown that prior meniscectomy is associated with higher likelihood of chondral lesions, whereas prior meniscal repair is not [38]. Factors associated with an increased likelihood of undergoing meniscal repair during ACL reconstruction include younger patient age, lower patient BMI, involvement of both menisci, sports medicine fellowship training of the surgeon, higher surgeon case volume, and higher site volume [18].

It is also important to understand that meniscal injuries associated with ACL injuries do not behave in the same way as isolated meniscal injuries. Meniscal repairs during ACL reconstruction have a higher success rate compared to isolated meniscal injuries [27, 39]. It is also important that both injuries be treated since meniscal repair has a much higher failure rate if the ACL tear is not addressed [39]. In a review of patients younger than 18 years old treated with surgical repair of meniscal tears with concomitant ACL reconstruction, there was an overall 74% success rate, with a 90.9% freedom from failure rate at 2 years and 76.8% freedom from failure rate at 5 years [27]. Risk for repair failure include complex tears, bucket handle tears, medial tears, and skeletal immaturity [27]. However, complex tears associated with ACL injuries have a higher success rate than isolated injuries, perhaps due to increased perfusion secondary to the ACL ruptures [27].

Overview of Selected Meniscal Repair Techniques

Several techniques are available to the surgeon to repair meniscal injuries, including inside-out, outside-in, and all-inside approaches [27, 40–42]. A randomized controlled trial comparing all three demonstrated 100% healing rate for outside-in technique, 95% healing rate for the inside-out technique, and only 65% healing rate for the all-inside technique with a minimum follow-up of 1 year [43]. Mean surgical times were 38.5 min, 18.1 min, and 13.6 min for the outside-in, inside-out, and all-inside approaches, respectively [43].

The inside-out technique has the advantage of being able to treat nearly all types of tears in any location, including both simple and complex tears and even in those extending into the avascular zone [41, 42]. Vanderhave et al. reported on excellent results in 43 of 45 skeletally immature athletes who were all treated with inside-out approach regardless of tear pattern or location [40]. This approach may be used in young, active patients who may otherwise receive meniscectomy and be put at higher risk for loss of function from early osteoarthritis [41]. However, the inside-out approach has the disadvantage of increased risk of damaging neurovascular structures [42]. The outside-in technique avoids this risk to the neurovascular structures, but it has the disadvantage of requiring an additional small incision and difficulty with treating posterior tears [42]. The all-inside approach has become more popular with the rise of various devices [42]. A long-term follow-up study demonstrated that all-inside approach still offered protection from osteoarthritis and even with initial incomplete healing [44].

Meniscal repair should be attempted whenever possible to avoid meniscectomy, especially in younger, more active patients [41]. While all-inside approach may offer fast, easier fixation, suturing techniques may be necessary for more difficult or complex tear patterns [43].

Medial Collateral Ligament Injuries

While the ACL is the most common ligamentous injury to require surgery, it is the MCL that is the most common ligament injured in the knee [45, 46]. The MCL is also the most common ligament to be injured concurrently with an ACL injury [46]. Over half of all MCL injuries that occur with ACL tears will also present with a meniscal injury as well in what is called the "Unhappy Triad," with the most common injured meniscus being a tear to the lateral meniscus [6, 8, 9].

The diagnosis of an MCL injury can be made on the basis of the history and physical alone, with no need for advanced imaging or arthroscopy [6]. MCL injuries can be categorized as grade I, II, or III. The MCL is fully intact in grade I lesions, with no instability, a firm endpoint, only mild to moderate pain, and no radiographic changes [6, 45]. Grade II lesions are partial tears of the MCL and are associated with mild functional impairment, particularly in the acute period following the injury [45]. Valgus instability may be present in 30° of flexion, but there will be a firm endpoint with valgus stress testing [6, 45]. Grade III lesions are complete tears of the MCL, which may be accompanied by an avulsion of the femur or tibia, instability of the joint, no firm endpoint, and widening of joint space [6, 45]. Pain is often not proportional to the severity of the injury in grade III injuries whereas incomplete tears may be very painful but will not reveal instability when stressed [45, 47].

Treatment of Concomitant MCL Injuries

The treatment of MCL injuries can include surgical reconstruction or conservative management with brace or cast immobilization of the knee. The associated ACL injury can be treated simultaneously or at a later time [46]. However, there is evidence to suggest that operative management of both the ACL and MCL leads to higher rates of knee stiffness and decreased range of motion [6]. Instead, subacute ACL reconstruction is recommended to avoid the increased risk for arthrofibrosis [6].

Two randomized control clinical trials compared nonoperative and operative management of concomitant ACL and grade III MCL injuries and demonstrated similar outcomes in terms of ROM, quadriceps strength, valgus stability, return to activity, and subjective function as measured with Lysholm and IKDC scores. However, operative management requires more aggressive physical therapy and nonoperative management allowed patients to regain ROM and strength faster [48, 49]. In addition a meta-analysis of studies on combined ACL/MCL injuries showed that 38% of patients undergoing operative management of MCL injuries required additional procedures to regain ROM [46]. However, there may still be a role for surgical management in rare or more unusual presentations. For instance, Desai et al. described the case of a child with a complete disruption of the MCL that presented with intra-articular entrapment of the injured ligament requiring surgical repair and eventually return to full activity [50].

The MCL injury is treated first with immobilization to allow for decreased swelling, resolution of the acute inflammatory process, and return of full motion of the knee before reconstruction of the ACL [4, 6, 46]. A retrospective review of 12 pediatric patients treated for combined ACL-MCL injuries demonstrated good outcomes when the MCL was treated with a hinged brace followed by delayed ACL reconstruction [4]. At a mean follow-up of 5.3 years, all patients had stable Lachman tests, no laxity with valgus stress, a mean Lysholm score of 96°, and an average range of motion (ROM) of 146° [4].

Evidence also suggests that nonoperative management of the MCL injury yields favorable results compared to the reconstruction of both ligaments [6, 46]. This is the case for all grades of injury, but most injuries that present will be grade II or III since grade I injuries usually resolve without coming to medical attention [6, 46]. The key principle for the treatment of grade II injuries is to allow for restoration of motion while protecting the knee with immobilization, limited weight bearing, and the use of cruthches [6]. Physical therapy should be initiated to work on range of motion and improve knee stability and quadriceps strength [6]. Subsequent reconstruction of the ACL is recommended, particularly for younger patients and athletes [4, 6]. Grade III injuries are treated in a similar fashion to grade II lesions but with an increased emphasis on protection of the knee [6].

The treatment and natural history of the injuries is also affected by which portion of the MCL is avulsed in grade III injuries [6]. Avulsion of the femoral end of the ligament and midsubstance injuries have a tendency for more stiffness and less laxity. These injuries are treated with a short period of immobilization followed by physical therapy for ROM and protection of the knee with a hinged brace [6]. Tibial avulsions tend to have more laxity and should be treated with 2–4 weeks of immobilization in a cast. Laxity can be reassessed at 2-week intervals, and immobilization can be continued if there is no firm endpoint with valgus stress testing at 30° of knee flexion [6].

It is important to delay ACL reconstruction until full ROM has been achieved. For grade III lesions this may not be achieved until at least 7–8 weeks after the injury. If stiffness persists, physical therapy should be continued. There may be consideration for patients with lower demand to return to high intensity activity to be treated without ACL reconstruction [6]. Once full range of motion has been achieved, patients, particularly younger patients and athletes, can undergo ACL reconstruction [6]. At the time of ACL reconstruction, the knee should be assessed for valgus instability, and MCL reconstruction may be considered at that time if laxity is still present [46]. Any concomitant meniscal pathology may also be addressed at the time of ACL reconstruction. Given that the meniscus has time to heal during knee immobilization for the MCL injury, some menisci, such as lateral meniscal tears, will not require treatment and can be left alone [6].

Chondral Injuries

Chondral lesions are more common in chronic ACL deficiency and make up approximately 5% of concomitant injuries. These lesions likely result from pathogenic processes that develop following the original injury, in addition to changes in the mechanics of the knee associated with prolonged knee instability [3, 12, 13, 16, 17]. Lesions have a tendency to occur more frequently in the compartments of the knee with an accompanying meniscal injury, and the most common location is the medial femoral condyle [10, 36, 51]. This is particularly true for medial meniscal injuries and following meniscal resection, as these are important risk factors for the development of chondrosis and the progression of osteoarthritis following ACL reconstruction [10, 11, 38]. Over half of patients treated for chondral lesions will develop early radiographic signs of osteoarthritis [52].

Risk factors for chondral injuries include higher BMI, meniscal pathology, age, gender, and delayed presentation following ACL injury [3, 10, 15, 25]. In addition, there is a significant association with meniscal injury. Patients are more likely to have femoral condyle or tibial plateau articular cartilage lesions when there was an associated meniscal injury in the same compartment [10]. BMI has also been shown to increase the risk for chondral lesions, with a 10% increased risk for chondral lesions per BMI point increase [3, 25]. The risk for chondral lesions is also associated with age, and is more common in patients older than 15 years [10]. Chronic ACL injuries and delay in treatment are also important risk factors for chondral lesions, osteoarthritis, and degenerative changes [3, 13, 15]. Patients who underwent ACL reconstruction more than 12 months after the injury were more likely to have chondral injuries, particularly in the lateral and patellotrochlear compartments [15]. This risk has been estimated to increase by 6% per month of delay from the time of injury [3]. Males tend to have a higher incidence of chondral injuries, which may be related to the fact that males have a tendency to have a more delayed presentation [3]. The severity of the lesion is also proportional to the time delay [15]. Knee instability is an important risk factor for chondral lesions because the greater the subjective sense of instability and the number of episodes of the knee "giving way," the greater the likelihood of acquiring chondral lesions [15].

It is important to recognize and treat these injuries since the long-term outcome of chondral lesions secondary to ACL injury is loss of function [12, 52]. These patients have been dubbed "young patients with old knees" [12]. Long-term follow-up studies have demonstrated that concomitant injuries with ACL reconstruction are associated with the development of osteoarthritis [12, 53]. After 10–20 years after ACL reconstruction, over half of patients will have signs of early osteoarthritis [12].

Treatment of Concomitant Chondral Injuries

Treatment decisions regarding chondral lesions discovered in association with ACL injuries may be difficult as many of these lesions are asymptomatic and even when patients do have symptoms, it is difficult to correlate these with an underlying chondral lesion [51]. A study comparing outcomes for isolated ACL reconstruction and ACL reconstruction with associated Grade III or IV chondral lesions demonstrated that the concomitant injuries did not have a significant effect on the need for additional surgeries or on the type of additional surgeries performed [51]. Although the reoperation rate may not be affected, a similar multicenter study found that grade 3–4 articular lesions predicted worse outcomes on International Knee Documentation Committee (IKDC) and Knee Injury and Osteoarthritis Outcome Score (KOOS) scores at 6 years follow-up [36].

The most common procedures for chondral lesions are microfracture, chondral shaving, osteochondral autologous transfer/mosaicplasty (OATM), and autologous chondrocyte implantation (ACI) [1, 54]. In children, chondral shaving for partial thickness lesions is the most common procedure performed and autologous implantation for large full thickness lesions the least [1]. With the increasing incidence of ACL reconstruction in children, there has also been an accompanying increase in the rate that chondroplasty is being performed. However, during this time, there has also been a decreasing rate of microfracture and osteochondral graft transfer in children ages 10–14 years [1]. In older 15–19-year-olds, however, there has been no significant change in the incidence of microfracture, shaving chondroplasty, or osteochondral graft transfer [1].

Autologous chondrocyte implantation has been shown to be an effective treatment modality for large chondral lesions, particularly in pediatric and adolescent patients [55]. A study in adolescents showed that there were favorable outcomes and improved function and quality of life for patients treated with ACI, as measured by the IKDC and the KOOS-QL tools [55]. However, these procedures were accompanied by a high rate of reoperation, as high as 37.8% [55]. The most common reasons for reoperation are debridement, meniscectomy, microfracture, and loose body removal [55]. Long-term follow-up at 14–15 years in a randomized trial of ACI vs. microfracture for single articular lesions showed that there is no significant difference in terms of treatment failure or need for eventual total knee arthroplasty [52]. Both treatments lead to significant improvement in functional status and quality of life compared to preoperative baseline status [52]. ACI has also been shown to have a lower treatment failure rate compared to OATM [54].

A systematic review of osteochondral graft transfer and microfracture demonstrated superior outcomes for OATM compared to microfracture, with a higher rate of return to sports and improved maintenance of sports activity [54]. Microfracture is associated with a higher reoperative rate and a tendency towards clinical deterioration [56]. A randomized controlled trial comparing OAT with microfracture for grade 3–4 lesions in pediatric patients showed that after 4 years only 63% of the microfracture group maintained good results compared to 83% in the OAT group [56]. There was also a 41% failure rate in the microfracture group and nearly all of those patients required an OAT revision surgery [56].

Posterior Cruciate Ligament and Multiligamentous Injuries

Compared to the presentation of ACL injuries, PCL injuries are less likely to present with a history of the classic “pop” associated with ACL injuries [57]. Instead, they tend to have vague complaints of unsteadiness and poorly localized pain that can either be posterior or anterior and are exacerbated with deceleration, descending hills or stairs, and running [57].

Physical exam will reveal a positive posterior drawer sign or posterior “sag” sign [57]. Translation of the knee in the anteroposterior plane is used to grade PCL injuries and evaluate for additional ligamentous injuries [57, 58]. PCL injuries can be classified as grade I, II, or III by the amount of translation on exam [58]. Grade I injuries have 0–5 mm of translation, grade II injuries have 5–10 mm of translation, and grade III injuries have >10 mm of translation [58]. Translation of >8 mm is consistent with a complete tear, and history of knee dislocation or translation of >12 mm is an indication of likely multiligamentous injury [57]. These injuries should be evaluated with plain films and stress radiographs, especially when additional pathology or complete tears are suspected [57]. Combined injuries often result from knee dislocations and are at high risk for injury to the surrounding vessels and nerves [58, 59]. MRI is also useful in the evaluation of these injuries with almost 100% sensitivity and 97–100% specificity [57].

Multiligamentous injuries are more common in the setting of trauma than in sports injuries. 69.9% of combined, multiligamentous injuries occur in the setting of trauma while only 30.4% occur in the setting of sports injuries [58, 60]. Hemarthrosis in the setting of trauma is an important finding [61]. While PCL injuries account for only 3% of acute knee injuries in the general population, they are found in 37% of trauma patients with hemarthrosis [61]. Furthermore, 96.5% of such injuries will have concomitant ligamentous pathology [61]. The most common combined injury is the ACL/PCL combination, which occurs in 62% of all combined injuries [60]. Often, the collateral ligaments, most notably the MCL, are involved as well [59]. Meniscal injuries are also associated with ACL/PCL injuries, and meniscectomy and meniscal repairs occur at a rate of 41% and 7%, respectively [60].

The posterolateral corner (PLC) of the knee, often referred to as the “dark side of the knee” is a complicated structure comprised of three main stabilizes, the lateral collateral ligament, the popliteus tendon, and the popliteofibular ligament [62, 63]. PLC injuries are rare in the pediatric population and usually take the form of tibial or femoral osteochondral avulsions of the ligaments [64]. While these injuries are rare, they are important to recognize because undiagnosed lesions may lead to instability, meniscal damage, early degenerative changes, and graft failure of PCL and ACL reconstructions [62–64].

Treatment of Concomitant PCL Injuries/Multiligament Injuries

While PCL injuries can be managed conservatively if isolated, they are increasingly being treated operatively for chronic injuries and those associated with additional ligamentous injuries [57, 60]. A review of a national database demonstrated that surgical treatment for PCL injuries is most common for acute injuries, accounting for 74% of all PCL injuries treated operatively. Multiligamentous injuries account for 68% of all PCL injuries managed operatively [60].

Knee dislocation is the most common setting for combined ACL/PCL injuries, and three out of four major ligaments are usually injured. These injuries result in severe functional instability and threaten the neurovascular structures of the knee and should be treated operatively [59]. Injuries that present with a MCL component can be managed on a subacute timeline once it is determined, after a thorough evaluation, that the patient is neurovascularly intact [58, 59]. In ACL/PCL/MCL combined injuries, the MCL can potentially be treated conservatively with immobilization followed by reconstruction of the ACL and PCL [58, 59].

Outcome studies of operative treatment of combined ACL/PCL injuries have demonstrated good results. In a retrospective review, 35 patients with at least ACL/PCL combined injuries, all with grade III laxity at presentation, were assessed preoperatively and at 2 and 10 years follow-up. Postoperatively, 46% had a normalized posterior drawer sign and mean scores of 91.2, 5.3, and 86.8 on the Lysholm, Tegner, and Hospital for Special Surgery knee ligament rating scales, respectively [65].

PLC injuries rarely occur in isolation, but may occur in as much as 48% of all multiligamentous injuries of the knee [66]. In skeletally immature patients, treatment decisions may be complicated by the potential for growth arrest, however delaying treatment may put the patient at risk for additional injuries. Anderson describes a case of patient with PCL/PLC injury who failed nonoperative management. Good outcomes were achieved by combining an intra-articular physeal sparing PCL reconstruction with an extra-articular reconstruction of the PLC structures [64].

Summary

The incidence of ACL injuries and concomitant pathology continue to rise, and this increase is most pronounced in the pediatric population. Historically, there have been reservations about treating ACL injuries early due to concerns regarding injuries to the physis and the resultant growth disturbance. However, there is a clear trend towards early evaluation to rule out or identify treatable concomitant injuries and early treatment to prevent further injuries.

Over half of all children with ACL injuries will have a concomitant intra-articular injury of the knee. The most common injuries are meniscal injuries, chondral lesions, and additional ligamentous injuries. These injuries should be sought with a high index of suspicion in an effort to identify them early, as many of the injuries result from the initial insult to the knee and may be treatable. In addition, early recognition and treatment may prevent progression or development of additional injuries. The natural history of unrepaired ACL injuries is progression of instability and loss of functionality of the knee, including higher risk for and acceleration of degenerative changes and osteoarthritis of the knee. As such, the current trend is towards knee preservation to prevent the loss of function that may result from degenerative changes due to ACL and concomitant pathology.

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18

Rehabilitation and Return to Sports After Anterior Cruciate Ligament Reconstruction in the Young Athlete

Mark V. Paterno and Alyson Filipa

Introduction

Children are not small adults and the application of adult rehabilitation principles to a young, developing body may not be optimal to improving outcomes within this patient population. The primary medical goal following ACL injury in a skeletally immature patient is to provide functional knee stability, to preserve the menisci and to avoid any potential growth disturbances after potential surgical interventions [1–3]. Rehabilitation following ACL injury should facilitate the achievement of these goals while trying to safely return to patient to their highest level of desired functional activity. Current evidence suggests high re-injury rates [4] and low return to sports rates [5] in this population. Further, the risk of developing osteoarthritis in 5–10 years is unacceptably high [6], therefore interventions should also be designed to protect the joint and facilitate return to desired pre-injury level of activity. Postoperative ACL reconstruction rehabilitation in skeletally mature patients has been described extensively in the current literature [7–11], and rehabilitation guidelines that are accepted practice in adults are often applied to skeletally immature patients who present with open growth plates. Surgical technique-specific factors, patient-specific factors, as well as psychosocial factors related to the pediatric patient must be considered in the development of more age-appropriate rehabilitation guidelines. The literature in this area is scarce, demonstrating that the physical therapy profession is in the preliminary stages of shaping the most appropriate rehabilitation guidelines for this patient population after ACL reconstruction [3, 12].

Rehabilitation Considerations

The postoperative management of the skeletally immature patient after ACL reconstruction is unique. Rehabilitation in young children with the use of adult ACL guidelines could potentially result in an inadequate management plan of key impairments and ultimately a poor outcome. Typical patient goals in this young population focus on return to pre-injury or an unrestricted level of activity. These aspirations often result in high levels of exposure to high risk activity when these young patients are discharged after ACLR. Coinciding with these activity-specific goals are joint preservation goals. Current evidence suggests 50–100% of young patients with ACL injuries will show early signs of osteoarthritis in their knees within 5–10 years after injury [6, 13]. For the pediatric

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or young adolescent patient, that could translate into knee OA as young as 18–22 years of age. For the skeletally immature patient, the therapist must place an increased focus on joint protection, consider modifications based on graft type and surgical technique, and highly emphasize the importance of proper biomechanical technique specific to their particular sport. This may mean that they have a unique return to sport plan to help properly reintegrate them back into their activity, specific to the demands required for their sport.

Joint protection after ACLR in young patients is focused on acute phase modifications to control stress on the healing joint, but can extend to the end stages of rehabilitation. Greater than 50% of children and adolescents have concurrent meniscal or chondral injury at the time of ACL reconstruction [14]. With a primary goal of protection from further menisci and articular cartilage damage to maximize the potential for improved long-term joint health, these modifications may help reduce long-term complications after ACLR. Modifications to traditional postoperative management of ACLR may start prior to surgery. A higher emphasis on preoperative rehabilitation to promote better postsurgical outcomes is recommended for better long-term outcomes postoperatively [15, 16]. Following surgery, postoperative acute modifications include early bracing for protection, an extended period of partial weight bearing (PWB) with crutches, and a slow progression of load with both open and closed kinetic chain strengthening activities. Later phase modifications may include an intentionally slower and more graded return to play progression compared to typical recommendations for adults after ACLR.

In addition to the unique psychosocial needs of the younger patients, surgery-specific needs in this population should be addressed. Surgical modifications to ACLR in the skeletally immature patient focus on protection of the growth plate. This may include a physeal sparing procedure such as the "over-the-top" ACLR with an extra-articular approach to the femur [17] or the "all-epiphyseal" approach with femoral drill holes which avoid the growth plates [18]. Alternatively, some surgeons may elect to proceed with a traditional adult reconstruction, with special considerations to graft type (typically soft tissue only) and reduction of the width of the tunnels, to minimize potential growth plate injury. Each of these factors should be considered when implementing a rehabilitation program.

Pre- and Postoperative Evaluation

A proper evaluation begins the process of managing young patients with ACL injury, both prior to and following surgical intervention. The patient history must include patient demographic information, social history, school history, growth and development status, living environment, medications, medical history, general health status as well as current chief complaint(s) and functional status. Objective examination should include appropriate systems status review as well as assessment of anthropometric characteristics, assistive device status, nerve integrity, gait and balance, coordination, skin integrity, motor function, motor control, pain, posture, range of motion, appropriate reflexes, and sensory integrity [19]. Following appropriate assessment, the patient is ready to enter the preoperative physical therapy phase of the rehabilitation program.

Preoperative Physical Therapy

Preoperative physical therapy is an essential component to start the patient on their road to a successful outcome after their ACL surgery. At the time of injury, several factors may present which, if left unaddressed preoperatively, can hinder progress after surgery. Most notably, these factors may include pain, joint effusion, loss of motion, and quadriceps femoris weakness. Historically, preoperative goals have globally focused on achieving a "quiet knee," which consists of eliminating knee effusion and achieving full knee range of motion prior to surgery [20]. However, expert opinion along with emerging research suggests that more than simply achieving a quiet knee is required prior to surgery to improve outcomes [15, 21]. Patients that have participated in preoperative rehabilitation programs have shown to have better outcomes 2 years after ACL reconstruction [15, 16].

Despite this recent evidence which supports the use of preoperative physical therapy to improve postoperative outcome after ACLR, there remains wide variation in the optimal interventions used preoperatively. Specifically, the ideal duration and specificity of exercise components of preoperative rehabilitation programs remain unknown. Beyond the restoration of normal range of motion and reduction in the post-injury hemarthrosis, recent emphasis has been on restoration of quadriceps femoris activation and strength. This goal has been achieved through a variety of exercises, so consensus on optimal interventions has yet to be achieved [15, 21–23].

Due to the variation in care and lack of specificity related to exercise prescription, a specific evidence-based preoperative protocol has yet to be developed for this population after ACLR. The Royal Dutch Society for Physical Therapy instructed a multidisciplinary group of Dutch ACL experts to design a clinical practice guideline underpinned by systematic review and expert consensus. This group suggested that if a patient had a preoperative deficit in quadriceps strength of greater than 20%, the patient had a significant negative consequence for self-reported outcome 2 years after ACL reconstruction [16]. Based on this study, setting a criterion-based expectation to have a patient try to achieve less than a 20% quadriceps strength deficit prior to surgery, may help give some objective criteria prior to ACL reconstruction. In addition to having less than a 20% quadriceps strength deficit, other criteria related to the "quiet knee" should still be considered basic components necessary to minimize the potential for motion complications postoperatively and to determine if your patient is ready for surgical intervention.

Post-Operative Physical Therapy (Table 18.1)

Phase I: Acute

Phase I represents the acute management phase of rehabilitation. At this time, the goals are to minimize knee effusion, develop quadriceps muscle activation and control, initiate patellar mobilization, and progress knee range of motion (ROM). The practice of postoperative knee brace usage in this phase is highly variable. Prior evidence suggests there is little effect of postoperative brace usage on outcome in adult patients after ACLR [24]. Despite this, some rehabilitation protocols for young patients after all-epiphyseal ACLR recommends use of a brace to stabilize in full extension during WB activity to protect the younger child against unanticipated stress on the knee with a fall or unexpected movement [12]. Typically, no brace is utilized throughout the acute phase of rehabilitation in our protocol in order to promote knee range of motion, use of the quadriceps muscle, and promote normalizing gait mechanics as soon as possible. However, if patient-specific factors exist which suggest a postoperative brace would be a safer option, bracing may occur, especially in the initial postoperative days after surgery to protect the knee joint and potentially assist with pain reduction. Range of motion is allowed to progress as tolerated immediately following surgery with baseline goals required to minimize the potential for motion complications (Figs. 18.1 and 18.2). Full knee extension is critical to achieve as soon as possible after ACLR. Patients who fail to achieve full extension are known to have a higher incidence of knee OA and greater difficulty with higher level functional activity such as running [25]. Therefore, achieving full extension as soon as possible postoperatively is crucial. With respect to knee flexion, a minimal expectation exists, of achieving 90° flexion at week one postoperatively, 100° flexion by week two, 120° by week three, and 135° by week 4. With respect to weight bearing, the patient is permitted to weight bear as tolerated (WBAT) with two crutches after surgery. Immediate weight bearing does not affect knee laxity and may even decrease the incidence of patients experiencing anterior knee pain [16].

With respect to strengthening, the patient is permitted to begin isometric quadriceps exercises from the first week postoperatively [16]. The focus of quadriceps femoris isometric exercise is to encourage a return of volitional control of the quad

Table 18.1 Overview of rehabilitation phases after ACL reconstruction in the pediatric patients

Phase	I	II	III	IV	V	VI
	Acute (0–4 weeks)[a]	Subacute (4–8 weeks)[a]	Technique/muscular development (8–16 weeks)[a]	Pre-functional (16–24 weeks)[a]	Return to activity (24–36 weeks)[a]	Return to unrestricted activity (36–52 weeks)[a]
Goals	1. Minimize effusion 2. Regain quad control 3. Progress ROM 4. Initiate Patellar mobilization	1. Regain neuromuscular control of quad 2. Improve LE strength 3. Normalize ROM 4. Reduce abnormal forces on knee with ADL's	1. Improve endurance/strength 2. Introduce technique with functional movements while protecting the ACL/PF joint	1. Maximize strength and endurance 2. Initiate impact activities once isokinetic peak torque to body weight deficit of 20% or less for strength and endurance 3. No pain 4. Full knee ROM 5. No swelling 6. Balance with eyes open and closed for 30 s 7. Good movement patterns prior to initiation of plyometric activity	1. Progress strength, muscle performance, and neuromuscular control in multiple planes of motion 2. Progress impact activities to become more sport specific 3. Transition from the rehabilitation setting into restricted activity participation	1. Successful transition from end stage rehabilitation to safe, unrestricted participation in sports
Immob.	Inconclusive	–	–	–	–	–
ROM	Knee flexion and extension ROM as tolerated with minimum goal of: Week 1: 0–90 Week 2: 0–100 Week 3: 0–120 Week 4: 0–135	ROM as tolerated with goal of attaining full knee flexion and extension as compared to the uninvolved side	–	–	–	–
WB	WBAT with two crutches	Progress off crutches when: 1. Good quad (minimal to no extensor lag noted) 2. Full knee extension 3. Minimal effusion 4. Minimal pain 5. Able to attain SL balance for proper weight shift	–	–	–	–

Exercises	• Ankle pumps	Add:	Progression of balance and stability activities	Initiate plyometric activity once criteria met	Progress lateral, rotational, and transitional activities	
	• Quadricep isometrics	CKC activities:	– Dynamic surfaces	No best way to progress but suggest a slow and gradual approach (50 or less foot contacts)	Add unanticipated perturbations on unstable surfaces	
			– DL to SL support			
		• Toe raise	– Add functional movements		Multiple activities simultaneously	
				Ideas for progression	Return to game play in a systematic fashion (noncontact drills, contact drills, full practice, scrimmage play, game play)	
			Progression of endurance and strength	– DL broad jump		
	• Patellar mobilization			– DL wall jump		
		• Wall sits		High focus on proper biomechanical form vs. repetition	Modify participation time, speed, and demand of participation as needed for safe reintegration into restricted activity	
	• SLR x 4	• Mini squat	– Focus on both DL and SL activities	– Progress to transitional jumps		
	• Stretching (HS, Gastroc			– Initiate straight line jogging (combination walk/jog program)		
		Isotonics:		– Unrestricted recreational play running not recommended		
	• A/PROM	Leg press ((protected range/ week)	– Add weight, reps, as able			
	• Gait retrain					
	• Initiate balance and proprioception (weight shifts)	Leg extension (protected range/week		– Progress to SL hops in a single plane		
		Progress ROM activity				
		Progression of balance and proprioception—side stepping, balance, BOSU, stability and perturbation training				
		Neuromuscular training				
Modalities	EMS-NM reeducation	EMS-NM reeducation	As needed			
	Cryotherapy/ Vasopneumatic device for pain and effusion control	Cryotherapy				
Cardiovascular	–	Bike	Bike	Elliptical	Sport-specific cardiovascular training to prepare for return to sport	–
		Swimming-aquatic (exercise based vs. lap swim	Elliptical (towards end of this phase)	Initiation of a return to walk/ jog program (when has adequate strength and neuromuscular control		
		Treadmill walking	Treadmill walking			

(continued)

Table 18.1 (continued)

Phase	I	II	III	IV	V	VI
	Acute (0–4 weeks)[a]	Subacute (4–8 weeks)[a]	Technique/muscular development (8–16 weeks)[a]	Pre-functional (16–24 weeks)[a]	Return to activity (24–36 weeks)[a]	Return to unrestricted activity (36–52 weeks)[a]
Pivot/cutting	–	–	–	–	Initiate pivoting and cutting drills Progression of sports-specific training	
Test/assess	• Effusion • Quad strength by MMT • Weight acceptance	Effusion Quad strength Hamstring strength SL balance	• Biodex isokinetic at 12 weeks with a protected ROM of 90-45 degrees [16]	• Biodex isokinetic testing in a full arc of motion Hop test Additional screens per clinical judgement	• Biodex • Isokinetic testing in a full arc of motion stability Hop test	
Goals/criteria to progress to next phase	1. Fair quad control (3+/5) 2. ROM 0–135 3. Good patellar mobility 4. Minimal effusion	1. Good quad control (4-/5) 2. Full knee ROM 3. Good patellar mobility 4. Minimal effusion 5. No patellofemoral pain	1. Good quad control (4+/5) 2. Maintenance of ROM and patellar mobility 3. No effusion • No PF pain or anterior knee pain. • Isokinetic peak torque to body weight side to side deficit of 30–35%	1. Pain resolved during activity 2. Effusion resolved during all activity 3. Full AROM compared to uninvolved LE 4. QF and HS strength ≥85% of the uninvolved side 5. 5/5 MMT for all relevant musculature 6. IKDC score ≥85% 7. Demonstrate LSI ≥ 85 on all SL hop tests 8. Demonstrate appropriate mechanics during additional screens per clinical judgement	1. Pain and effusion resolved during all activities 2. QF and HS ≥90% of the uninvolved side 3. IKDC score ≥90 4. SL hop tests, LSI ≥90 5. One or more of the following criteria • Drop vertical jump, demonstrate appropriate mechanics • Tuck jump assessment, less than six flaws • Star excursion balance test, composite reach distance ≥94 6. Demonstrates appropriate mechanics during activity-specific maneuvers and drills	

[a]Timelines are provided as general guides as to how long it may take for a patient to achieve the necessary criteria to advance to the next phase of rehabilitation. Time lines are NOT used as criteria to progress to the next phase of rehabilitation

Fig. 18.1 Heel slides demonstrating an active assisted range of motion of the surgical knee (*right*) to promote knee flexion. Can be done passively by pulling a towel that is looped around the ankle

Fig. 18.2 Active assistive motion of the surgical knee (*right*) to promote early knee flexion range of motion in prone

activation quickly after ACLR to minimize the potential for further disuse atrophy as well as to provide a functional superior mobilization to the patellofemoral joint. The patient is also permitted to begin strengthening proximal and distal to the involved joint, such as gluteal isometrics, hip strengthening and active ankle plantar flexion and dorsiflexion. In addition, core stability training can be initiated as soon as tolerated by the patient.

The ideal method of strengthening after ACLR continues to be a debate. A systematic review showed that starting eccentric quadriceps training in closed kinetic chain (CKC) 3 weeks after ACLR is safe and helps lead to a bigger

Fig. 18.3 Early balance activities involving side to side weight shifts onto the involved limb (*right*)

improvement in quadriceps strength than concentric training alone [16, 26, 27]. Open kinetic chain knee extension exercises can be introduced in a limited range (90-45° knee flexion) [16]. OKC hamstring strengthening is safe to begin in the acute phase of rehabilitation with patellar tendon grafts and allografts with adults; however, with hamstring grafts, this is delayed until week four postoperatively and restricted to a range of 90-45°.

Gait retraining begins at the onset of rehabilitation to minimize the risk of developing antalgic gait patterns secondary to effusion, quadriceps femoris weakness, or pain. Finally, patients begin to participate in entry level balance and proprioception activities, as their weight bearing status will allow. This may begin with simple weight shifting onto the involved limb during a PWB status and then progress to more single leg stand activities when WB allows (Fig. 18.3). With respect to modalities, NMES is utilized early in rehabilitation to ensure quadriceps muscle activation and minimize any chronic quadriceps inhibition [28]. Van Melick et al. [16] noted the use of electric stimulation combined with traditional postoperative rehabilitation may enhance quadriceps femoris strength return, especially within the first 2 months postoperatively. If available, a vasopneumatic device or cryotherapy can be utilized to help minimize knee effusion and as an adjunct for pain management [16]. When the patient is able to demonstrate fair quadriceps control (MMT 3+/5), ROM from 0° to 135°, good patellar mobility and minimal effusion, they are ready to progress to phase II of the protocol.

Phase II: Subacute

The goals of phase II during this phase are to regain neuromuscular control of the quadriceps musculature, improve lower extremity strength, normalize knee ROM, and reduce abnormal forces on the knee during activities of daily living. A baseline level of quadriceps strength is critical to regain early in rehabilitation [29]. In conjunction with strength, neuromuscular training is important to emphasize early within rehabilitation as, in conjunction with strength training, it can decrease compensatory changes in muscle activation patterns and facilitate joint stability [16].

ROM continues to progress as tolerated in this phase with the goal of attaining full knee ROM by the end of week eight compared to the uninvolved side. Patients are permitted to discontinue crutch use when they are able to demonstrate a good quad contraction (minimal to no extensor lag), full knee extension, minimal effusion, minimal pain with gait, and proper weight acceptance onto the involved limb. Patients are weaned from crutch use by a gradual progression from two crutches, to one, and ultimately to no assistive device (Fig. 18.4).

Exercises are progressed at this time as weight bearing continues to progress. Open kinetic chain exercises can now begin to work within new ranges of motion. Early data suggested limiting full extension with resisted OKC quad strengthening until 4–6 months after ACLR [30]. More recent work suggests increasing knee extension ROM at week 5, with a progression to 90-30°, 90-20° at week 6, and 90-10° in week 7 and full ROM in week 8 [16]. It is important to once again highlight the need to delay adding weight to hamstring strengthening in OKC until week 8–12 to protect the graft from elongating [16]. Finally, a slow and gradual progression of balance and proprioception activities is introduced within this phase in alignment with weight bearing status (Fig. 18.5). Cardiovascular conditioning activities can be progressed at this time to include biking, treadmill walking, and aquatic exercises (not involving lap swim).

When the patient is able to demonstrate good quad control with a MMT of 4−/5, full knee ROM, good patellar mobility, minimal knee effusion, and no patellofemoral pain, he or she is able to progress to phase III of the protocol.

Fig. 18.4 Gait training with a patient who had right knee ACL reconstruction to help transition from two to one crutch without gait deviations. Use of stepping over cones with the involved limb with a focus on knee flexion during swing and a heel-toe gait pattern during initial contact and loading response, helps facilitate normal gait mechanics during both the stance and swing phase of gait

Phase III: Dynamic Strength and Endurance Training

The dynamic strengthening phase of rehabilitation after ACLR focuses on continued development of the foundation of strength and an initiation of more dynamic movements. The goals during phase III include improvement of muscular endurance and strength, introduction of proper biomechanics and neuromuscular control with functional movements while protecting the ACL graft and patellofemoral joint.

During phase III, the baseline strength and proprioception activities initiated in phase II of rehabilitation are progressed. Strengthening activities

Fig. 18.5 Early balance activities such as tandem stance to help transition off crutches (right limb is involved limb)

are progressed through the addition of weights, sets, repetitions, and focus on the involved, single limb activities (Figs. 18.6, 18.7, 18.8, and 18.9). These activities should continue to be executed on both limbs, but can be done with each leg individually to increase the demand placed on the target muscle group. Balance and stability activities can be progressed through the incorporation of more dynamic surfaces, progression from double limb support to single limb support, and the addition of functional movements. Conditioning activities should be advanced at this time in both intensity and duration. The elliptical machine is another cardiovascular option for conditioning towards the end of this phase. Successful completion of phase III of the program occurs when quad control is good (4+/5 MMT), ROM and patellar mobility are WNL, no effusion is present, no patellofemoral pain and isokinetic peak torque to body weight side to side deficit of 30–35% or less is present by the end of this phase.

Fig. 18.6 Single leg press to focus on improving quadriceps and hamstring strength on the involved limb (*right*)

Fig. 18.7 Step ups with progression of free weights on the involved limb (*right*)

Phase IV: Pre-functional

The main goals of phase IV are to maximize strength and endurance in preparation for the initiation of impact activities for the patient's specific return to sport needs. Continued progression of strength and endurance are necessary until the patient is an isokinetic peak torque to body weight deficit of 20% for both strength and endurance [31]. A sufficient foundation for strength is necessary to safely participate in dynamic movements without developing abnormal compensatory movement patterns. In addition to strength, it is suggested that the patient also have no pain, full knee range of motion, no swelling, can balance with eyes open and closed for 30 s, and has good movement patterns prior to initiating plyometric activity [31].

Once strength is adequate and all other criteria are met, initiation of impact and plyometric activity can occur. Currently, there is little consensus on the best way to progress plyometric activity [31]. Therefore, it is important to remember all of the training variables that must be considered when creating any basic plyometric progression. These variables include neuromuscular overload (change of direction of a limb or body without external load), spatial overload (muscle activation and stretch reflex initiated within a specific range of motion), temporal overload (short amortization phase, timing), intensity (amount of effort required to perform the activity), volume (total work performed in a single session), frequency (number of exercise sessions that take place during the rehabilitation cycle),

Fig. 18.8 Dead lifts while standing on the involved limb (*right*) with progression of depth and free weights

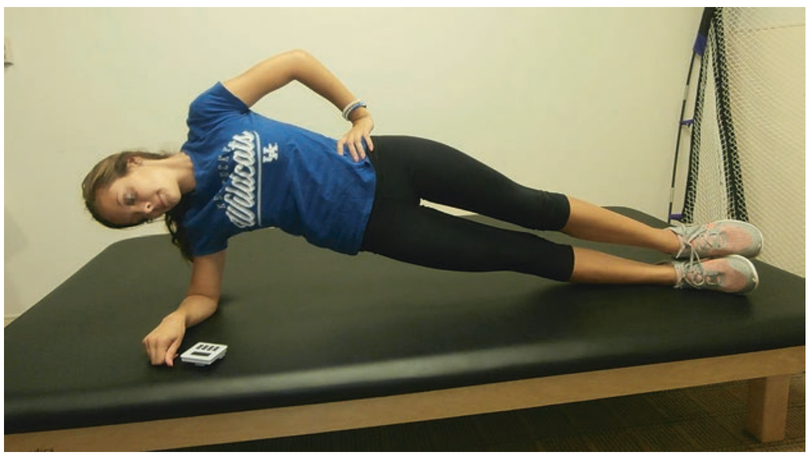

Fig. 18.9 Side planks to focus on hip and core strength for proximal stability

recovery time (time between sets and rehabilitation sessions), and specificity (plyometric movements specific to their sport) [31].

Specific to the pediatric ACL patient, it is important to highlight volume and proper recovery time. When initiating impact, a slow and gradual approach is recommended to minimize overuse stress to healing tissues. With respect to recovery, there is limited research on the optimum recovery times following plyometric exercise. Despite this lack of consensus, the muscle physiology literature recommends an optimal recovery time between training sessions of 48–72 h [31]. This recovery time is sufficient to allow lower extremity musculature to recover from the load of the plyometric exercise, but also minimized repetitive stress on the graft. Emerging basic science research has begun to question the ability of the healing graft to endure repetitive micro-stress and ultimately recover to its native length. Subsequently, the concept of necessary time to recover to minimize chronic elongation of the graft suggests at least 24 h may be necessary to minimize creep of the graft [32].

An ideal plyometric activity to initiate impact activity is a double leg broad jump or a double leg wall jump. Both activities can leverage the use of a double leg impact activity to balance forces through the involved and uninvolved limb and provide an opportunity to master technique in such a way to minimize high risk asymmetries with these movements. Asymmetries with double limb tasks have been identified as predictors of future ACL injuries in this population [33]. The progression of impact activities should be deliberately slow (50 foot contacts) [31] with a high focus on proper biomechanical form versus repetition and submaximal effort prior to max effort. Until the patient can demonstrate proper technique with takeoff and jump landings, they should not be advanced to higher level impact activities.

When proper double leg jump form is demonstrated, the patient can begin transitional jumps that allow the patient to develop neuromuscular control from a double leg jump to a single leg hop. Around this same time straight line jogging can begin. A combination walk and jog program is suggested as a way to slowly reintegrate the patient into unrestricted running. It is important to note that differences in training environments such as treadmill running vs outdoor running may need to be considered. It is important to remind the patient that unrestricted recreational play running is not recommended at this time in the rehabilitation process.

Once a return to running program is established, a further jump progression should continue to work on developing SL hops in a single plane that are, once again, completed with good biomechanical form. Some may argue that a single leg hop should be demonstrated prior to initiating a return to running program. With the pediatric population, some patients may struggle with a single leg hop as it is a novel isolated skill, who are able to return to running, which is a known skill, with ease. Either way, a deliberately slow progression with high emphasis on low repetition and proper biomechanical form is still warranted and needs to be of the highest priority.

The athlete is ready to progress to phase V pending successful attainment of phase IV goals. These goals include continued resolved pain and effusion during all activities, full AROM compared to the uninvolved LE, MMT of 5/5 for all relevant musculature, isokinetic strength ≥85% of the noninvolved limb, IKDC score of ≥85, SL hop tests with a limb symmetry index of ≥85%, and demonstration of appropriate mechanics during additional screens per clinical judgement.

Phase V: Transition to Sport

The main focus on phase V is to transition the individual from the rehabilitation setting and begin the gradual return of the athlete to their specified activity or sport once they have sufficient baseline strength and technique as outlined in the goals for entry into phase V. During this phase, the patient will participate in therapeutic activities that functionally progress and optimize their strength, muscle performance, and neuromuscular control in multiple planes of motion to focus on pivoting and cutting maneuvers and then begin to transition from the rehabilitation setting into restricted activity participation.

In order to safely progress the patient, strength and muscle performance activity progressions that alter planes of movement are now appropriate for the patient to attempt. A focus on lateral, rotational, and transitional activities along with the addition of unanticipated perturbations or an unstable surface are now appropriate. Activities that challenge multiple trunk and lower extremity muscle groups simultaneously are now appropriate. It is also important to think about making multiple activities occur simultaneously or make movements sequential to make the task more challenging for the patient.

Neuromuscular control should be progressed to position specific sport activities and drills to help promote the transfer of skills from the clinic to the field or court. A focus on high level plyometric activities, specifically related to power generation during takeoff and force attenuation during landing, can be initiated. Activity progressions should include a progression of impact loading, single leg to double leg transitions and vice versa, altered planes of movement that focus on cutting and pivoting and transition activities, sport-specific perturbations, more challenging support surfaces, or adding sequential or simultaneous activities.

In order to safely reintegrate into the desired sport, a progressive reintegration is needed into the desired activity. This reintegration must include a mastery of movement technique as well as a progression of cardiovascular endurance to insure a prevention of fatigue and the potential decrements in performance that can result. As such, activities in the clinic must focus on maintaining appropriate performance technique as well as advancing cardiovascular and sport-specific endurance.

Initial return to play consists of noncontact drills and conditioning activities. Modifications to the amount of participation time along with speed/demand of participation (ex; 50% effort progressing to 100% effort) can be made. Once this is safely done, the patient can be progressed to contact drills and full practice. Modifications to the amount of participation time, speed, and demand of participation can be made. Finally the patient can be progressed to a scrimmage and game time setting. Modifications to the time of participation can be made.

The athlete is ready to progress to phase VI pending successful attainment of the following goals. These goals include continued resolution of pain and effusion during all activities, isokinetic strength ≥90% compared to the noninvolved limb, IKDC score of ≥90%, SL hop tests with a limb symmetry index of ≥90%, and demonstration of appropriate mechanics during activity-specific maneuvers and drills. In addition, the patient must pass one or more of the following criteria: (1) demonstrates appropriate mechanics on the drop vertical jump assessment, (2) is able to pass a tuck jump assessment with less than six flaws [34], or (3) is able to complete the Star Excursion balance test with a composite reach distance of ≥94.

Phase VI: Return to Unrestricted Play

The patient can be cleared for unrestricted activity participation once they have achieved the goals for entry into phase VI. Discharge from therapy is based on clinical judgement, attainment of goals, and successfully participating in their desired activity. Several authors in multiple systematic reviews have highlighted the wide variation and lack of standard assessments used to determine readiness to return to sport after ACLR in an adult population [16, 35–37]. Van Melick et al. suggested, based on their systematic review and expert opinion, an extensive battery of tests should be used to dynamically assess readiness to return to sport [16]. Further, higher criteria to successfully pass these functional assessments should be considered to best identify those patients specifically ready to return to sports [16]. For example, limb symmetry values of 85% compared to the uninvolved limb on strength tests and functional hopping tests may be sufficient to return to ADL’s, but fall short of readiness to participate in pivoting and cutting activity. Perhaps, LSI values of 90–95% or greater on these assessment are necessary to help insure success with return to dynamic, cutting activity [16]. This may be even more appropriate in young athletes who very often seeks to return to the highest level of activities, which also pose the greatest risk for future injury. Ultimately, once the patients achieve these necessary criteria to return to sport, a functional transition to acclimate and ultimately released to desired activity is most appropriate. Follow-up with the physical therapist to ensure successful reintegration and participation in the unrestricted activity participation is also recommended.

Conclusion

Rehabilitation after ACL reconstruction in the young athlete is a modification of traditional rehabilitation used with adult patients after this procedure. A modification of the intensity of the progression, a systematic approach to safely advancing the patient through each phase of rehabilitation and a focus on achieving appropriate criteria to be released to return to pivoting and cutting sports are a few of the modifications necessary to insure a good outcome in this population. Improving ability to return to activity and minimizing second ACL injury rate should be the primary goals of rehabilitation in this population.

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Complications of ACLR, Including Revision ACLR

19

Eric J. Wall

Up until recently, ACL reconstruction was rarely performed on young athletes with open growth plates, especially on those who are prepubertal (≤10 years old). Growth disturbance of overgrowth, undergrowth, or angulation can always complicate a pediatric ACL reconstruction (ACLR). This growth risk is very rare, and is usually outweighed by the risks of permanent cartilage and bone damage from repeat giving way episodes in a young athlete who refuses to limit their sports activity with an unfixed ACL. The most common serious risks after ACLR in immature patients are graft re-tear, opposite knee ACL tear, and stiffness. Despite these complications, ACLR in young patients allows a higher level of return to sports with a lower level of subsequent meniscal injury and giving way compared to nonoperative treatment.

Graft Re-tear

The leading major complication in children and adolescents who undergo an ACL reconstruction is an ACL re-tear (Fig. 19.1). This can be a re-tear of their reconstructed graft or a tear of their opposite normal knee. Several recent studies have cemented the fact that younger athletes have a much higher graft re-tear rate than adults. This was best illuminated in the reports from a multicenter ACL study group focused on outcomes and complications in which the odds of re-tear decreased by 9% for each year increase in age [1]. Ho et al. found an overall failure rate of 9.6% in a cohort of pediatric and adolescent ACL reconstructions with an average age of 15.4 years (range 5–19) [2]. One study found a 44% reoperation rate for graft disruption, removal of prominent hardware, and failed meniscal repair in 16 skeletally immature patients [3]. Yarbroudi et al. noted a 14% ACL re-tear rate in athletes <18 years old that was significantly higher than the 2% rate seen in athletes ≥24 years old [4]. These high rates of graft re-tear are likely due to the very high activity levels and high rates of sports return after ACLR of children versus adults. Most children on high school, junior high, and selective club teams play or practice over 200 hours per year, which is rare for adult nonprofessional athletes on recreational teams.

Due to a lack of data, the rate of re-tear in very young, prepubertal children is not clearly known. It is likely to be the highest of any age group including the high school athlete. Mid-term results of the physeal sparing intra/extra-articular technique show a low 4.5% revision rate [5]. An all-epiphyseal technique similar to that of Anderson et al. had an 11% re-tear rate [6].

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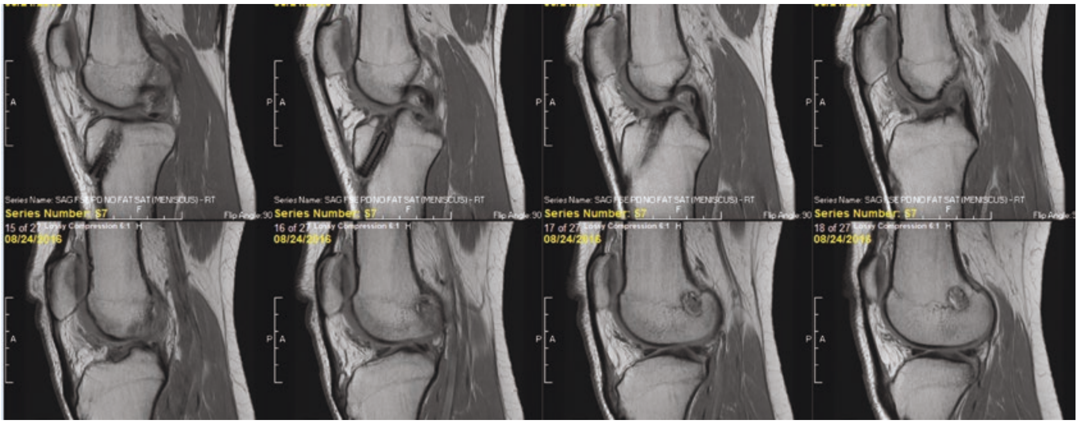

Fig. 19.1 ACL graft mid-substance failure after transphyseal tibial tunnel and epiphyseal femoral tunnel 2 years after index procedure

It is clear that young patients who are reconstructed with tissue bank allografts (versus their own autografts) have a much higher re-tear rate than those with autografts, with reports up to 37% graft failure [7–9]. Autografts are strongly preferred over allografts in the young age group. In rare cases in which the patients has insufficient length or diameter autograft tendons, an allograft can supplement their autograft to make a hybrid graft.

In very young patients, smaller graft size may also contribute to a higher rate of graft failure (Table 19.1). It is unknown if an 8 year old's new ACL autograft or allograft can grow in size and strength as the athlete grows in size and strength. Researchers found that graft size decreased by 25% between sizing at surgery as compared to MRI measurement at follow-up [10]. Adults who underwent ACLR with a graft diameter <8.5 mm had a higher rate of re-tear than adults with a graft diameter ≥8.5 mm [11]. In the range of 7–9 mm, researchers found a 0.82 times lower likelihood of being a revision case with every 0.5 mm incremental increase in graft diameter [12].

Nonanatomic tunnel placement is described as the leading cause of ACL graft re-tears in adults. The most common anatomy problem is that the femoral tunnel is placed too anterior in the notch. Intra-articular reconstructions such as transphyseal and all-epiphyseal are designed to place the graft in the anatomic footprint of the native ACL. The use of fluoroscopy to place all-epiphyseal tunnels close (but not through) the growth plate of femur and tibia may also help confirm that the femoral tunnel is not anterior. A study found that anatomic femoral tunnels (vs. transportal tunnels) failed earlier [2]. A large study using transphyseal drilling technique reported very good results with a 3% re-tear rate [13]. The graft placement from of the intra-articular/extra-articular physeal sparing technique is not anatomic, but the re-tear/revision rate is reportedly low at only 4.5% [5].

Pediatric ACL reconstructions often use newer, nonstandard techniques of fixation, especially in

Table 19.1 Prevention of Re-tear

• Large diameter graft >8 mm. Triple (or quadruple) the semitendinosis and double the gracilis for a 5 (6) strand graft if necessary (Fig. 19.2)
• Drill bone tunnels in the anatomic footprint (nonanatomic is considered by most experts to be the #1 cause of graft rupture)
• In multi-strand graft, sew or affix all ends of the graft individually so you can apply even tension to all strands when graft is tensioned in the patient (don't sew strands together side-by-side)
• Pre-tension the graft at 15–20# on a graft board
• Tension the graft at 20# during fixation
• Consider extending rehab for 9–12 months in very young patients
• Need ≥90% strength of both legs before return to sports

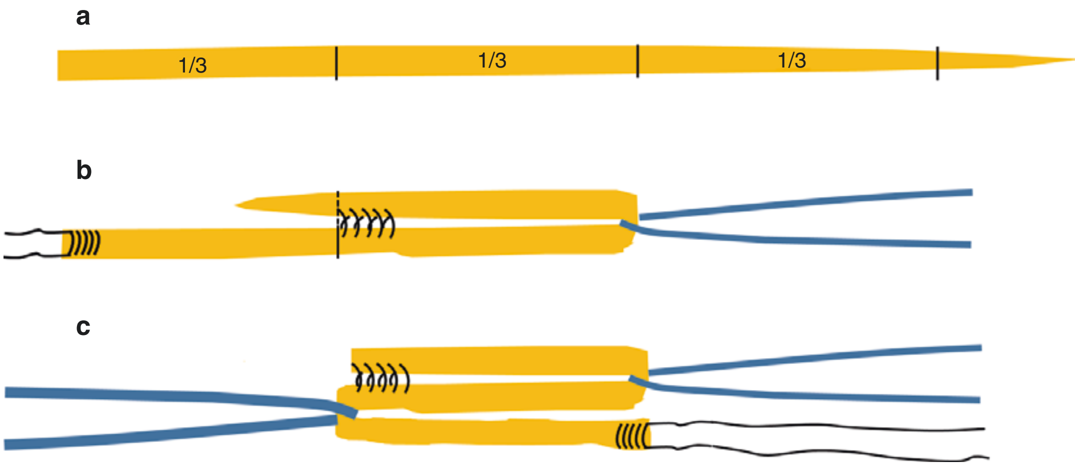

Fig. 19.2 (**a**) The semitendinosis graft is laid flat and the bulky portion (excluding the thin proximal tip) is divided into thirds to give an ultimate tripled graft length of about 7–9 cm. (**b**) The proximal third is folded back on itself and sewn side to side with a Krackow locking suture of #2 high strength suture. A similar suture is placed in the distal (tibial insertion) of the tendon. An umbilical tape is looped through the loop in the tendon. (**c**) The proximal tip of the ST tendon is trimmed, and the *left side* of the tripled graft is looped through a suspensory fixation device. The *right side* of the graft is tensioned with a suture thought the looped graft and with the sutures previously placed in the free end of the graft

the thin tibial epiphysis, which may be subject to slippage or loss of fixation. The intra/extra-articular physeal sparing technique relies on suturing to the periosteal membrane at two out of the three graft fixation points versus the adult gold standard of fixing the graft in a bone tunnel fixation [5]. The all-epiphyseal technique in which the graft, the tunnels, and the fixation reside exclusively in the epiphysis may use tunnels that are shorter, and potentially less secure, than standard adult techniques, especially in the thin tibial epiphysis.

Most pediatric sports surgeons exclusively use soft tissue autografts to minimize the risk of bone bar formation (bone block epiphysiodesis) from placing a patellar tendon or quadriceps tendon bone block near or across the physis. The growth plate of the distal femur is precariously close (2–3 mm) to anatomic origin of the ACL. If the child with a failed graft (ACL re-tear) is still skeletally immature, then the patellar tendon graft, with its bone plugs at each end is not a good option due to the risk of iatrogenic bony bar formation across the adjacent femur and tibial growth plates. If hamstrings were the original graft, then the IT Band can be harvested for either a repeat epiphyseal or transphyseal reconstruction, or an intra/extra-articular technique. Another option is to harvest the quadriceps tendon as a pure soft tissue graft, or as a single bone plug graft. The bone plug can be placed in the femoral tunnel and the soft tissue end can be pulled through the joint and out the tibial tunnel with a screw/post in the metaphysis. An allograft is a poor option in a revision ACL surgery due to the high risk of re-tear of allograft versus autograft in children.

The standard principles of revision should be followed. The original bone tunnels on the preoperative MRI or CT scan should be measured for tunnel widening. If the tunnels measure >14 mm diameter, then tunnel bone grafting may be a necessary first stage of a two stage revision. If the original tunnels are in an anatomic position, then the failed graft ends can be removed from the bone tunnel using an arthroscopic shaver and curettes, which is an arduous process. The cleared tunnels can then be reamed up to the size of the new graft. If the child has matured substantially since the original growth plate friendly ACL surgery, an original all-epiphyseal technique can be converted to a transphyseal or a standard adult technique. Drilling new tunnels is much easier in a revision than cleaning and reclaiming the old tunnels. If the child is essentially mature at the time of revision, then a patellar tendon autograft is a great graft. If interference screw fixation is planned for a patellar tendon revision, it is handy to have oversize screws available to compensate for any tunnel widening up to 14 mm.

Contralateral ACL Tear

Any athlete who tears their ACL is at risk to tear their opposite knee ACL. This risk can be higher than re-tearing the original graft. Paterno et al. report a 30% re-tear rate within 2 years after an ACLR in young patients, with 70% being the opposite knee tear, and 30% being ipsilateral knee graft failure. Ho et al. found that contralateral ACL tore in 8% of pediatric patients versus 9.6 ipsilateral graft tears [2]. Rehab of a reconstructed ACL should include the contralateral uninjured ACL. Systematic reviews of ACL prevention programs usually find a positive effect, but this is controversial [14, 15].

Meniscal Tear/Re-tear

Meniscal tears are common among the very young athletes who sustain an ACL tear. Almost all meniscal tears in the young should be candidates for a meniscal repair. Many tears are bucket handle tears and these often involve capsular detachment of the whole meniscus and run from the anterior to the posterior horn (Fig. 19.3). Inside-out repair technique using high strength 2-0 sutures is recommended due to the high number of sutures needed for the extensive meniscal repair. All inside suture devices may not be optimal with bucket handle repair due to the high number of implants necessary which can overpopulate the meniscus with the nonabsorbable end toggles of each implant. Peripheral menisco-capsular tears cannot be sewn together with an all-inside suture device that is for intra-meniscal tears. These peripheral tears must anchor the meniscus down to the capsule. Root avulsions, root tears, complex tears, radial tears, and in folded parrot beak tears can be reduced and sutured, but require advanced meniscal suturing techniques. Outside-in technique is particularly helpful for anterior horn tears. In a review of 30 patients with all-epiphyseal ACL reconstruction, there were four re-tears of bucket handle meniscal repair, so the author recommends multiple high strength non-absorbable sutures that grab a big bite of the

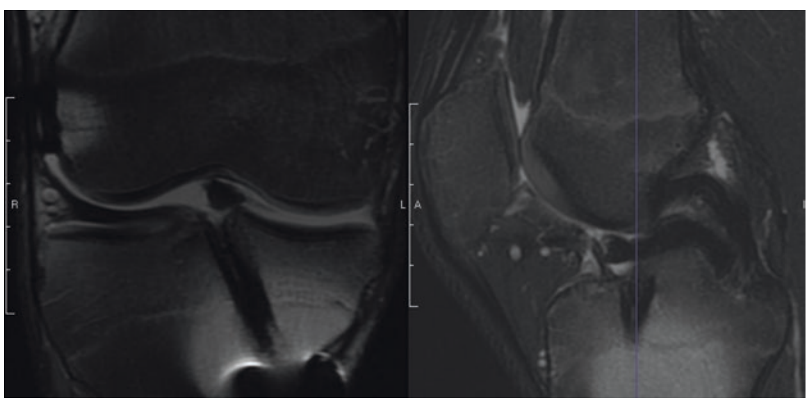

Fig. 19.3 Re-tear or bucket handle tear that was previously repaired in a transphyseal ACL reconstruction. "Ghost meniscus" (*arrow*) seen with notch displacement on left image. *Right image* shows "double PCL sign" (*arrowheads*)

meniscus and repair it to the joint capsule. Kocher et al. also noted four meniscal re-tears in their series of 44 intra/extra-articular physeal sparing ACL reconstructions in very young patients [5]. Any meniscal tear, whether virgin or a re-tear of a previously repaired meniscus should raise suspicion of a lax or unstable ACL graft. Carefully check Lachman's and pivot shift tests in the operating room, along with inspection of the ACL graft.

Growth Disturbance

Overgrowth can be more common than undergrowth in young children and physeal sparing techniques do not completely eliminate all risk of a growth disturbance after ACL reconstruction in the skeletally immature [16, 17]. The authors suspect that overgrowth may be due to periosteal stimulation near a growth plate, similar to femur overgrowth in femur fractures, and the Cozen phenomenon seen after minor proximal tibia fractures as Chotel et al. suggested [18]. Leg lengths and leg alignment should be measured/inspected at each pre-op and post-op visit until the patient is skeletally mature (Fig. 19.4). If there is a trend toward overgrowth, manifested as an increasing limb length discrepancy or an angular knee deformity, a minimally invasive percutaneous epiphysiodesis can be performed to correct the overgrowth or angulation, as long the patient has adequate growth remaining [19].

Cases of growth arrest causing limb shortening or angulation have been sporadically reported in the literature [18, 20–22]. These can be caused by bony bar formation across the growth plate, or by the tether effect of hardware such as an interference screw, a staple, a suture loop suspensory device, or even sutures placed across a growth plate. Anderson et al. mentioned that they found no growth disturbance in 50 cases using his all-epiphyseal technique. They recommend drilling the smallest tunnels that will accommodate the patient's hamstring graft diameter. They minimized the suture bulk of the graft by sewing the semitendinosis and gracilis tendon ends together with a single suture [23, 24]. Most importantly, a well tensioned and firmly anchored soft tissue graft placed across the growth plate can also cause a growth arrest due to the tether effect. The traditional mantra for transphyseal tunnels is to drill vertical tunnels that are ≤6–8 mm diameter [21, 25]. Unfortunately recent studies have shown that vertical tunnels can lead to persistent rotary instability despite good anteroposterior stability and that graft size (in adults) ≤8 mm is associated with increased graft failure.

In animal studies *almost every* well tensioned and well fixated graft placed across a wide open growth plate can cause a growth arrest [26–31]. Un-tensioned and poorly anchored grafts that violate over 7% of the growth plate's cross-sectional area can also cause a growth arrest [32, 33]. One unique advantage of all-epiphyseal techniques of ACL reconstruction in the skeletally immature is that the theoretical risks of growth arrest from both drilling though the growth plate and from the tether effect are eliminated. Anatomic transportal techniques for drilling a transphyseal femoral tunnel will ream out a much larger swath of the distal femoral growth plate due to their oblique trajectory verses a trans-tibial drilled tunnel. Anatomic transphyseal techniques should be avoided in patients with wide open growth plates. A transverse all-epiphyseal tunnel or a physeal sparing intra/extra-articular technique is preferred in the very young athlete [5, 34].

Stiffness/Arthrofibrosis

Stiffness can complicate 8% of ACL reconstructions in young patients [35]. The author rehabilitates his immature patients identical to adults with immediate weight bearing as tolerated without

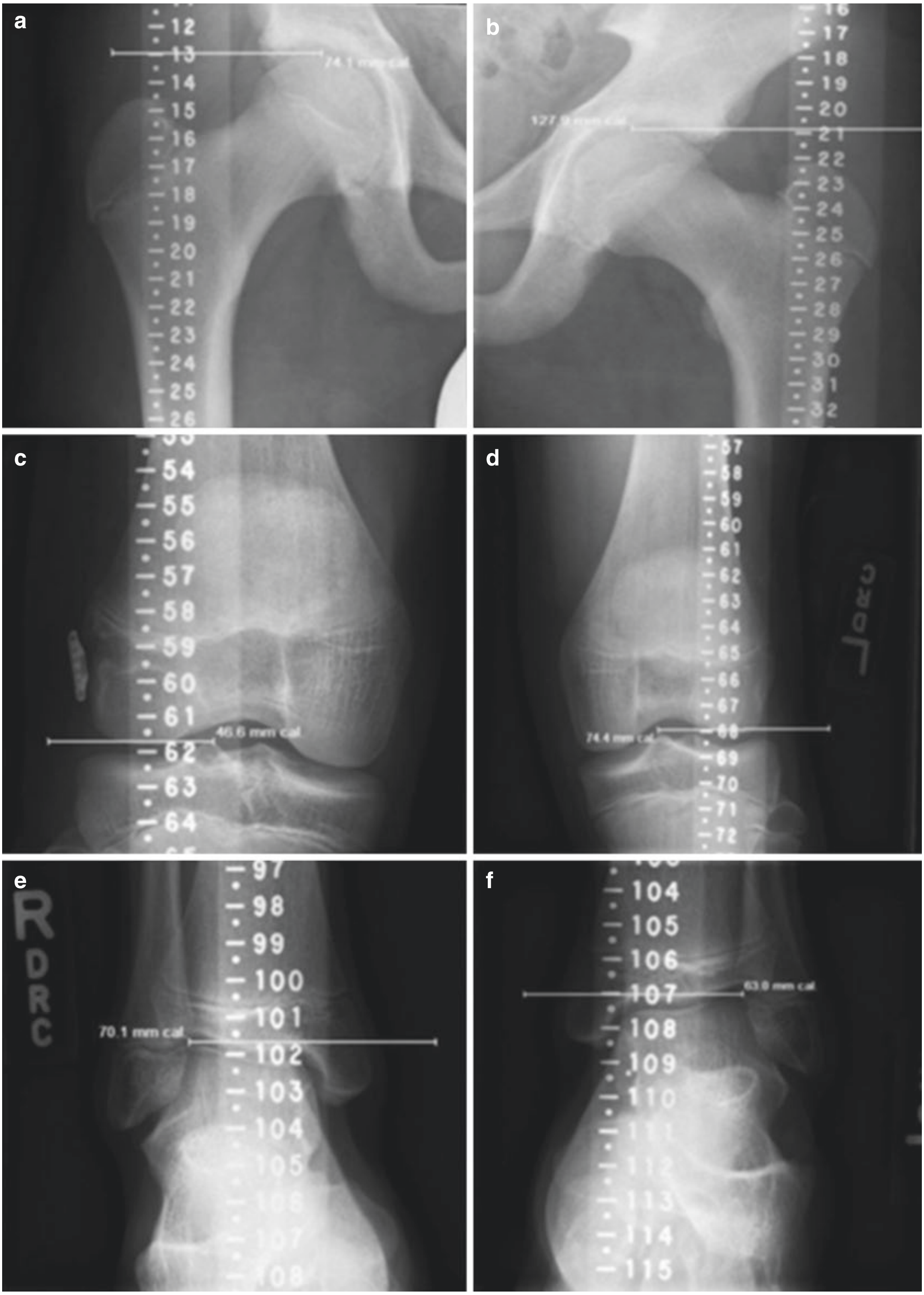

Fig. 19.4 3 years after an all-epiphyseal ACL reconstruction the right leg is 2.6 cm longer than the left. The patient underwent a screw epiphysiodesis which reduced the leg length discrepancy down to 0.5 cm at maturity [17]

any limits on motion. Patients may remove their post-op knee immobilizers at any time, and are instructed to remove it by post-op day #3 for slow gentle knee extension and flexion. It should be totally discontinued by post-op day #7. Swimming is encouraged to start on post-op #7. Formal physical therapy is started on about post-op day #7. Crutches are discontinued at about 3 weeks post-op when the physical therapist deems the patient safe for unassisted ambulation.

The author performs a 2–3 mm lateral and anterior notchplasty, especially when inserting a quintupled hamstring graft (tripled semitendinosis, doubled gracilis) which often measures 8.5–10 mm diameter. The author also places a tibial tunnel aperture as medial as possible with the tibial guide pin touching the lateral edge of the PCL. With an anatomic femoral tunnel the graft can impinge along the lateral wall of the notch especially at flexion angles >45° and can lead to stiffness and require manipulation under anesthesia and revision notchplasty in rare cases. If by 4–6 weeks postoperative the patient has greater than 10 degrees of full extension or cannot flex past 90 degrees then the author considers manipulation under anesthesia. The author uses an extension board starting at the first post-op visit (POD#7) if the patient has unusual stiffness. Serial extension casting (without surgery) can also be effective for mild to moderate knee flexion contracture in the first 6 weeks after surgery [36].

Laxity

ACL graft laxity should be a rare complication given the security most of the new fixation devices tailored to immature ACL reconstruction. The position of a suspensory button or toggle device that flips can be confirmed with fluoroscopy to make sure it is fully deployed on the outer surface of the bone. Care should be taken to not over pull these devices once outside the bone tunnel because they could deploy on the surface of the iliotibial band, which can cause graft laxity. If there is any question of graft fixation security, then it is best to reinforce with a post/washer or staple device at the time of surgery. Graft tension should be carefully inspected arthroscopically and with the Lachman's test after fixation. If not guitar-string tight, the fixation device should be removed, the graft re-tensioned, and then re-fixed. Occasionally an outside-in interference screw, which is popular with all-epiphyseal techniques in the femur tunnel, will push the graft into the tunnel and create laxity.

Physical therapists worry about "stretching out" the graft. The author believes that physical therapy would be a rare cause of graft stretch. The author feels this is most likely caused by improper graft preparation (suture or knot slippage) or insecure fixation. The author worries that in children under 8 years of age, and those with congenital, syndromic, or neuromuscular causes of their ACL deficiency can have osteopenic bone. The author will often place these patients in an above knee walking cast for about the first 6 weeks.

Infection

A septic knee with an ACL graft in place is a rare but serious complication. Because the harvested graft has absent or minimal blood supply in the early postoperative period, it is at high risk of being ravaged by the joint infection. Any sign of infection such as fevers, increasing pain, and swelling/stiffness should be aggressively worked up with a CBC and diff, ESR, CRP, a joint aspiration, and an urgent knee arthroscopic washout. The tibial graft harvest/tibial tunnel incision can be infected without infecting the knee joint, but an initial tibial graft site infection can spread into a septic knee. After knee washout, the author recommends treating with IV antibiotics due to the avascular graft which acts as a foreign body. High gradients of antibiotics are necessary to diffuse into the infected graft that usually is not perfused. Once the CRP has normalized then the patient may switch to oral antibiotics. Chronic or resistant infection that does not respond to washout and antibiotics may require graft removal. Occasionally a sterile inflammatory reaction to a bio-absorbing interference screw can mimic a postoperative infection, but in these cases infection needs to be aggressively ruled out.

Stitch reactions with localized cellulites are common over the anterior knee incision and can be treated with oral antibiotics and local would care. A randomized controlled study showed that standard arthroscopy portals do better with steri-strips rather than a suture, due to the high incidence of stitch reactions.

Pain and Nausea

Pain and nausea are common complications in the immediate postoperative period. Multimodal anesthesia and long-acting femoral and sciatic pain catheters can carry a patient through the difficult first 3–7 post-op days. Pre-emptive Celebrex, Neurotin or Lyrica, Clonidine, and Scopalamine can minimize post-op pain, and the need for post-op opiates. Intraoperative IV Tylenol, Toradol, and Zofran can supplement and minimize the need for narcotics and their associated nausea. Femoral and sciatic single shot nerve blocks work well in the first 12–24 h postoperatively and femoral and sciatic catheters can make the first 3–4 days much more comfortable. Ultrasound guided blocks/catheters may minimize the risk of intra-neural injection of local anesthetic. A recent retrospective study on pediatric ACL reconstruction patients who underwent femoral nerve block showed isokinectic but not functional deficits at 6 months postoperatively [37].

Wound Problems

Wound dehiscence should be a rare complication given the small incisions. Stitch abscess or stitch reaction are common problems and are minimized by avoiding subcuticular stitches and excessive stitches. The author tries to close the graft harvest incisions with a single deep 2-0 inverted PDS suture and two inverted subcutaneous Vicryl sutures followed by wound tapes. With a stitch reaction, if there is no sign of infection, then local would care with wet to dry saline dressing changes should suffice.

Hematoma occurrence can be minimized by not closing all the portals to allow egress of fluid/hematoma. Steri-strips are superior to suture closure of arthroscopy portals. A tense hematoma can be aspirated using sterile betadine preparation and draping, but smaller hematomas will spontaneously resolve with incident.

DVT/PE Younger patients have a much lower incidence of DVT/PE than teenagers and adults. The author will use either aspirin or low molecular weight heparin as prophylaxis in children with risk factors of obesity, a family history of DVT/PE, smoking, or oral birth control pills. These risk factors should be low in the skeletally immature ACL patient. The author obtains a duplex flow leg ultrasound on any patient that complains of calf pain postoperatively.

Nerve CRPS/RSD Children as young as 10 can exhibit signs of complex regional pain syndrome (CRPS)/reflex sympathetic dystrophy (RSD). The three cardinal signs are allodynia, swelling, and vasomotor changes. CRPS/RSD needs to be identified early and initial treatment is physical therapy with contrast, desensitization, and sensory processing and pain control modalities. The author will add Neurontin starting at 100 mg 1 h before bedtime for the first 3 days, advance to 200 mg QHS for the next 3 days, then 300 mg QHS thereafter. Depression and suicide ideation contraindicate Neurontin, so the author queries the patient and parent about these issues before prescribing. The author refers severe or refractory patients to pediatric anesthesia pain service where they see an anesthesia pain physician, a pain physical therapist, and a psychologist.

Nerve injury should be a rare complication. The author forewarns the patient that saphenous nerve leg numbness can be a complication of hamstring graft harvest. This complication may be diminished with an oblique versus a vertical skin incision [38]. The common peroneal nerve is at risk for injury during lateral meniscal tear repair, especially with the inside-out technique of the posterior horn. The author recommends an open lateral counter incision with careful dissection between fibula collateral ligament and biceps femoris tendon and the placement of a protective spoon under the lateral gastrocnemius tendon just outside the joint capsule. Inside-out meniscal repair has a very high risk of needle stick injury to the surgeons and the assistants.

Intra-neural local anesthetic injection is also a cause for postoperative numbness or neuralgia. This risk may be decreased with ultrasound guidance of nerve blocks and nerve indwelling catheters.

Hardware Complications

Bioabsorbable screws can cause a reaction of synovitis in some patients which may resemble an infection and cause a sterile joint effusion. Even worse, the screw may cause a localized bone reaction that may cause bone resorption (tunnel widening) which inhibits tendon to bone incorporation and can lead to graft fixation failure.

Bio-screws are also more prone to breakage than metal and the surgeon must make sure that the screw is loaded on the proper insertion screwdriver. Most screw sets have 2–3 screwdrivers that get progressively larger for increasing sizes of screws. The surgeon must confirm that the surgical scrub nurse or technician has mounted the screw on the largest screwdriver that will fit in the screw. If a smaller screwdriver is used, the screw will slip or even crack on the screwdriver during insertion.

Metal screws can cut the graft during insertion and should be used with care against a soft tissue graft and the tendon portion of a patellar or quad tendon graft. The author prefers metal screws over bio-screws for the fixation of patellar tendon or quadriceps tendon bone blocks.

The author has patients avoid NSAIDs in the first postoperative week out of fear that the anti-osteogenic properties may inhibit graft incorporation into bone tunnels.

It is important to make sure that tibial interference screw fixation is flush or countersunk beneath the tibial surface to avoid postoperative prominence. Some screw devices are 30 mm long, so it is important to make sure that the bone tunnel is of adequate length, especially in the tibia, so that the screw does not protrude into to the joint or out the anteromedial surface of the tibia or on the lateral surface of the femoral epiphysis for all-epiphyseal tunnels.

The graft harvest site can be problematic with occasional hamstring harvest injury to the saphenous nerve causing numbness over most of the anterolateral tibia. Children rarely have neuromas but these can be treated with nerve repair, or excision of the neuroma. Patella tendon and quad tendon harvest can leave the patella prone to fracture. This complication may be diminished with bone grafting the harvest site with bone harvested from the proximal tibia.

Despite all the complications reported in this chapter, several large studies show that ACL reconstruction can be safely performed in children, adolescents, and teens. In children aged 10–17 the overall complication rates of ACL reconstruction are usually similar in those with open growth plates and those with closed growth plates [2, 39, 40].

In a systematic review of the literature researchers found that ACL reconstruction in youth athletes results in an improved rate of return to athletic activity when compared with nonoperative treatment [41].

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20 The Pediatric ACL: Tibial Spine Fracture

Keith R. Bachmann and Eric W. Edmonds

A textbook focused on anterior cruciate ligament (ACL) injury in pediatric patients would be incomplete without a diversion into tibial eminence fractures. Early reports of pediatric knee ligament injuries were sparse due to the prevailing thought that fibers of the ligament were stronger than the physis [1]. Thus, fractures of the tibial eminence have historically been given the moniker of the pediatric ACL equivalent; however, despite being typically associated with pediatric patients the injury does occur in adults. In fact, Neer described a series of 42 fractures in 1958 noting that 21 fractures were in adults [2]. Noyes' study on ACL failure in both maturing and mature primates sheds some light on the mechanism of failure wherein the creation of an avulsion fracture or mid-substance ACL tear was dependent on rate of deformation rather than maturity [3].

In the current environment where participation in sports at a young age and at heavy usage rates is increasing; sports injuries of the knee are becoming more frequent in a young age group. Despite this, tibial eminence fractures remain a somewhat rare entity. In 6 months of patients with traumatic knee effusions Luhmann only diagnosed one patient with tibial eminence fracture [4]. This therefore remains an important differential diagnosis but somewhat of a fringe entity when it comes to care of the pediatric ACL.

The fibers of the ACL insert onto the tibial eminence [5] (Fig. 20.1) and therefore with strain can result in an avulsion fracture of the tibial eminence. Fractures of the tibial eminence were first classified by Meyers and McKeever in 1959 [6, 7] in the scheme still commonly used today. The classification is based on a lateral radiograph of the knee and includes type 1 with marginal displacement of the anterior portion of the tibial eminence, type 2 with displacement of the ante-

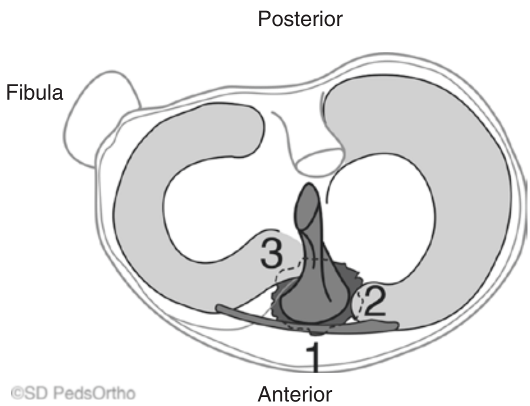

Fig. 20.1 Top down view of the tibial plateau demonstrating ligament insertions of the ACL anterior and PCL posterior as well as simulated fracture pattern demonstrating potential sources of entrapment: 1 = inter-meniscal ligament, 2 = anterior horn of medial meniscus, 3 = anterior horn of lateral meniscus

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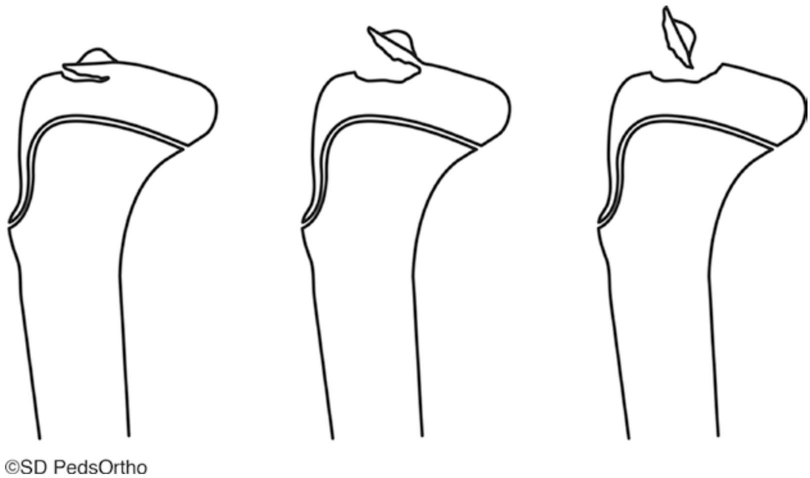

Fig. 20.2 Meyers and McKeever classification: type 1 marginal displacement of the anterior portion of the tibial eminence, type 2 with displacement of the anterior third to half of the tibial eminence but an intact posterior hinge, and type 3 the most displaced with no fragment continuity remaining

rior third to half of the tibial eminence but an intact hinge of bone posterior, and type 3 the most displaced with no fragment continuity remaining. They also advocated a type 3+ where the avulsed fragment rotated. Zaricznyj in 1977 added a type 4 to allow for comminution of the fracture fragment [8] (Fig. 20.2).

The standard of care at that time included open reduction and fixation with stainless steel pull through wire. Meyers and McKeever felt these injuries were being over-treated: their fixation consisted of a simple suture into the meniscus after open reduction. They advocated nonoperative treatment for types 1 and 2 with hemarthrosis aspiration and long leg cast application. They were opposed to reduction in extension as the eminence does not articulate with the condyle and hyperextension might put the ACL on tension worsening the displacement. They would aspirate the fracture hematoma and then place the patients in a long leg cast with the knee in 20 degrees of flexion for 6–12 weeks. They suggested that the knee would regain its motion 3 months after cast removal. There have been advancements in musculoskeletal care since those original descriptions, and these advances tend to push the need for stable fixation in order to advance early rehabilitation. Other important factors associated with the treatment of tibial eminence fractures include operative versus non-operative care, open or arthroscopic procedures, fixation type, residual laxity, and complications such as arthrofibrosis.

Evaluation

The evaluation of a tibial eminence fracture begins as an evaluation of a patient with knee pain and likely effusion after an injury, most commonly either hyperextension and femur rotation such as attempting to stop abruptly on a bicycle and sporting injuries or a direct blow to the femur with a flexed knee [9]. Radiographic evaluation should proceed first to ensure there are no other skeletal injuries and then distal neurovascular function should be assessed to ensure that the hyperextension did not injure the popliteal artery or nerve. Varus and valgus stress can be applied to ensure the collateral ligaments are intact but with radiographic diagnosis of a tibial spine fracture Lachman and anterior drawer testing should be avoided. In a low energy injury patient it is uncommon for there to be other ligamentous injuries although associated meniscal pathology is common [10–12]. In a higher energy injury such as a pedestrian struck by a motor vehicle multiple ligament injuries may be seen [1].

Plain radiography establishes the diagnosis of tibial eminence fracture and the Meyers and

Fig. 20.3 Lateral radiograph demonstrating type 2 tibial eminence fracture

McKeever classification can be established (Fig. 20.3). In a recent study, measurement of fracture displacement was found to be consistent between plain films and CT scan with a difference of 1 mm between modalities [13]. Therefore, the authors concluded that advance imaging may not be necessary to evaluate displacement, but that there could be a need for MRI to establish an association of other injuries, such as meniscus tear or articular extension of the fracture.

Early clinical and MRI studies [14] noted meniscal pathology in adult injuries but considered associated pathology rare in children. More recently MRI studies [10–12] have found rates of 30–40% of meniscal tears as well as meniscal entrapment and bone contusion to be present in association with tibial eminence fractures advocating for MRI evaluation. In these studies there were no associated meniscal tears or entrapment associated with type 1 fractures; therefore it remains logical that more displaced injuries are more likely to have associated pathology.

Kocher used plain radiographs in 2004 [15] to compare notch width index to see if this was predictive of whether the patient would suffer an ACL tear or a tibial eminence fracture. They found that on average the ACL tear group had narrower notch width indices (0.230 vs. 0.253, $p = 0.020$). However, Samora in 2015 [16] also evaluated notch width index and found no statistical difference between ACL, tibial eminence fracture, and controls, but did find that the intercondylar roof inclination angle was less, indicating a steeper intercondylar roof, in ACL tear patients compared to controls. Tibial eminence fracture patients had a flatter intercondylar roof as evidenced by a larger intercondylar roof angle compared to controls.

Our current practice includes MRI imaging on borderline cases with displacement close to 5 mm on plain film that would not otherwise be treated operatively. If the displacement is more than 5 mm after any attempted reduction, then we proceed with operative reduction in order to minimize risks in outcomes. Associated injuries are then evaluated and treated at the time of surgery without the need for preoperative advanced imaging.

Meniscal Entrapment

Noted above there is an association with entrapment of the meniscus causing residual displacement or blocking reduction. The typical culprit is the medial meniscus (Fig. 20.4) although intermeniscal ligament and lateral meniscus have also been reported [17, 18]. While this is debated by some authors [19], others report rates of 26–30% entrapment of meniscus in type 2 fractures that do not reduce in extension and 48–65% of type 3 fractures [10, 17]. Edmonds and colleagues found a rate of 32% meniscal entrapment in their comparative study, and case reports

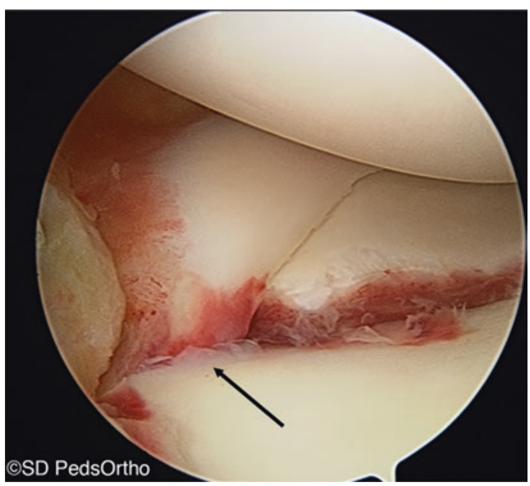

Fig. 20.4 Arthroscopic image showing tibial eminence fracture with entrapped anterior medial meniscus as a block to reduction

and series have been published highlighting this entity including 9 out of 10 entrapped medial menisci in a series by Mah [20–23]. These numbers validate an operative strategy involving any fracture with residual displacement, whether classified as type 2 or 3.

Operative Approach

Once the decision is made to operate the approach must be decided. Residual laxity and arthrofibrosis are common complications of operative intervention for tibial eminence fractures. Early reports involved open reduction with or without fixation. McLennan in 1982 demonstrated that arthroscopic reduction and pin fixation could be an effective treatment for type 3 fractures [24]. There have been 3 comparison studies of open and arthroscopic management of tibial eminence fractures. Melzer et al. found that 14 arthroscopic and 14 open reduction patients resulted in similar isokinetic evaluation of knee joint musculature with a slight decrease in extensor muscle strength [25]. Watts, Larson, and Milbrandt in a recent study found that the main factors contributing to arthrofibrosis were delayed time to surgery >7 days and prolonged operative time >120 min; and although their study was likely underpowered to perform this multivariable analysis, their conclusion that surgeons should approach these fractures in whatever manner they can achieve comfortably and efficiently is likely a good one [26].

The aforementioned study by Edmonds et al. found that the amount of reduction obtained open versus arthroscopic was similar (means: 9.1 mm and 8.6 mm, respectively) and both methods were able to obtain a statistically significant better reduction than closed treatment (mean: 2.3 mm). There was a similar rate of arthrofibrosis between the two surgical methods (ORIF 11.1%, Arthroscopic 12.5%) and there was no arthrofibrosis in the closed management group although the closed management group had a 16.7% risk of need for future operative intervention [13]. This study also highlighted the risk of arthrofibrosis as two patients suffered physeal fractures during manipulation of arthrofibrosis. From these studies it seems that the outcomes achieved are not dependent on open or arthroscopic approach to the fracture. Once again, it appears that the approach can be dependent on surgeon preference between open and arthroscopic techniques.

Fixation

The overwhelming majority of literature regarding tibial eminence fractures consists of case series focusing on the type of fixation best utilized [27–64]. This includes suture anchors, suture-button suspensory devices, meniscal pin fixation devices, no fixation relying on tucking the fracture fragment under the inter-meniscal ligament to maintain reduction, screws, and series utilizing a combination of these fixation methods. All of these series demonstrate the technique of the authors and demonstrate good results validating the fixation choice.

The biomechanical testing of these fixation types has yielded a variety of results regarding fixation performance. Bong in 2005 compared three strands of #2 Fiberwire sutures vs. a 4.0 mm cannulated screw in 7 matched pairs of fresh frozen human cadaveric knees with a mean specimen age of 76.8 years [65]. Simulated fracture was performed with an osteotome and then fixed so that each cadaver received both fixation methods, one in each knee. These specimens were then loaded at 20 mm/min to failure. The mean ultimate failure load in the Fiberwire group at 319 N was significantly higher than the screw fixation at 125 N. The mean stiffness was not statistically different with Fiberwire 63.0 N/mm and screw 49.9 N/mm. The screws all failed by pullout of cancellous bone representing an issue with using older cadavers to test methods of fixation and translating to use in teenagers with improved bone mass.

In 2007 Eggers et al. evaluated 1 screw, 2 screws, 1 mm Ethibond and #5 (0.8 mm) Fiberwire in a pig model [66]. They found that the Fiberwire had the highest initial stiffness when loaded to failure, the Ethibond and both screw groups were similar indicating that a second screw did not add any stiffness to the construct. After 1000 loading cycles to simulate early postoperative ambulation only 3 of 8 specimens in both screw groups survived while all 16 of the specimens in the two suture groups were intact with 2.7 mm displacement in the Ethibond group and 1.3 mm displacement in the Fiberwire group. The specimens were then loaded to failure after the cyclic testing and found to have similar yield loads. Taking into account the failures during the cyclic loading this group favors suture fixation with Fiberwire based on the ability to withstand trauma during initial rehab as indicated by the initial stiffness as well as maintain reduction during cyclic loading such as during postoperative rehabilitation.

Mahar et al. in 2008 used bovine specimens to compare #2 Ethibond sutures, 3 resorbable nails, 1 resorbable screw, and 1 metallic screw and found no statistically significant difference in initial stiffness or ultimate failure force between cohorts [67]. They did find that after 200 cycles of loading there was 1 mm more displacement in the suture fixation and resorbable screw group when compared to the resorbable nails and metal screw group indicating possible clinical significance of increased laxity.

Aoki in 2011 found that at least 2 strands of #2 Fiberwire would place ultimate failure load above 500 N which they felt was a goal threshold for physiologic ACL stresses during walking [68]. Sawyer in 2012 noted statistically significant higher ultimate load (340 N) with a suture bridge construct using anchors compared to a 3.5 mm cannulated screw and a single #2 Fiberwire suture [69]. The displacement after cyclical loading was not found to be statistically significant. Anderson in 2013 evaluated physeal sparing methods of fixation and found that two strands of #2 Fiberwire tied over a suture button is biomechanically superior to 4 strands of #0 PDS suture button and a single 3.5 mm cannulated screw with higher median yield load, 100% survival after 1000 loading cycles, less median creep after 1000 loading cycles, and a higher median peak failure load after cyclic testing [70]. They also tested two suture anchors loaded with 2 strands each of #2 Fiberwire finding wider inter-quartile indexes indicating less consistent fixation although median ultimate load to failure was similar to the FiberWire suture button. They advocate Fiberwire tied over a suture button despite their initial hypothesis that suture anchors would provide the best fixation. These studies overall highlight that suture fixation provides stronger initial fixation and performs well under cyclical loading that will result from early rehabilitation.

Suture configurations often involve tying the suture over a post in the tibia. There are concerns for physeal tethering if nonabsorbable suture is left tied across the physis. Schneppendahl in 2013 investigated absorbable suture material (#5 Vicryl and #2 PDS) compared to #5 Fiberwire and found that PDS failed to reach a steady state during cyclical testing with 4 of 6 specimens suffering elongation of more than 2 mm [71]. After 200 cycles at up to 150 N they tested the Fiberwire and Vicryl to failure and found a statistically significant performance of the Fiberwire 306 N compared to 220 N for the Vicryl. Their conclusion however is that with the performance during cyclical testing Vicryl could be used as a bioabsorbable alternative to Fiberwire for suture fixation but that PDS should be avoided.

Suture comparison has also been performed clinically: Brunner et al. in 2016 looked at absorbable suture versus nonabsorbable suture tied over a post in a retrospective comparison and found no significant difference in IKDC score, Lysholm scores, and rolimeter testing between the two groups [72] (Fig. 20.5). There were three cases of arthrofibrosis in the absorbable suture fixation group and only one in the nonabsorbable tied over a post; however, all three arthrofibrosis in the absorbable suture group had a delay of at least 4 weeks prior to surgery and preoperative loss of motion. Eight out of 10 patients required removal of the post in the nonabsorbable group highlighting a major benefit of the nonabsorbable suture group. Liao et al. also in 2016 compared nonabsorbable sutures to absorbable suture anchors and found no significant difference comparing Lysholm and IKDC post-op scores. There was no arthrofibrosis reported in either group and there were three total cases of residual laxity with

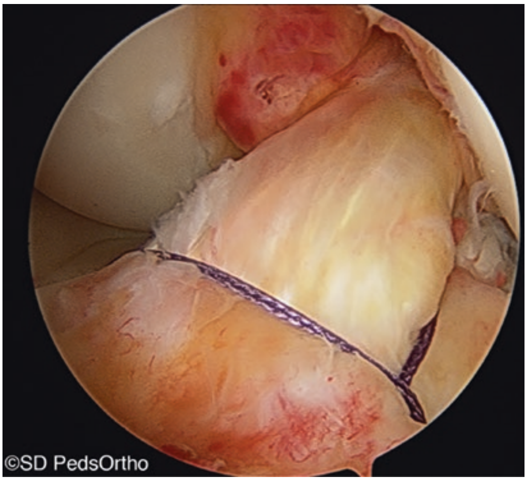

Fig. 20.5 Arthroscopic image after reduction and fixation with Vicryl suture

no difference in Lachman testing between the two groups.

The results of the biomechanical studies as well as the clinical tests demonstrate that suture fixation of a tibial eminence fracture yields reliable healing of the fracture with no need for hardware removal. The biomechanics of screw fixation are less clear with some studies finding suture fixation superior and others finding less fragment displacement with screw fixation and advocating fixation method choice being left up to the treating surgeon.

Outcomes of Treatment

Current narrative within published reports on this fracture type has tended to include more operative fixation than conservative management, to note objective laxity despite subjective stability, and to focus on arthrofibrosis as the least desirable outcome. Yet, the initial case series by Meyers and McKeever as well as Zaricznyj advocated operative treatment for only the most displaced type 3 fractures [6–8]. In 1981, Molander reported on 35 patients noting that only 3 underwent operative intervention and other than healing with a noticeable prominence on radiographs, the nonoperative patients did well [73].

The late 1970s and early 1980s began to change the discourse on tibial eminence fracture outcomes. Initial reports in the Italian trauma literature began to highlight residual instability. Smith in 1984 [74] identified a patient treated 2.5 years previously for tibial eminence fracture who subsequently presented with residual instability, serving as a sentinel event within his practice. Historical commentary suggested that this was not an issue with some authors reporting good outcomes with even ACL excision as part of the treatment: 2 patients in Neer's series and 3 in Meyers and McKeevers. Smith subsequently reviewed 15 patients of which 12 had type 3 injuries and underwent open reduction and internal fixation. In his series, only seven patients were completely free of symptoms. The other eight reported mild activity related pain and some avoidance of certain activities such as direction changes or skiing. On examination all had normal range of motion, four had atrophy of the thigh measured by thigh circumference compared to the contralateral thigh. One patient had a positive pivot shift, 11 had a positive anterior drawer test and 13 had a positive Lachman test.

In 1988 Baxter and Wiley reported on 45 patients 3–10 years after tibial eminence fractures. In their cohort of 32 total patients, they demonstrated a mean difference of 3.5 mm on anterior drawer testing whether treated by closed reduction or open reduction. There was no varus or valgus instability except in patients who had been pedestrians struck by an automobile. There was loss of full extension in 27 patients and 23 patients had a positive anterior drawer test; none of the patients complained of knee instability although 29 patients were aware of a difference between knees [75]. Willis, in 1993, performed clinical exam, KT arthrometer measurements, and subjective evaluation at a mean follow-up of 4 years and found 64% clinical instability, 74% objective instability, 10% complaints of pain, but no complaints of instability in 50 patients. Moreover, they found no difference in rates of instability whether treated closed or open [76].

In a report from 1995, McLennan performed second look arthroscopy on 10 patients with type 3 tibial eminence fractures. He found a correlation with the best function (based on Lysholm ratings, Tegner levels, and IKDC grade) and improvement in displacement with treatment by open reduction and fixation. The cohort that had undergone open reduction alone did not fair as well, but those treated by closed methods only had the worst overall outcomes in all rating scales. He concluded that open reduction and internal fixation should be performed for type 3 tibial eminence fractures [77]. Also in 1995 Janarv looked at mean 16 year follow-up for 61 patients and found 87% excellent or good knee function based on Lysholm score and no reports of poor subjective knee function despite a rate of 38% laxity among the cohort. They do note in their discussion that only five subjects had a Tegner score greater or equal to seven and only five subjects stated they had a lower level than desired on Tegner. They note that whether conscious or unconscious the patients who suffered tibial eminence fractures performed at a lower activity level making high satisfaction scores easier to achieve for these patients [78].

More recently Kocher [79] examined six children after arthroscopic reduction and fixation with a 3.5 mm cannulated screw and found 5 of 6 patients had an abnormal Lachman examination, 4 of 6 demonstrated differences in KT-1000 testing greater than 3 mm side to side and 2 of 6 patients had an abnormal pivot shift. Despite these findings of laxity the mean Lysholm score was 99.5, mean Tegner score was 8.7, and the mean Marshall score was 49. All of these studies point to excellent clinical results despite instrumented or other objective signs of ACL laxity after fixation.

A more recent study by Mitchell and colleagues used surveys to locate 73 patients from a 20-year span who were treated for tibial eminence fracture and found a 19% rate of subsequent ACL reconstruction [80]. There were no statistically significant associations with fracture classification, sex, or mechanism of injury and need for future ACL reconstruction. They did find increasing age at time of initial injury to be predictive of future ACL reconstruction with odds ratio of 1.3 for each year of age. Interestingly in their study, they had three patients with Meyers-McKeever type 2 fractures who went on to ACL reconstruction due to residual laxity after closed treatment without any further knee injury. All other patients who went on to ACL reconstruction had another traumatic event.

This present literature demonstrates that the overall satisfaction and stability afforded the knee after healing of a tibial eminence fracture is subjectively excellent in those patients treated for tibial eminence fractures. There is residual laxity, whether due to stretch of the ligament prior to failure of the bone, or displacement of the healing fragment it is not known. Across various methods of fixation however residual laxity occurs without notice from the patient.

Complications/Arthrofibrosis

Residual laxity may be considered a result of the injury, but arthrofibrosis resides at the other end of the spectrum and is more truly a complication of treatment. In a report in 2010 Vander Have and colleagues reported data from four pediatric centers compiling 32 patients with arthrofibrosis after fixation of a tibial eminence fracture [81]. All patients underwent operative stabilization with 28 undergoing arthroscopic reduction and fixation with sutures or screws, three patients underwent open reduction and internal fixation with a screw and one patient underwent closed reduction and pin fixation. Twenty-four patients underwent arthroscopic lysis of adhesions with adhesions identified in all patients. Eight patients underwent manipulation under anesthesia and three of these patients suffered distal femoral physeal fractures and two went on to growth arrest subsequently becoming two of the three patients who never regained full motion. The other 29 patients at 1 year had motion within 5 degrees of the contralateral side.

Patel and colleagues, in 2012, found that mobilization within 4 weeks of definitive treatment limited the risk of developing arthrofibrosis [82]. This included patients treated nonoperatively although none of those patients went on to develop arthrofibrosis. A similar result was found in the comparative study by Edmonds et al.

that found arthrofibrosis only in the surgically treated patients at a similar rate whether treated arthroscopic or open [13]. Of note, the period of immobilization was similar across both operative groups and the closed reduction group in this series and all three groups were immobilized for a mean duration of just over 4 weeks. Watts found delayed surgery more than 7 days from injury and prolonged operative time longer than 120 min to be predictive of the risk of arthrofibrosis [26].

Parikh et al., in 2014, detailed aggressive management of postoperative stiffness intervening at the time of screw removal (Fig. 20.6) for both intra-epiphyseal and trans-epiphyseal screws [83]. The epiphyseal screw group was indicated for screw removal based on loss of terminal extension or hardware prominence while all of the transphyseal screws in skeletally immature patients were removed. A third of the epiphyseal and transphyseal screw patients underwent removal of screw and debridement of scar tissue in the notch. At final follow-up there was no arthrofibrosis noted and there were no cases of growth disturbances from temporary transphyseal screws. Kocher recently detailed pediatric patients being treated with dynamic splinting including 21 patients after tibial spine fracture and noted 58% success in avoiding manipulation or lysis of adhesions in the total cohort [84].

Fig. 20.6 AP and Lateral radiograph after open reduction and internal fixation with screw fixation

Loss of extension could be due to malunion of the fracture (Fig. 20.7). If epiphyseal screw does not achieve adequate purchase during fracture fixation, it should be replaced with transphyseal screw. This would help avoid loss of reduction and resultant malunion [83]. The strength of fixation is also important so that early postoperative mobilization can be performed to attempt to limit the risk of arthrofibrosis. Should arthrofibrosis occur, treatment should consist of physical therapy and dynamic splinting if desired; but, operative management should include only arthroscopic lysis of adhesions. Avoidance of manipulation without debridement is advised, given reports of at least five physeal fractures as a result of this treatment method.

Arthrofibrosis is the number one complication in surgical series, but special attention should be shed on physeal injuries related to treatment of these injuries. There are three reports in the literature, the first was by Ahn in

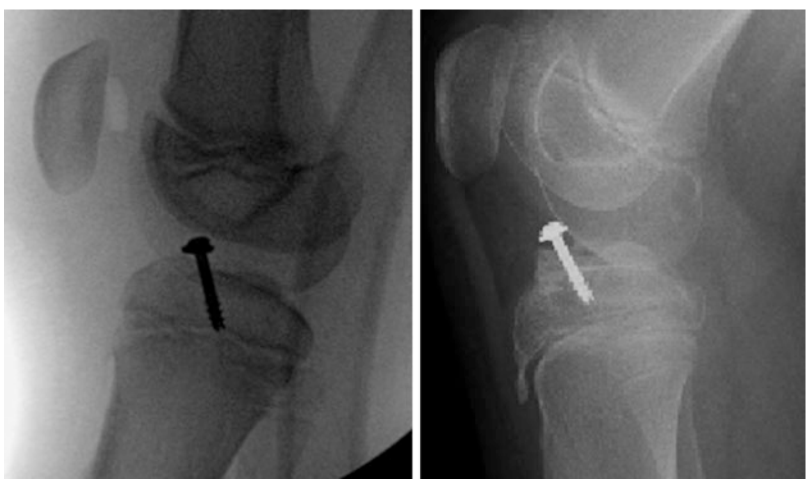

Fig. 20.7 Lateral fluoroscopy image shows internal fixation with an epiphyseal screw. At follow-up, the screw has backed out leading to a malunion of the fracture (Courtesy: Shital Parikh, MD)

2005 who noted a 6 year old with 10 degrees of genu recurvatum compared to the contralateral side after suture fixation of a tibial spine fracture [85]. She and another patient in the series also had leg length discrepancy of 1 cm with the operative limb being long. Mylle, in 1993, noted a patient with 25 degrees of anterior tibial slope after an anterior growth arrest due to a transphyseal screw in the anterior portion of the tibial physis [86]. Fabricant in 2011 reported on the need for growth modulation with tension band plating after an iatrogenic valgus deformity of the proximal tibia was formed after transphyseal screw fixation obliquely into the lateral portion of the proximal tibial physis of a tibial eminence fracture [87]. The effect on growth seems to be based on tethering rather than damage to the physis as transphyseal screws when removed in the first months after fixation have not shown any growth disturbance [83].

Conclusions

Fracture of the tibial eminence remains a relatively uncommon injury. Despite historical consideration as the pediatric equivalent of an ACL tear, most physicians who treat children and adolescents much more commonly see mid-substance ACL tears than a tibial eminence fracture. At the senior author's institution treatment now involves initial evaluation with plain radiographs. Type 1 fractures are treated with weight bearing as tolerated within a long leg cast for 4 weeks, followed with range of motion exercises after removal. Type 2 fractures if displaced more than 5 mm undergo attempted closed reduction in extension. If the residual displacement is near 5 mm MRI is obtained to evaluate for concomitant injury or meniscal entrapment that may indicate a need for surgical treatment. Fractures with residual displacement more than 5 mm on plain film, type 3 and 4 injuries are all treated with open or arthroscopic reduction (based on surgeon preference). Careful inspection at the time of surgery for incarceration of anterior meniscal horn or inter-meniscal ligament serving as a block to reduction is paramount to fracture reduction. Fixation can be achieved with nonabsorbable or absorbable (Vicryl) suture material or screw fixation depending on surgeon preference, and comminution of the fragment. Depending on the child's age, the postoperative regimen involves either a cast (in the younger cohorts) or a hinged knee ROM brace in the older cohort. Casting is used for 3–4 weeks followed by physical therapy to assist with range of motion. If a hinged knee brace is utilized, and fixation was felt to be secure, then range of motion activity is begun at 1 week post-op to help prevent arthrofibrosis. As with any treatment involving the growth plate (particularly with the fixation method in this fracture type) consideration for iatrogenic growth disturbance should be considered and monitored during treatment.

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21 Femoral Avulsion Fracture of ACL

Shital N. Parikh

Femoral avulsion fracture of ACL, in contrast to tibial spine avulsion fracture or proximal ACL tear, is a very uncommon injury. By definition, femoral avulsion of ACL would imply an osteochondral or chondral avulsion fracture of ACL from its femoral attachment site. This chapter is a review of literature to discern pertinent findings related to femoral avulsion fracture of ACL.

In 1989, Angel and Hall reported on 27 children and adolescents with ACL tear [1]. At arthroscopy, 2 of 27 patients had femoral avulsion of ACL. One underwent suture repair in an over-the-top position and the other was treated conservative. At follow-up, both patients had returned to sporting activities without limitation. No further information like age and gender, mechanism of injury, radiographic analysis, or surgical techniques were available from this report. Also, it is not clear if femoral avulsion injury in this report meant bony or cartilaginous avulsion of ACL or a proximal tear of ACL. The older literature is deficient due to lack of detailed reports on such injuries. Prior to this report, there were two cases of femoral avulsion of ACL reported in the literature (Table 21.1) [2, 3].

Biomechanically, it is unknown as to why an ACL avulsion fracture from the femoral side is so rare, compared to an ACL avulsion fracture from the tibial side which is relatively common. Possible causes of these different patterns of injury could be related to the ACL insertional characteristics and to the magnitude, direction and rate of force exerted on the ACL. Most cases in the literature are secondary to a violent injury with forceful flexion of the knee and internal rotation or abduction of the lower leg. In few cases, the leg was caught while patient had a fall from a height. Table 21.1 lists the cases reported in the literature related to bony or cartilaginous avulsion fracture of ACL from the femoral side in skeletally immature patients. We excluded five cases of femoral ACL avulsion fractures in adults [4–8]. The avulsion injury could be missed on routine AP and lateral radiographs [3] or it may be misdiagnosed as ACL tibial avulsion fracture [9]. The notch view appears to be diagnostic for an ACL bony avulsion fracture from lateral femoral condyle. With current widespread use of MRI in patients with traumatic hemarthrosis, the injury is unlikely to be missed. Most patients have been treated with a knee arthrotomy, suture through the proximal ACL stump and pull-through from the lateral condyle using two drill holes. The drill holes have been placed either in the epiphysis or through the physis (transphyseal). The sutures have been tied over a bone bridge or around a post. An ACL guide may help to make the drill holes in the bed of the injury. In the last decade, few cases of arthroscopic assisted fixation have been reported. The outcomes

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Table 21.1 Case reports of femoral avulsion of ACL in skeletally immature patients

Reference	Age (years)	Gender	Mechanism	Diagnosis	Other injuries, comments	Treatment	Follow-up
Robinson and Driscoll [2]	13	M	Motorbike	Notch X-ray	Tibial avulsion Fx, MCL tear	ORIF, sutures	12 m
Eady et al. [3]	7	F	Fall from monkey-bars, leg caught	Notch, lateral X-ray		ORIF, sutures	15 m
Wasilewski and Frankl [10]	12	M	Fall from bus	Notch X-ray		ORIF, sutures	132 m
Corso and Whipple [11]	3	M	Not known	Arthroscopy	Cartilaginous piece	Cast in 10° flexion	2.5 m
Tohyama et al. [12]	14	M	Skiing	Notch, MRI	Past Tibial avulsion Fx	ORIF, sutures	24 m
Kawate et al. [13]	3	M	Fall from merry-go-round, leg caught	Lateral stress X-ray, arthroscopy	Cartilaginous piece	ORIF, stainless steel wire	156 m
Lakshmanan et al. [14]	11	F	Skiing	MRI		ARIF, sutures	13 m
Edwards et al. [15]	11	M	Twist in rugby	X-rays, MRI		ORIF, sutures	24 m
Bengston and Giangarra [16]	10	M	Tackle in football	MRI, CT	Comminuted piece	ORIF, sutures	24 m
Pai et al. [9]	11	M	Fall from roof	Arthroscopy	Distal fibula fx	ORIF, sutures	6 m
Wardle and Haddad [17]	11	F	Fall from tree	MRI, CT		ARIF, tightrope	30 m
Langenhan et al. [18]	14	F	Sports injury	X-rays, MRI		ARIF, K-wire	24 m

have been satisfactory and no reported cases have subsequently required an ACL reconstruction.

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The Role of Primary Repair in Pediatric Anterior Cruciate Ligament Injuries

22

Jelle P. van der List and Gregory S. DiFelice

Introduction

Injury of the anterior cruciate ligament (ACL) was considered to be rare in the pediatric and adolescent population in the twentieth century. However, with the increase in sports participation of this patient population, and the greater clinical awareness along with modern diagnostic imaging [1–4], the incidence of ACL injuries has increased over the last decades in this population [5]. It is now estimated that ACL injuries represent a third of all knee injuries in this population [3, 5, 6]. The standard treatment of ACL injuries is single-bundle reconstruction, but this treatment has significant potential disadvantages, such as high failure rates [7, 8], growth plate damage with subsequent growth retardation [9], and inadequate prevention of osteoarthritis [10, 11]. Over recent years, there has been an increase in popularity for arthroscopic primary repair of ACL tears in the adult population, and this treatment is also well suited for pediatric patients. The treatment is minimally invasive, no or only small tunnels need to be drilled nor grafts harvested, and the growth plate is not violated. Furthermore, the native tissues and proprioception are preserved, and no bridges are burned for a possible future reconstruction surgery, if the repair happens to fail. It is therefore not surprising that recently several reports and case series of arthroscopic primary repair in pediatric patients have shown promising results [4, 12, 13].

In this book chapter, we first discuss the history and recent resurgence of primary repair that initially occurred in the adult population but is also important for understanding the role of primary repair in pediatric patients. Then, we will discuss the patient selection for this treatment, the advantages of this treatment, the surgical techniques with case examples, and the outcomes of arthroscopic primary repair in pediatric patients that have been reported in the recent literature.

History of Open Primary Repair

The first surgical treatment of an anterior cruciate ligament (ACL) injury was performed in 1897 by Mayo Robson and consisted of open primary repair [14]. He noticed that the ACL and posterior cruciate ligament (PCL) were both torn off the femoral wall, stitched both ligaments back to the femur using catgut ligatures, and reported excellent outcomes at 6-year follow-up. Over the ensuing decades, the acute treatment of open primary repair was further popularized by Ivar Palmer in the 1930s and 1940s [15, 16] and Don O'Donoghue in the 1950s and 1960s [17, 18].

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In the 1970s and early 1980s, several authors reported promising short-term results of open primary repair [19–22]. Feagin and Curl, however, noted that the encouraging short-term results deteriorated at midterm follow-up [23]. Similarly, others also noted deterioration of their results at midterm follow-up in both the adult [24–26] and adolescent population [27]. Because several randomized and prospective studies in the late 1980s and early 1990s showed better results of augmented repair and ACL reconstruction when compared to open primary repair [28–32], the treatment of open primary repair was abandoned, and ACL reconstruction was adopted as the new standard of care for all patients.

In 1991, around the time that primary repair was abandoned [33, 34], Sherman et al. attempted to find an explanation for the deterioration in their midterm results [26]. Uniquely, they performed an extensive subgroup analysis and found a trend of better outcomes in patients with proximal (type I) tears and excellent tissue quality when compared to patients with midsubstance (type III or IV) tears and fair or poor tissue quality. Although several studies over the following years indeed reported excellent outcomes of open primary repair for proximal (type I) tears in the adult [35–37] and pediatric population [38], the treatment of open primary repair was ultimately abandoned, and ACL reconstruction became the gold standard in all patients.

Resurgence of Arthroscopic Primary Repair

Over the last two decades, many modern advances have contributed to the resurgence of interest in primary repair. First of all, magnetic resonance imaging (MRI) has been developed and improved, which enables the orthopedic surgeon to make a preoperative assessment of the tear location and tissue quality. Secondly, arthroscopic surgery has been further developed and improved, which permits confirmation of the tear location and tissue quality and ultimate repair of the tissues, using a minimally invasive approach. Finally, in the open primary repair studies, patients were immobilized in a long-leg cast for 4–6 weeks, while modern rehabilitation programs have shown that early range of motion (ROM) improves the outcomes and decreases the incidence of pain and stiffness [39, 40]. These improvements have led to the development of a modern technique of arthroscopic primary suture anchor repair for proximal tears. In 2008, the senior author (GSD) started using this technique for proximal tears, initially only in adults with low demands. After successful outcomes were noted, the senior author also started treating high-level athletes and pediatric patients of ages ranging from 8 to 57. Over the last 2 years, several studies with excellent outcomes following primary repair in adults [41, 42] and pediatric patients [4, 12, 13] have been reported.

Patient Selection

Tear Type and Tissue Quality

Learning from the historical literature on open primary repair, patient selection is critical for this technique. Several historical studies have taught us that midsubstance tears are not amendable for primary repair and that good outcomes can only be achieved in appropriately selected patients. Therefore, we have recently proposed a classification system of different tear types to identify which tear types can be treated with primary repair [43, 44]. These different tear types include type I bony (femoral) avulsions, type I proximal soft tissue avulsion tears (tear at >90% of distal to proximal length), type II proximal tears (75–90% of length), type III midsubstance tears (25–75%), type IV distal tears (10–25%), type V distal soft tissue avulsion tears (<10% of distal to proximal length), and type V bony (tibial) avulsion. Type I bony avulsions and type V bony avulsions can be treated with open or arthroscopic reduction with internal fixation if the bony avulsion fragment is large enough for screw or pin fixation [45]. In cases where the avulsion fragments are comminuted or too small for fixation, primary repair of the ligament is an excellent treatment option. Furthermore, type I and type V soft tissue tears are also excellent candidates for primary repair [43, 44] (Fig. 22.1, green zone). In patients with type II tears in which the length of the distal remnant is not long enough for reinsertion in the femoral wall, the senior author uses augmented repair with a soft tissue hamstring graft through the center of the ligament remnant, after which both are tensioned over a proximal button [43, 44]. Recently, Murray et al. reported on performing open primary repair using a biological scaffold for patients with type III tears, but clinical results have yet to be published [46].

MRI can be effectively used to make a preoperative assessment of the tear types, although the final decision for eligibility of repair is made during arthroscopy. We have recently performed a MRI study in which we assessed the distribution of the different tear types using this classification system and found substantial interobserver and substantial to nearly perfect intra-observer reliability [47]. In approximately 350 MRIs of adult patients with acute ACL tears, we have found that 16% had type I tears, 23% had type II tears, and only 2% had distal type V bony or soft tissue tears. In our unpublished data on pediatric patients, we have noted that femoral bony avulsion tear types are very rare, as we have not encountered this tear type in over 250 pediatric MRIs. Furthermore, it was noted that nearly all acute ACL tears were distal bony avulsion in pediatric patients of ≤10 years of age. In children aged 11–14, we noted that approximately 20% had type I avulsion tears and 20% had type V bony avulsions, while in patients aged 15–17, the pattern of tear type distribution was similar to adults [47]. Although these numbers may provide a rough estimation for the eligibility of a patient for primary repair, the final decision is still made during arthroscopy when the ligament is directly assessed. In adults, for example, it was noted that 90% of the type I tears on MRI were indeed eligible for repair (green zone, Fig. 22.1), whereas this was only 50% for type II tears (orange zone, Fig. 22.1) and 14% for type III tears (red zone, Fig. 22.1). It should therefore be emphasized that MRI can be used to make a preoperative assessment but that the final decision is made during arthroscopy. The most important criteria for eligibility for primary repair are (I) that sufficient tissue length is present to tension the remnant to the femoral or distal insertion and (II) sufficient tissue quality to hold stitches is present.

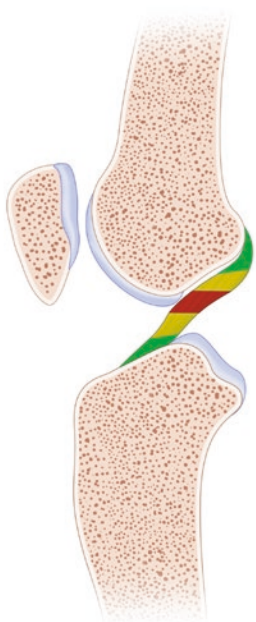

Fig. 22.1 This schematic drawing of the knee with the ACL shows the different ACL tear locations. The green zones indicate the location of tears on MRI that have a high chance of repairable tears, orange zones indicate a medium chance for repairable tears, and the red zone indicates a low chance of a tear that is repairable. Using these tear locations, a preoperative assessment can be made for the eligibility of primary repair of the ligament

Timing

Traditionally, primary repair was performed in the acute setting, as ligament retraction and absorption were reported to already occur after only a few weeks [17, 18]. As a result, several studies used strict time criteria, such as performing surgery within the first week [27]. However, when reviewing the recent case series on arthroscopic primary repair in pediatric patients, it can be noted that the days from injury to surgery ranged from 7 days to 123 days [4, 12]. Generally, surgery should not be performed in the first week after injury if the soft tissue swelling and inflammatory response in the knee are severe. With regard to delay, it is our belief that the tissue length and tissue quality are more important than the days of delay. The senior author has performed arthroscopic primary repair in patients that had a delay between injury and surgery of 4–11 years after injury [48], because these patients had sufficient tissue length and tissue quality. In cases such as these, it is most often in the case that the ACL has reattached to the PCL there by maintaining the tissue quality. Generally, however, the surgery is performed between 1 week and 3 months, as this has a lower risk for arthrofibrosis, while sufficient tissue length and quality are still present.

Advantages in the Pediatric Population

There are several advantages of primary repair for pediatric patients. Conservative treatment is sometimes performed in this population, but there is a high risk of meniscal and cartilage damage with conservative treatment [49, 50]. Primary repair is a minimally invasive surgery in which no tunnels (when using suture anchors) or only small tunnels (when tying over button) need to be drilled, no grafts harvested, and the procedure is relatively quick. Furthermore, the native tissue is preserved and the proprioception is maintained [51, 52]. As a result, in our practice, patients generally only need to use pain medication for 1 or 2 days, return to work or school within a week, return to full range of motion and can walk without a limp within 10 days to 2 weeks, and have a much quicker return to sports. In patients with previous contralateral ACL reconstruction, they describe that the repaired knee feels more normal and that the pain experienced and difficulty of recovery are significantly less, and they say that the knee feels better when compared to the other side. Finally, because high failure rates with ACL reconstruction are seen in pediatric patients [7, 8], surgeons should consider the impact of revision surgery [53]. Following failed primary repair, revision surgery is similar to a primary ACL reconstruction, as no or only small tunnels have been drilled and no graft has been harvested. Following failed ACL reconstruction, however, tunnels have been drilled, and there may be problems with widening of the tunnels, malpositioning of hardware, and harvesting of more graft tissue [54–56]. As a result, the outcomes of revision reconstruction surgery have been inferior to primary reconstruction [57–59].

Experimental Studies

Over the last decade, the research group of Murray has performed many experimental studies on primary repair, and some of these studies focused on the skeletally immature [60–63]. In these studies, they performed primary repair in which they used a biological scaffold around the repair that should protect the healing clot against the joint fluid. Murray et al. first assessed the role of skeletal maturity on ACL healing in Yucatan minipigs and found that a better healing response and better restoration of kinematics were seen in skeletally immature minipigs when compared to skeletally mature minipigs [60]. Furthermore, other studies from this group also showed that more growth factors, larger number of capillaries, and more fibroblast activity in the ACL were present in the skeletally immature pigs when compared to the mature pigs [61–63]. Interestingly, in another study with Yucatan minipigs, they found that following primary repair less posttraumatic osteoarthritis occurred when compared to ACL reconstruction [64]. This is especially of interest for pediatric patients, as ACL reconstruction changes the contact pressures in the knee [10, 65] resulting in high incidence of osteoarthritis (up to 78% after 14 years) [11, 66], which could be problematic for these young patients.

Femoral Bony Avulsions

Outcomes in Literature

Femoral bony avulsions are very uncommon in the pediatric and adult population [67]. In our

MRI study in which we assessed the incidence of different tear types [47], we noted that no femoral bony avulsion tears occurred in 353 adult patients and in over 250 pediatric patients. In the literature, only a handful of case reports on femoral bony avulsions have been reported. Most of these tears had osteochondral avulsions [68–71], whereas a few cases had cartilaginous avulsions [72, 73]. These cases have been treated with transosseous repair, but the follow-up is generally short [68, 71, 74, 75]. Systematic reviews or multicenter studies are necessary to assess outcomes of these injuries. The surgical technique with transosseous repair will be explained in the next section of proximal soft tissue avulsions.

Proximal Soft Tissue Avulsion Tears

Surgical Technique

We will discuss the surgical technique here briefly as it has been more extensively described in the recent literature [44, 48, 76]. It should be noted that in most of these patients, an internal bracing of #2 FiberTape is added to these patients in order to protect the ligament, as we have learned from the reconstruction literature that these patients are a high-risk population [7, 8]. We describe the surgical technique with the case of a 14-year-old girl.

A 14-year-old skeletally immature girl came in the clinic, as she suffered a twisting injury during a cheerleading contest 2 months ago. MRI revealed a subacute complete proximal tear that appeared to be attached to the PCL (Fig. 22.2). Physical examination revealed full ROM and a grade 2B Lachman and 2+ pivot shift in an otherwise stable knee. She was taken to the operating room, and it was agreed that primary repair would be performed in case of sufficient tissue length and quality, and otherwise an augmented repair [43, 44] or reconstruction would be performed.

During arthroscopy, it was noted that the ACL was indeed reattached to the PCL and an empty wall sign was present (Fig. 22.3). First the ACL was freed from the PCL. Starting distally, the anteromedial bundle was then sutured in an alternating, interlocking Bunnell-type pattern using a Scorpion suture passer (Arthrex, Naples, FL) with #2 FiberWire suture (Arthrex, Naples, FL). Approximately 3–4 stitches were made before the final pass exited at the avulsed end of the ligament toward the femur (Fig. 22.4a). Then, a similar process was performed for the posterolateral

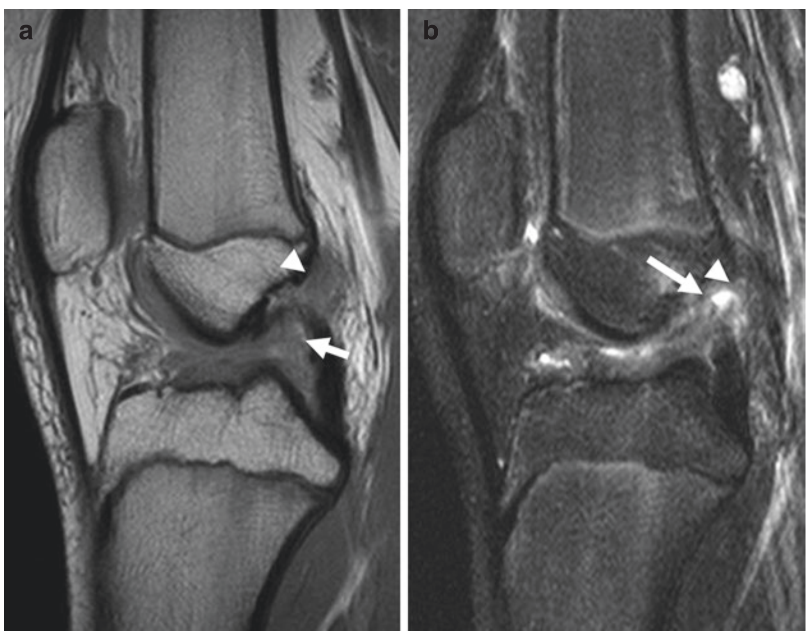

Fig. 22.2 MRI images of a left knee of a 14-year-old girl. (**a**) Sagittal T1-weighted image shows a complete ACL tear with only a few proximal fibers on the femoral wall (*arrowhead*) and distal fibers reattached to the PCL (*arrow*). (**b**) Sagittal T2-weighted image shows a proximal type I tear with indeed almost no fibers on the femoral wall (*arrowhead*) and a proximal tear with sufficient tissue length (*arrow*)

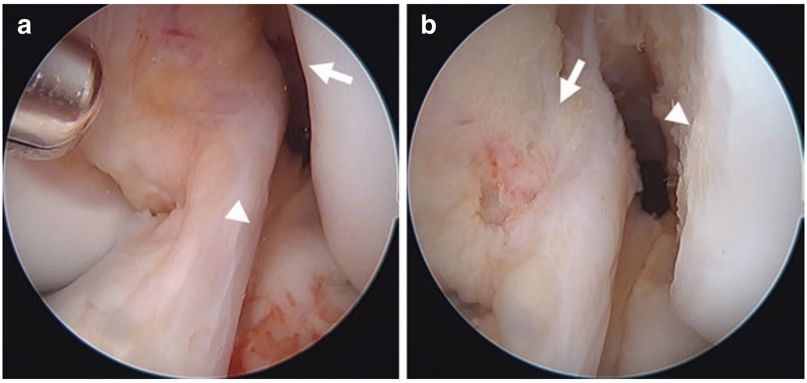

Fig. 22.3 Arthroscopic view of the left knee of the same 14-year-old girl. (**a**) The ACL (*arrowhead*) is reattached to the PCL and the femoral footprint is empty (*arrow*). There seems to be sufficient tissue quality, characterized by the fibers running in the same direction in intact fashion. (**b**) A more proximal view of the ACL shows again an empty femoral footprint (*arrowhead*) and ACL reattachment to the PCL

bundle using #2 TigerWire suture (Arthrex, Naples, FL) (Fig. 22.4b).

At this point, the sutured ligament can either be repaired with suture anchor fixation, which is the preference of the senior author due to the aperture fixation and minimal morbidity, or with transosseous fixation, which can also be performed for the aforementioned femoral bony avulsions.

In this case, suture anchor fixation was chosen, and although fluoroscopy was not used because the physes were mostly closed, it can easily be used to ensure safe placement of the anchors. Initially, an accessory inferomedial portal is made to facilitate access to the ACL femoral footprint. Through this portal a hole was tapped in the posterolateral origin of the femoral footprint with the knee flexed to about 115°. Using a 4.75 mm Vented BioComposite SwiveLock suture anchor (Arthrex, Naples, FL), the sutures were then deployed in the femoral wall, while the repaired ligament was tensioned to the wall (Fig. 22.4c). The same process was then repeated for the anteromedial bundle with two differences being that the knee is flexed to 90° and that the anteromedial suture anchor was preloaded with TigerTape (Arthrex, Naples, FL) (Fig. 22.4d). After the repair was complete (Fig. 22.4e), the internal brace was fixed distally. A pin was drilled up from the anteromedial cortex of the tibia to the anteromedial footprint. This was then switched for a straight Micro SutureLasso (Arthrex, Naples, FL) (Fig. 22.4e), and its nitinol wire was used to pass the TigerTape along the ACL substance anteriorly and down through the tibia where it was fixed with another suture anchor with the leg held near full extension after cycling the knee. The suture anchor ACL primary repair with internal brace was then completed (Fig. 22.4f).

If transosseous fixation is chosen, antegrade or retrograde parallel drill holes are made at the origin of the anteromedial and posterolateral bundles. A separate lateral incision is necessary to facilitate drilling and retrieval of the sutures out the lateral cortex of the femur. Suture passage can be accomplished either antegrade or retrograde according to surgeon preference. If the femoral physis is still open, then fluoroscopy can be helpful to stay in the epiphysis with the drill holes. Once the sutures are retrieved laterally, then they can be tensioned and tied over a ligament button.

The girl recovered quickly, which is typically seen with proximal repairs, and had ROM of 0–110° after 3 days and full ROM within 2 weeks. She used pain medication for a few days, and her leg felt “pretty normal” after 2 weeks. Lachman examination was negative with good endpoint, and pivot shift was negative and remained so throughout her course. She returned to basic maneuvers with the cheer team after 3 months

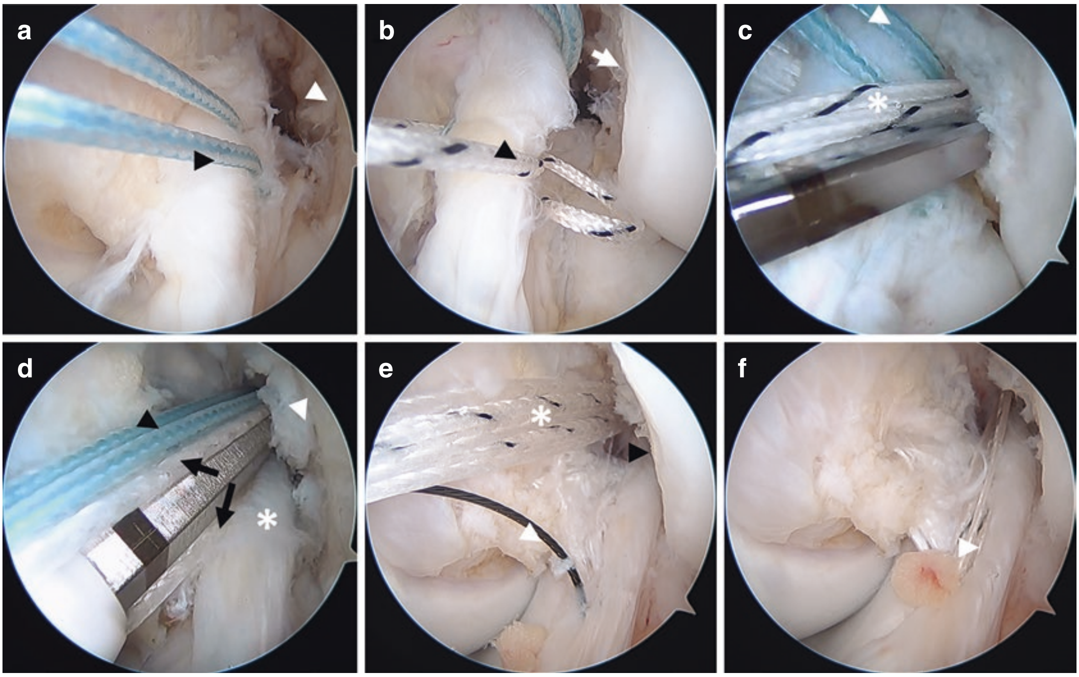

Fig. 22.4 Arthroscopic view of the left knee of the same 14-year-old girl. (**a**) #2 FiberWire sutures are passed through the anteromedial bundle (*black arrowhead*), and the footprint is further visualized (*white arrowhead*). (**b**) #2 TigerWire sutures are passed through the posteromedial bundle (*black arrowhead*), with again the empty footprint visualized (*arrow*). (**c**) A suture anchor with the posterolateral bundle stitches (*asterisk*) is deployed in the posterolateral origin of the femoral footprint. Note the relatively low position of the posterolateral suture anchor. The sutures of the anteromedial bundle are visualized (*arrowhead*). (**d**) A suture anchor with the anteromedial bundle sutures (*black arrowhead*) is deployed in the anteromedial origin of the femoral footprint (*white arrowhead*). The already inserted posterolateral bundle can be seen (*asterisk*). The internal brace can be visualized (*black arrows*). (**e**) After the repair is complete (*black arrowhead*), the internal brace (*asterisk*) needs to be channeled down. A nitinol wire (*white arrowhead*) is passed through the tibia to retrieve the internal brace. (**f**) The primary repair with internal bracing is complete. The internal brace is now tensioned and disappears in the distal part of the ACL (*arrowhead*)

and joined competitive cheerleading at national competition after 4 months using a brace. At 9-month follow-up, the knee was completely stable and had been competing on a national level for 5 months, and the patient and her parents were satisfied with the procedure.

Outcomes in Literature

In 2010, Frosch et al. performed a systematic review on the outcomes of open primary repair in pediatric patients and found a rerupture rate of 2.9% (2/69) and no growth disturbances (0/69) [9]. Most of these studies indeed treated proximal tears but were historical studies using an open approach [9]. Over the last 2 years, three studies reported the outcomes of primary repair of proximal tears [4, 12, 13], of which one study reported long-term outcomes of an open technique [13]. Smith et al. were the first to report on arthroscopic primary repair of proximal tears in pediatric patients with additional internal bracing [4]. They reported excellent outcomes in two patients aged 5 and 7 at clinical follow-up, and the ACL appeared healed with re-arthroscopy at 3 months, when they removed the internal brace. Bigoni et al. recently reported the first case series on five patients treated with arthroscopic primary repair of type I tears [12]. They found excellent outcomes at 3.6-year follow-up with a mean Lysholm score of 93.6 and a negative Lachman test in four patients and 1+ Lachman test in the fifth patient. Both of these studies used transosseous fixation for their patients. In very young patients, it may be preferable to use transosseous fixation, as with anchor fixation the suture anchors can endanger the growth plate due to the small epiphysis.

Distal Soft Tissue Avulsion Tears

Surgical Technique

Distal soft tissue avulsion tears are relatively uncommon in children, but distal bony avulsions are frequently seen in patients younger than 12 years [45]. Open or arthroscopic reduction with internal fixation (ORIF or ARIF) of these fractures remains outside the scope of this chapter and is discussed in another chapter in this book. Comminuted type IV McKeever tibial spine fractures or distal soft tissue avulsion tears cannot be fixed with these techniques, but they can be treated with primary repair. With this technique, the principles are similar to proximal tears, but then in an inverted manner. We describe the technique with the case of a 14-year-old boy.

He came in the clinic with a twisting injury 2 weeks prior during a lacrosse game. Physical examination revealed full ROM, grade 2B Lachman, and 2+ pivot shift. The MRI revealed a type V distal soft tissue avulsion tear (Fig. 22.5), and the patient was taken to the operating room 6 weeks after the injury.

During arthroscopy, the distal avulsion was confirmed (Fig. 22.6). First, the distal avulsed ligament and tibial footprint were roughened as the tear was already 6 weeks old. Then, #2 TigerWire sutures were passed in the anteromedial bundle from proximal to distal, and the same technique was repeated for the posterolateral bundle using #2 FiberWire sutures (Fig. 22.7a and 22.6b). Both sutures were then exited at the distal end at the locations of the anteromedial and posterolateral footprint locations (Fig. 22.7b). Then, using a cannulated drill, two small tunnels were drilled transphyseally from the anteromedial tibial cortex to the anatomic footprints of the anteromedial and posterolateral bundles. In this case, fluoroscopy was not used, but it can be used to guide the drilling. Both sutures were then exited through the drilled tunnels (Fig. 22.7c) and were tied distally over a button after the knee was cycled. The distal repair was then complete (Fig. 22.7d).

At the first follow-up visit at 8 days postoperatively, the patient had 0–100° of ROM, a negative Lachman test, and not much pain. The patient had 0–125° at 1 month and was wearing a brace and had crutches. The patient was weaned of the crutches and brace and regained full ROM after 6 weeks and was walking without a limp. Stability

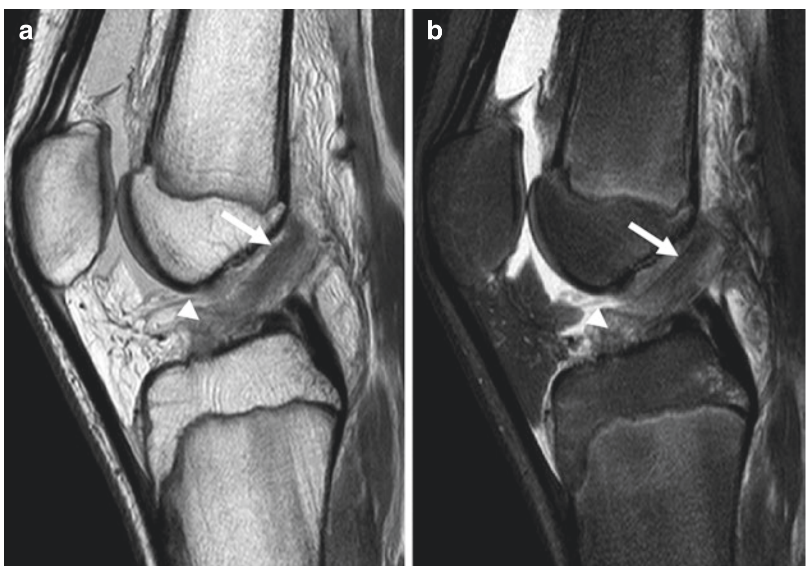

Fig. 22.5 MRI images of the left knee in a 14-year-old boy. (**a**) Sagittal T1-weighted image shows a complete ACL tear around the distal insertion (*arrowhead*) with an intact proximal remnant with excellent tissue quality (*arrow*). (**b**) Sagittal T2-weighted image also shows a distal ACL tear (*arrowhead*) with a few fibers attached to the tibia and an intact proximal remnant with excellent tissue quality (*arrow*)

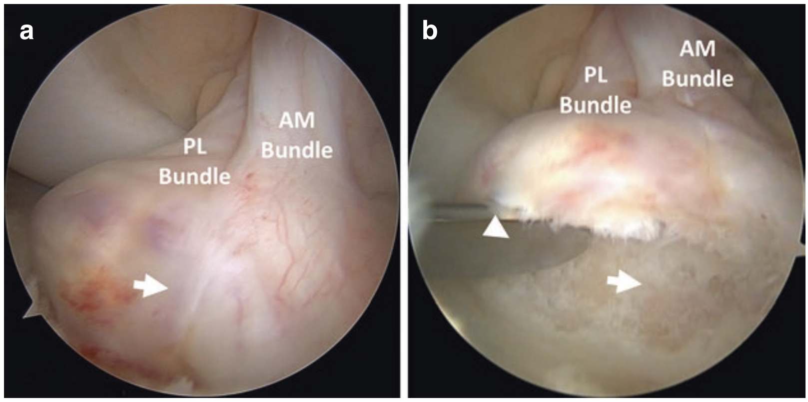

Fig. 22.6 Arthroscopic view of the left knee of the same 14-year-old boy. (**a**) The ACL is torn distally (*arrow*) with intact anteromedial (AM) and posterolateral bundles continuing proximally. (**b**) The ACL can be lifted proximally off the tibial footprint (*arrowhead*) and fixation is needed. Note that this is a soft tissue avulsion (*arrow*)

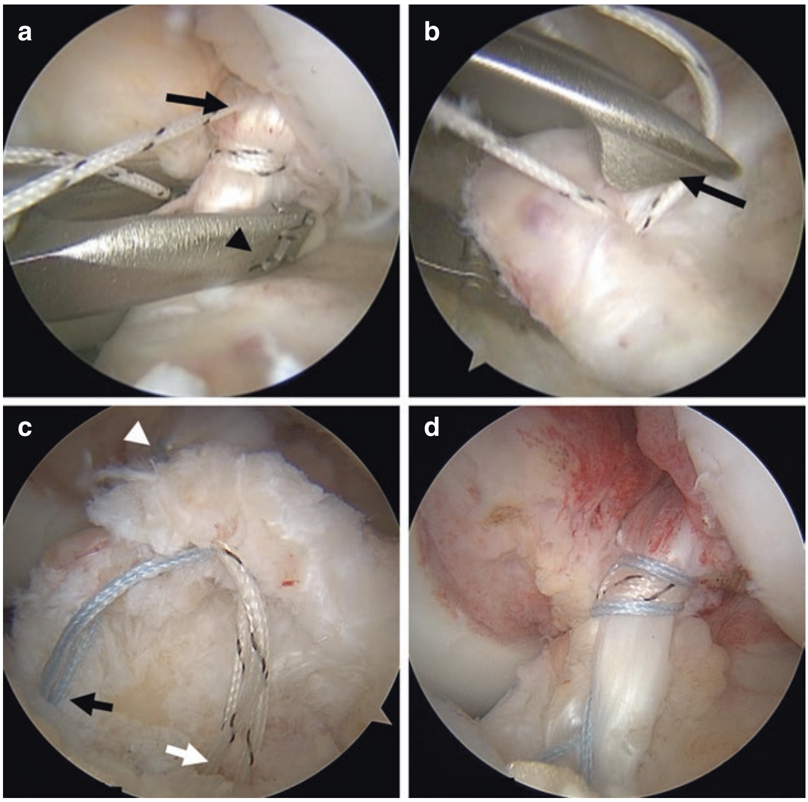

Fig. 22.7 Arthroscopic view of the left knee of the same 14-year-old boy. (**a**) #2 TigerWire sutures are passed through the anteromedial bundle using a suture passer (*arrowhead*) starting distally (*arrow*). (**b**) The last pass of the anteromedial bundle suture is exited at the avulsed site of the ligament using the suture passer (*arrow*). (**c**) After drill holes are made in the anteromedial and posterolateral origins of the tibial footprint, the anteromedial #2 TigerWire suture (*white arrow*) and the posterolateral #2 FiberWire suture (*black arrow*) are channeled through the tibia. The white arrowhead indicates the sutures advancing through the proximal part of the posterolateral bundle. (**d**) The distal repair is complete

examination remained negative over the course. The patient returned to play lacrosse after approximately 9 months. At 3.5-year follow-up, he has a negative Lachman test, a trace pivot shift, 100 Lysholm score, 100 modified Cincinnati score, and 100 SANE score and had returned to his pre-injury Tegner level of 9. He went on playing lacrosse at college level.

Outcomes in Literature

The senior author has performed this technique in pediatric patients of ages ranging from 8 to 15 years. The patient in this case had some difficulties regaining full ROM, which is commonly seen with distal avulsion tears that are primarily fixed [77]. It is difficult to assess outcomes of primary repair of soft tissue avulsions, as most studies report outcomes of tibial bony avulsions [78]. Cotel et al. recently reported outcomes of seven patients with cartilaginous avulsions that were treated acutely with distal repair [79]. They reported two failures and mean Lysholm and IKDC scores of 98 and 97, respectively, at 10-year follow-up. Xavier et al. reported long-term outcomes of primary repair in ten patients with tibial avulsion tears [13]. They noted no failures, two reoperations (one for partial meniscectomy and one for diagnostic arthroscopy for pain that was inconclusive) and excellent outcome scores at mean 15-year follow-up. Smith et al. reported a case report of one patient treated with arthroscopic primary repair with temporary bracing and reported excellent objective and subjective outcomes at 21-month follow-up [4]. As this type of injury is relatively rare, it is difficult to assess the outcomes in the literature with sufficient number of patients. Future systematic reviews or multicenter studies are necessary to review the failure rates and incidence of arthrofibrosis and decreased ROM. The study by Cotel et al. showed a failure rate of 29% (2/7) at 10-year follow-up, which is relatively high. It should be noted, however, that 71% of patients were "saved" from a more invasive ACL reconstruction (which has similarly high failure rates in this age group [7, 8, 80]) and that this is a relatively easy procedure with the advantages of preserving the native ACL tissues.

Conclusions

Historically, open primary repair of ACL injuries was a common treatment in the 1970s and 1980s, but the results were disappointing. Modern advances, such as MRI and arthroscopy, and increased knowledge on patient selection have led to a resurgence of interest for arthroscopic primary repair of proximal and distal avulsion tears.

Primary repair has several advantages over conservative treatment and ACL reconstruction, as it is a minimally invasive procedure with preservation of the native tissues and proprioception. Furthermore, no or only small tunnels need to be drilled, there is no risk for growth disturbance, no graft tissue to be harvested, and, if treatment fails, no bridges are burned for future reconstructive surgery. Finally, experimental studies have shown that primary repair can prevent posttraumatic osteoarthritis that is commonly seen after ACL reconstruction, which is especially important for pediatric patients. In light of all of these variables, we feel that it behooves us as surgeons to be more conservative in our surgical approach to the treatment of ACL injuries in children.

Patient selection is critical for arthroscopic primary repair, and this treatment can be performed in patients with proximal type I tears and distal type V tears. Recently, excellent short-term outcomes have been reported with this technique, and studies with longer-term follow-up are necessary.

Conflict of Interest Author Jelle van der List declares that he has no conflict of interest. Author Gregory DiFelice is a paid consultant and receives research funding from Arthrex (Arthrex, Naples, FL, USA).

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Congenital Absence of the Anterior Cruciate Ligament

23

Matthew C. Beran, Walter P. Samora, Kevin E. Klingele, and Shital N. Parikh

Introduction

Congenital absence of the anterior cruciate ligament (ACL) is a rare condition, with a reported prevalence of 0.017 per 1000 live births [1, 2]. First described by Giorgi in 1956 in a radiographic study [3], it has since been reported either as an isolated anatomical entity, or, more commonly, in association with other congenital lower extremity abnormalities [4–7]. The growth and development of ACL has been described in a previous chapter. From an embryological standpoint, the intra-articular structures of the knee form during the 7th and the 10th week of fetal development by the direct differentiation of the blastemal tissue of the interchondral disc [8]. The cruciate ligaments form from the articular interzonal mesenchyme, with the posterior cruciate ligament (PCL) being the first to become distinguishable. The congenital anomaly that causes absence of ACL development is thought to express itself around the 7–8 postovulatory week. Agenesis of the PCL alone has not been reported. PCL deficiency is present only in association with ACL deficiency. With absence of the ACL, lacking their stimuli to grow, the intercondylar notch and tibial spines subsequently fail to develop [9].

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Associated Anomalies

While isolated congenital absence of the ACL has been described, it is more commonly seen as part of a syndrome complex in association with other congenital conditions such as congenital knee dislocation, proximal focal femoral deficiency (PFFD), and fibular hemimelia. There is a constellation of pathologic clinical features typically seen in some combination with such conditions that includes absence/deficiency of the cruciate ligaments, proximal femoral focal deficiency, dysplastic lateral femoral condyle with valgus knee alignment, fibular hemimelia, ball-and-socket ankle joint, tarsal coalition, and absence of the lateral rays of the foot [10]. Congenital snapping knee is an extremely rare form of congenital knee instability, distinct from congenital knee dislocation, in which the tibia subluxes anteriorly on the femur every time the knee extends with a dramatic spontaneous

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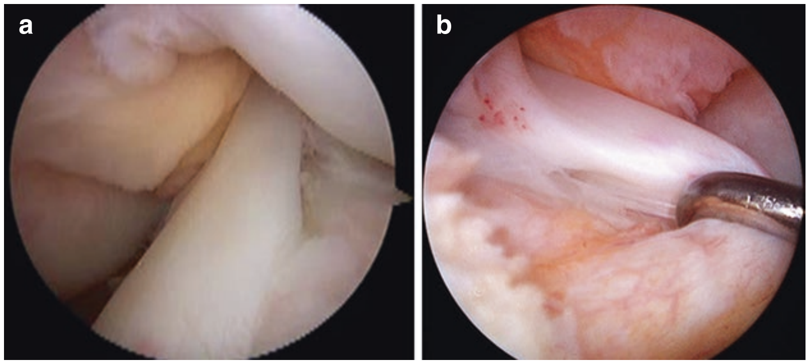


Fig. 23.1 Arthroscopic images demonstrate Type I ACL deficiency characterized by hypoplastic (**a**) and nonfunctional (**b**) ACL

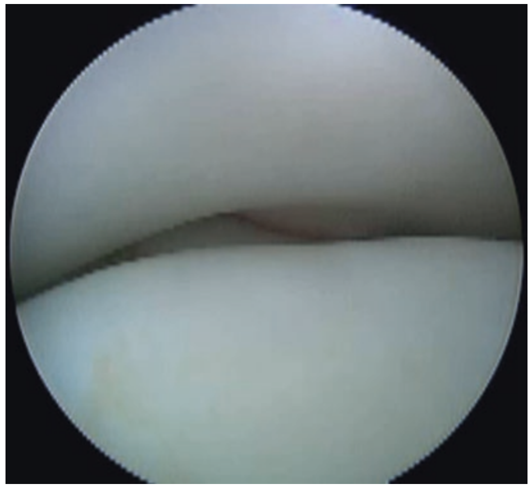
reduction in flexion and without significant quadriceps fibrosis or recurvatum deformity, and it includes a component of ACL deficiency [11]. Dysplastic growth at the knee, with varying degrees of instability, has been described in association with the thrombocytopenia and absent radius (TAR) syndrome [12]. Some associated intra-articular anomalies seen in knees with a congenitally deficient ACL include meniscal abnormalities (absent, hypoplastic, or discoid), osteochondritis dissecans lesions, and hypertrophy of the meniscal femoral ligament of Humphrey [13–15].

Classification

Manner et al. in 2006 developed a classification system, delineating three types of congenital deficiency of the cruciate ligaments and further identifying corresponding morphologic changes of the femoral notch and the tibial eminence, which can be observed on tunnel view radiographs [16]. Type I deficiency, which was most common in the series reported by Manner (55%), is a hypoplasia or aplasia of the ACL with a normal PCL (Fig. 23.1). There is a narrowing of the intercondylar notch and hypoplasia of the lateral tibial spine. Type II (21%) and III (24%) were seen in relatively equal numbers. Type II deficiency involves absence of the ACL with hypoplasia of the PCL. There is further narrowing of the intercondylar notch and attenuation of both the medial and lateral tibial spines (Fig. 23.2). In type III deficiency, the femoral intercondylar notch and the tibial eminence are completely absent and there is aplasia of both cruciate ligaments. Here the knee joint takes on a ball-and-socket appearance (Fig. 23.3). These plain radiographic findings may be utilized to differentiate absence of one or both cruciate ligaments as well as between a congenital ACL deficiency and traumatic ACL tear.

Fig. 23.2 Radiograph of a 13-year-old female show hypoplastic tibial spine and narrow intercondylar notch. MRI (not shown) showed absent ACL

Fig. 23.3 Arthroscopic image demonstrates ball and socket knee joint with absent tibial spine, narrow intercondylar notch, and absent cruciates, equivalent to a Type III ACL deficiency



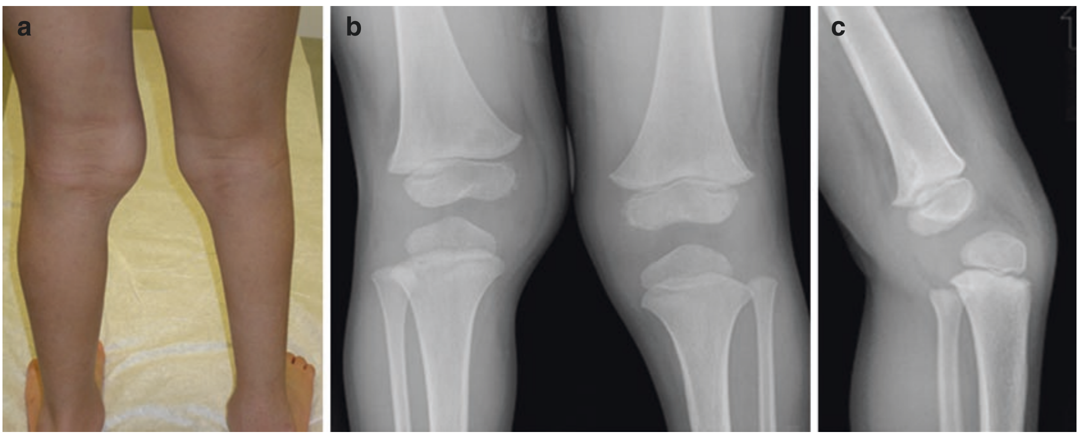


Fig. 23.4 Clinical evaluation of left knee of patient with ACL deficiency show lateral subluxation of tibia (**a**). Radiographs (**b**, **c**) show anterolateral subluxation of tibia

Clinical Presentation

The clinical presentation varies based on the degree of deformity and the associated congenital conditions present. When associated with a congenital knee dislocation, the condition is often obvious at birth with a varying degree of hyperextension at the knee, which can often be quite striking. When combined with severe fibular hemimelia or other significant congenital deformity (PFFD, congenital short femur) there is often obvious shortening of the limb with other abnormalities noted throughout the extremity. Older children/adolescents may present with more subtle findings. They may report increasing knee instability and exhibit increasing valgus subluxation and deformity about the knee (Fig. 23.4). They may present with issues related to a limb-length discrepancy or malalignment. It is important to recognize that congenital absence of the ACL may present as knee subluxation during limb-lengthening procedures (Fig. 23.5). Moreover, in what may be a common though under-recognized presentation, is the patient who presents with an "injury" to the knee and is found, on subsequent workup, to be ACL deficient, possibly not realizing it is a congenital absence.

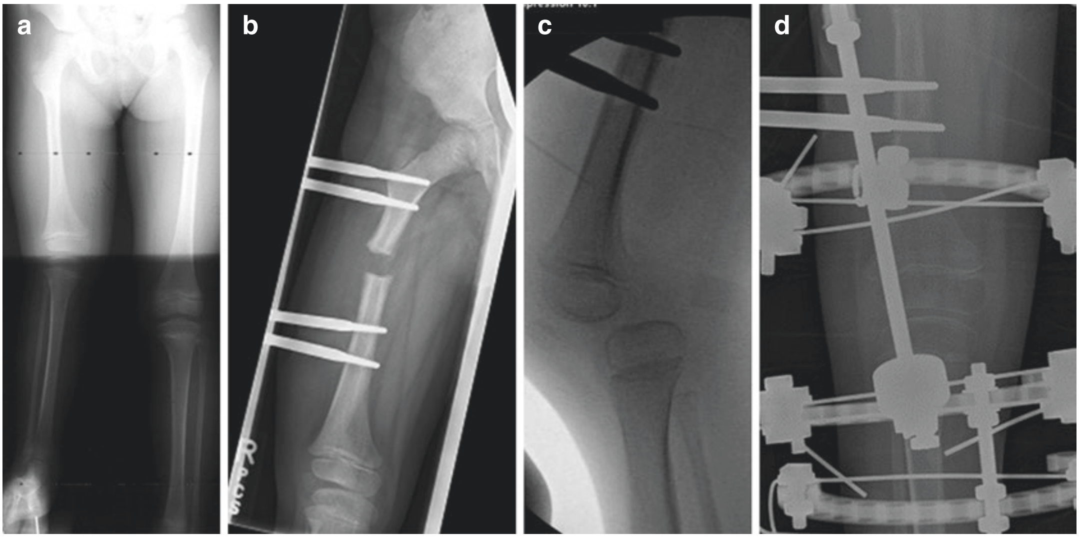


Fig. 23.5 Patient with congenital short femur (**a**) underwent femoral lengthening (**b**) using monoaxial external fixator. As gradual lengthening progressed, progressive subluxation of knee due to cruciate deficiency was recognized (**c**). The external fixator frame was extended with ring fixator to span the knee to control knee subluxation (**d**)

Physical Examination

Children with more severe disease and multiple anomalies may present at an earlier age with often obvious physical findings such as significant limb shortening or deformity consistent with their underlying condition. Patients with less severe involvement typically present to clinic with findings related to lower-extremity alignment and length. They may present with a gait abnormality, limp, or leg-length discrepancy. Rarely do they present with isolated instability of the knee.

Physical examination of the lower extremity should begin with the hip, with documentation of the range of motion compared to the opposite side. A rotational profile of the lower extremities should be performed. This includes the foot progression angle, internal/external rotation of the hip, thigh-foot-axis, and any abnormalities of the foot. Clinical leg-length discrepancy, if any, should be measured. This can be performed from the umbilicus to the ankle/foot, or from the greater trochanters to the ankle/foot. When measuring the clinical leg-length discrepancy it is important to include the size of the foot in the measurement, as measuring to the medial malleolus distally may underestimate the true discrepancy. As an alternative, wooden blocks can be placed under the shorter limb until the pelvis is leveled, which will show the global discrepancy of the extremity. Lower extremity examination should include coronal plane alignment, especially valgus of the knee joint. ACL laxity examination should include Lachman test, pivot shift test, and anterior and posterior drawer tests. Varus and valgus stability of the knee should be assessed in both full extension and 30° of flexion.

Roux and Carlioz in 1999 described the clinical examination and function of the cruciate ligaments in children with fibular hemimelia [17]. While they found a large percentage of patients to have physical findings of laxity (positive Lachman in 84%, anterior glide in 90%), only a much smaller portion of patients (16%) actually reported complaints of symptomatic instability. Valgus instability due to hypoplasia of the lateral femoral condyle was a common finding (83%).

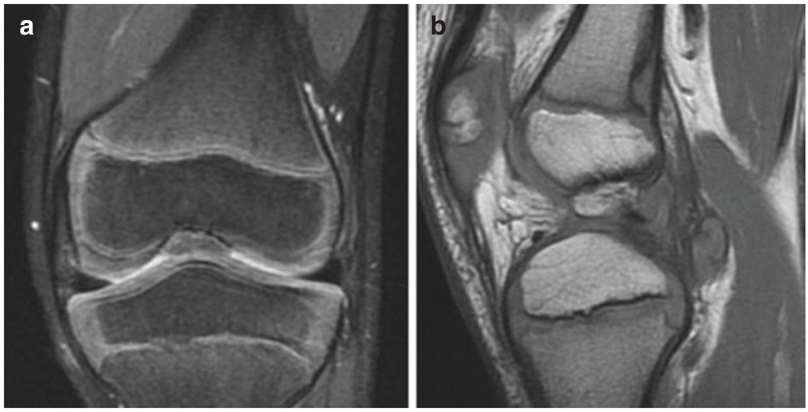


Fig. 23.6 Coronal (**a**) and midsagittal (**b**) MRI show hypoplastic tibial spine and absent cruciate ligaments

Imaging

Imaging of the lower extremity should include full-length standing anteroposterior (AP) alignment and knee radiographs. Common radiographic findings, which are typically indicative of fibular hemimelia, include hypoplasia of the lateral femoral condyle (98.5%), hypoplasia of the tibial spines (93%), patella hypoplasia (52%), lateral displacement of the patella (32%), and patella alta (12%) [17].

If indicated based on radiographic findings, magnetic resonance imaging (MRI) of the knee should be performed to further characterize the involvement of both the anterior and posterior cruciate ligaments, as well as the other associated structures of the knee (Fig. 23.6). Hypertrophy of the meniscofemoral ligaments could be seen on MRI and is thought to reduce symptomatic anterior instability [14, 15]. MRI will allow classification of the type of ACL deficiency and can help guide treatment options.

Management

Given the extremely rare nature of this condition, there is no consensus regarding the optimal management strategy. Furthermore, there have been no comparative studies published regarding surgical and nonsurgical treatment of congenital absence of the ACL. The literature related to management of ACL deficiency has been summarized in Table 23.1. The frequent occurrence of other congenital anomalies in the extremity, often very complex and requiring multiple surgical procedures themselves, further complicates the development of an algorithmic approach to this condition. Most of the studies involving syndromes in which congenital absence of the ACL is a component have focused primarily on the correction of malalignment or limb-length inequality that is often initially performed, with minimal attention to the instability secondary to ACL deficiency [1, 2, 5, 11, 18, 19]. Since most congenital ACL deficiency patients have other associated anomalies or dysplasia, the activity demand on the knee may be considerably less, thus masking the symptoms and manifestations of ACL deficiency.

When ACL deficiency is asymptomatic or an incidental MRI finding, close observation and follow-up are appropriate. If symptomatic, most authors would agree that initial nonsurgical management in the form of custom ACL braces, physical therapy and activity modification is appropriate. The correction of limb-length discrepancy and realignment procedures typically affords these patients functionally anatomic limbs and higher activity levels. Furthermore, the presence of a hypertrophied meniscofemoral ligament, described in conjunction with congenital

Table 23.1 Summary of studies of ACL deficiency

Study	Number of patients	Associated conditions	Management	Outcomes	Other notes
Chahla et al. [21]	2	Congenital short femur, LFC hypoplasia, PCL dysplasia	BTB autograft Achilles allograft ACL reconstruction	No instability	Notchplasty required to recreate an intercondylar notch [2] 30 year-old female presented with atraumatic instability Meniscofemoral ligament hypertrophy in all patients
Murali et al. [15]	1	Leg anisomelia	Resection of posterior horn medial meniscal tear	No instability at 2 year follow-up	Non-operative treatment of ACL deficiency
Sonn and Caltoum [22]	2	No associated conditions	BTB autograft ACL reconstruction	Return to high-level athletics	Monozygotic twins with no associated abnormalities
Lee et al. [23]	1	Limb length discrepancy of femur	Tibialis anterior allograft ACL reconstruction	No instability at 6mo. Follow-up	Extensive notchplasty incomplete medial meniscal tear
Gabos et al. [14]	4	Skeletal dysplasia [1], fibular Hemimelia [1], fibular hemimelia + congenital short femur [1]	ACL reconstruction with allograft [4]	No deficits in flexion Extension contracture of 10° [1] Negative Lachman [1]/1+ Lachman [3] Negative pivot shift [4]	Patients required avg. of 3.7 procedures prior to knee reconstruction
Johansson and Aparis [1]	6	Hypoplastic/ absent fibula [3] Short tibia [1] Absent 5th ray [1]	Arthroscopy without ACL reconstruction	Unknown	No arthroscopic or radiographic signs of arthritis

LFC Lateral femoral condyle, *PCL* Posterior cruciate ligament, *BTB* Bone patella bone

absence of the ACL, may aid in reducing anterior instability (Fig. 23.7) [14, 15].

The main indication for ACL reconstruction in this population is symptomatic instability of the knee, despite conservative treatment. Other indications for surgical stabilization include knee subluxation or dislocation during or prior to lengthening procedures and as a component of the surgical management of a congenital knee dislocation. Principles to consider in those patients requiring an ACL reconstruction include restoration of the mechanical axis of the lower extremity, respect of the physis based on the patient's skeletal maturity, reconstruction of all components of knee instability, and addressing any associated intra-articular pathology [14]. ACL reconstructions in these knees may be technically more demanding given the altered anatomy, including increased tibial slope, hypoplasia

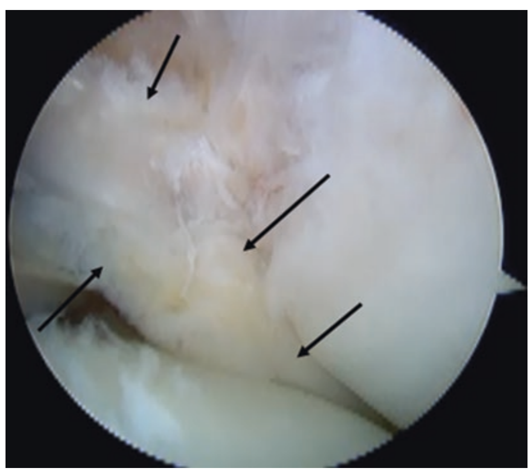


Fig. 23.7 Arthroscopic image during ACL reconstruction in a patient with absent ACL demonstrates hypertrophic meniscofemoral ligament (*arrows*) which is a frequent finding and may be responsible to confer some stability to the knee joint

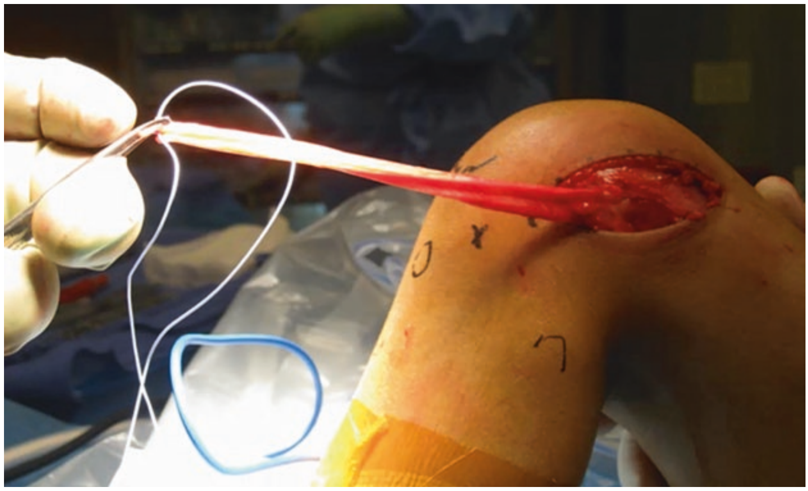


Fig. 23.8 A physeal-sparing ACL reconstruction using iliotibial band in a 7-year-old patient with symptomatic ACL deficiency

Fig. 23.9 Transphyseal ACL reconstruction in a 13-year-old female (same as in Fig. 23.2) with symptomatic ACL deficiency. The patient had satisfactory result at 2 year follow-up

of the lateral femoral condyle, and a rounded posterior femoral condyle [20]. Establishing realistic patient expectations and surgical goals is thus an important component of the decision-making process. Both physeal-sparing (Fig. 23.8) and transphyseal (Fig. 23.9) techniques, described in detail in other chapters in this book, have been utilized based on the age of the patient at the time of surgical intervention. Multiple case reports have shown the efficacy of ACL reconstruction in restoring knee stability for appropriately selected patients with congenital absence of the ACL [14, 21, 22]. When combined deficiency of ACL and PCL is present, isolated ACL reconstruction can lead to posterior subluxation of the knee, and this should be considered during management decision. Patient and family should be informed that a second-stage surgery (for PCL reconstruction) may be necessary at skeletal maturity.

Outcomes

The natural history of a knee with congenital ACL deficiency is still unknown. Multiple studies describe early cartilage damage suggesting progressive degenerative arthritis [23, 24]. It remains unknown whether the degenerative changes identified are secondary to recurrent instability of the knee or to the overall syndrome affecting the extremity and/or multiple reconstructive procedures already performed. As our techniques for physeal-sparing ACL reconstructions continue to improve, it is possible that earlier ACL reconstruction may minimize the degenerative changes noted with time. Further long-term natural history studies of reconstruction of the ACL-deficient knee with or without associated realignment or lengthening procedures are needed to further define the management principles for this rare condition.

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24 Special Consideration: Female Athlete and ACL Injury Prevention

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With well over 16,000 published research studies and countless news stories, anterior cruciate ligament (ACL) injuries have been a focused topic in sports medicine research, academic, and popular media for over 20 years. There are approximately 200,000 ACL injuries per year which accounts for nearly 3% of all sports injuries [1–4]. Comparatively there are approximately 20 million ankle injuries per year, accounting for 20% of all sports injuries [5–7]. At first glance, an emphasis on ACL injury might appear unwarranted, but does not consider the associated impact on the athlete who has suffered a ruptured ACL.

Consider:

- Of those who have sustained a primary ACL injury, 25–30% will re-tear either the surgically repaired ACL or contralateral lower extremity [8, 142].
- Those adolescent athletes returning to sport following ACLR have a 30–40 times greater risk of a secondary ACL injury compared with their uninjured peers [8].
- Risk of knee osteoarthritis following ACL injury increases by three to five times with more than 50% of youth injuring their ACL will develop osteoarthritis in as little as 10 years [9–13]. The estimated lifetime financial burden is more than $285,000 [14]. Maffulli and Del Buono indicate that up to 3% of all ACL injuries occur in children and adolescents [15]. Stated differently, ACL injury is more common in younger active individuals, but is coupled with an earlier onset of knee osteoarthritis [16].
- Quadriceps function decreases which may never normalize to pre-injury standard [17–19].
- Delayed ACL reconstruction (>12 months) increases risk of meniscus or chondral damage by fourfold [20].
- Increased BMI and body fat in females following knee injury [21].
- Cognitive impairments such as processing speed and memory [22, 23] and deficits in motor planning [24, 25] are affected with ACL injury.
- Fewer than 50% of those experiencing ACL injury will return to sport at their previous level of performance [26, 27].

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ACL Injury Prevention Versus Injury Risk Reduction

This chapter is focused on ACL injury prevention; it must be noted, however, that it is not possible to prevent all ACL injuries. Injury prevention means that doing certain things will stop an injury from happening. Taken literally, that is not something any program can honestly promise. An alternative, more liberal, definition would describe injury prevention as *reducing* the severity of injury before it occurs. Therefore, our focus is on reducing the relative risk of female athletes experiencing ACL injury. Understanding that there is a difference between true injury prevention and injury risk reduction, because of its use in both research and popular media, for the purposes of this chapter, the terms injury prevention and injury risk reduction will be used synonymously. After reviewing the research that supports the implementation of ACL injury prevention programs, this chapter will provide the reader with a stepwise approach to designing a training program. A sample program with exercises will be provided at the end to summarize and tie together the research and program design components.

Evidence for Implementing an ACL Injury Prevention Program

Due to the negative consequences following ACL injury, there is an obvious importance in designing and implementing a program to reduce the risk of ACL injury, especially in younger active individuals. While some studies have not shown a reduction in ACL injury rate attributed to performing injury prevention programs [28, 29], the majority of studies have shown improved biomechanics and reduced injury rate with participation in ACL injury prevention programs [29–57].

However, to be successful, participation must be consistent and adherence to program guidelines is necessary. Program compliance is a challenge and one of the most important mediators of efficacy with ACL injury prevention programs [58–60]. Greater compliance with injury prevention programs is associated with lower rates of ACL injury incidence in physically active young females [58, 59]. Program compliance is a combination of session attendance and completion. Attendance is calculated as the number of participants who completed a set number of sessions divided by the total number of program participants. Completion is the number of sessions a subject completes divided by the total number of sessions offered. Hägglund et al., recorded compliance and injury rate with an ACL injury prevention program for 2471 adolescent female soccer players [58]. They found that those in the high-compliance tertile (more than 66.6% attendance multiplied by completion) had an 88% reduction in the anterior cruciate ligament (ACL) injury rate, whereas the rate in the control group players was not significantly different from those in the low-compliance tertile. In addition, Sugimoto et al. found that athletes with low to moderate program compliance rates showed a three to five times greater risk of sustaining ACL injuries as compared to those with high compliance rates with the prescribed injury prevention protocols [59]. In other words, more compliant and consistent ACL injury prevention program participation lowers ACL injury incidence in athletes. Identified compliance barriers include lack of time by the student athletes and coaches feeling ill-prepared to provide the required instruction [60].

While participation in injury prevention programs can reduce injury rates [61], identification of athletes which may derive benefit may also be important. Individuals who have had an ACL injury and those that demonstrate high knee abduction moments during a drop vertical jump are at greater risk for ACL injury [62] and therefore might experience the greatest benefit of ACL injury prevention program participation [49].

Program Design

Effective ACL injury prevention programs are similar to training programs designed to improve traditional measures such as strength, power, and aerobic endurance. Training programs require a systematic coordination and manipulation of key variables that allow the body to adapt to change and improve the given outcome measure. When designing a program to reduce the risk of ACL injury—like other training programs—it is important to be mindful of three specific training concepts, specificity, overload, and progression.

Specificity, synonymously referred to as specific adaptation to imposed demands, or SAID, states that the type of demand or stress placed on the body determines the type of adaptation the body will experience. While some training programs focus on speed—like a sprinter—or shoulder strength—like an overhead athlete—programs designed to reduce the risk of ACL injury focus on addressing modifiable risk factors that have been shown to relate to ACL tear.

Overload is assigning a load, exercise, or program that is greater in intensity or complexity than the athlete is accustomed to. If overload is not provided, improvement is compromised. With traditional programs, there are several methods to overload the athlete, but one of the easiest ways is through load modification. For ACL injury prevention, load is likewise an important adjustment to overload the athlete's body to influence desirable adaptations, but, load is not the only factor to adjust when the goal is reducing the risk of ACL injury. Instead, focusing on the basics of ideal movement mechanics or isolating specific muscle groups with low to no weight is indicated. Stated differently, learning a new movement pattern and/or lower body alignment provides a sufficient overload, especially when implementing a new program. Once that alignment is accomplished at an appropriate level, the body must be overloaded to allow the athlete to improve. In addition to load, examples here might include movement complexity, surface variation, movement speed, training volume, and even rest periods between exercises. The goal of overloading the body so that adaptive strategies are developed that can provide a proper, planned stimulus to cause the desired adaptation; in this case, the desired adaptation is a reduced propensity to demonstrate biomechanics that increased the risk of ACL injury.

To provide an overload that leads to the desired adaptation, a well-designed ACL injury prevention program will include proper exercise **progression**. Progression is essential to promoting a long-term reduction in an athlete's risk of ACL injury. Like overload, program progression can be accomplished with a number of techniques to increase the training stimulus. In addition to the load used, changing the exercise to one that is more technically challenging or adjusting the training frequency are both common techniques used to provide progression. Specificity, overload, and progression all work together to systematically and gradually challenge the athlete which leads to the desired outcome of reduced risk of ACL injury.

In addition to specificity, overload, and progression, designing a program to reduce the risk of ACL injury requires the recognition of several program design variables. This chapter will discuss each of these variables and will provide a logical way for the rehabilitation or strength and conditioning professional to see how these guidelines can be integrated into a standard training program. These program design variables are presented as five steps:

1. Risk Factor Identification
2. Exercise Selection
3. Training Load and Volume
4. Training Frequency
5. Exercise Timing

Step One: Risk Factor Identification

The ACL serves as the primary restraint to anterior tibiofemoral shear forces and is stressed most when an anterior force is applied to the tibia [63–65]. The initial task when designing a program to reduce the risk of ACL injury is to identify the factors that contribute to this anterior shear [66]. Once identified, these risk factors will be targeted through training. When considering the factors that increase the risk of ACL injury it is necessary to categorize risk factors that are modifiable versus non-modifiable. These risk factors were covered in detail in Chap. 1, but are summarized in the next section.

Modifiable ACL Injury Risk Factors

Several factors of ACL tear can be modified in some form or another. These modifiable risk factors can be further subdivided.

Biomechanical Risk Factors

The first step in identifying modifiable risk factors is determining those based on movement, alignment, strength, and forces [67].

Movement and Alignment

When looking at how lower body anatomical structures relate to movement, the two categories of control are active and passive. Movement in the body occurs from muscular forces that move the skeletal levers about joints, i.e., bones; these muscles, then, are the body's active controls. Those levers and joints are held together by passive controls, like ligaments, retinacula, and other connective tissues. Landing from a jump with a smaller knee flexion angle and a larger knee valgus angle have been identified as risk factors for noncontact ACL injuries. The decreased active and passive controls of knee tend to put the knee at increased risk of ACL injury in female athletes; specifically dynamic knee valgus positioning, especially when coupled with increased knee joint loading, is predictive of ACL injury risk [37–40, 48, 50, 51, 68–71]. The knee joint is ill-equipped to decrease frontal plane loads (e.g., valgus) described above as the muscles that surround the knee joint work primarily in the sagittal plane. Because of this decreased local control, muscles that move the knee's bony structures at other joints play a greater role in frontal plane alignment. As an example, gluteus medius and minimus abduct the femur; the aforementioned dynamic valgus position has femoral adduction as a primary component. Stronger, more active gluteus medius and minimus muscles can therefore minimize the amount of dynamic valgus by resisting the medial knee movement.

On the other hand, the knee joint has strong active muscular restraints to adequately dampen knee joint loads in motions aligned in the sagittal plane (i.e., quadriceps femoris and hamstring muscle groups). However, when participating in sporting activities, females tend to display a relative decreases in knee flexion angles when landing and at initial contact when running. Landing with limited knee flexion increases anterior tibial shear loads large enough to injure the ACL [37–40, 72, 73].

Strength

Muscle weakness is somewhat controversial when it comes to risk of noncontact ACL injuries. It has been suggested that lower extremity strength deficits are not significantly associated with increased ACL injury risk [44]. However, there are several reports that indicate muscle weakness is a risk factor for ACL injury [32, 74–76]. In the lower body, strength of three muscle groups has been shown to factor into the female athlete's risk of ACL injury, quadriceps, hamstrings, and hip abductors.

Grindstaff et al. showed that an athlete demonstrated decreased ***quadriceps*** force measured 4 h prior to ACL injury, relative to baseline obtained a week prior [33]. Palmieri et al. reported that females demonstrated unbalanced (decreased medial hamstrings and quadriceps) muscular recruitment that predicted dynamic valgus load [75]. Females tend to have smaller knee flexion angles during landing when compared with males [68, 77, 78]. Perhaps counterintuitively, the muscles that control knee flexion angles when landing are the quadriceps. The quadriceps are active eccentrically to dampen or control knee flexion. If insufficient quadriceps strength exists, it is likely that athletes will avoid knee flexion positions that rely on those muscles for control.

Similarly, an investigation of elite female handball and soccer players found that increased EMG activity of the lateral quadriceps and decreased EMG activity of the medial ***hamstrings*** was demonstrated by females who would go onto ACL injury [76]. Females with low relative hamstrings EMG activity increased their risk threefold when compared to males when decelerating from a landing [79]. This group of females with greatly reduced relative hamstrings strength also demonstrated increased dynamic valgus load compared with male subjects. Decreased hamstrings strength relative to quadriceps strength is implicated as a potential mechanism for increased lower extremity and ACL injuries [48, 50, 51, 80–84].

To prevent the aforementioned dynamic valgus position, attention has been focused on the role of ***hip abductor*** strength. Khayambashi et al. found that decreased isometric hip abduction and external rotation strength independently predicted future noncontact ACL injury in competitive athletes [74]. In collegiate basketball players, greater hip abduction strength has been shown to result in less knee valgus angles during a single-legged medial drop landing in females and increased knee flexion angles with single leg landing in males [85], both thought to decrease risk of ACL injury. Increasing hip strength may play an important role in reducing abnormal frontal plane knee motion in athletes when landing.

Forces

Ground reaction forces (GRFs) during athletic tasks may influence the risk of ACL injury [86]. The quadriceps and hamstrings muscle groups must then function to control GRFs. Increased ground reaction force during a stop-jump task has been shown to result in greater quadriceps muscle force and greater ACL loading [87]. The ACL is subject to greatest loading immediately after initial contact when maximum vertical GRF occurs [88]. Further, both posterior ground reaction force and external knee flexion moment were significant predictors of anterior tibial shear during a stop-jump task with knee flexion moment having the greatest influence on this anterior shear force [89]. Increased landing forces over a shorter time (impulse) are associated with increased risk of ACL injury [68].

Fatigue

Fatigue is a substantial risk factor of ACL injury [90–98] and may alter knee kinematics while decreasing the ability of force dissipation in the knee joint. When fatigued, there is a loss of motor control especially during the landing phase of a jump [97]. When this control is altered, dissipating ground reaction forces, as previously discussed, becomes compromised; this compromised function may lead to an increased risk of acute knee injuries, including the ACL. In addition, studies have also reported that anterior tibial shear [92] and peak knee abduction angles significantly increase after fatigue [99, 100]. Stiffer landings (i.e., less knee flexion) have been cited as risk factors of ACL injury [68, 77, 78]. When fatigued, knee flexion angles, extensor moments, and force dissipation are greatly reduced 93].

Non-Modifiable ACL Injury Risk Factors

Anthropomorphic

Body changes—like bone length, body weight, and overall height—during adolescence play a significant role in ACL injury risk. Increased femur length [101] and increased tibia length [37–40] are associated with increased risk of ACL injury. During adolescence the tibia and femur grow at rapid rates [102]. The function of muscles and bones was previously discussed. When lever length (i.e., bone length) increases, muscles must adapt to this increased demand, if the muscles don’t respond with parallel increases in strength, the levers—bones—are harder to control. Therefore, this rapid increase in bone length, an increase in body mass, and subsequent increase of the body’s center of gravity necessarily challenge an athlete’s ability to control both the lower extremities and the trunk [35, 36, 103, 104].

Female adolescent athletes do not appear to adapt as well as males to these increased mechanical demands [35, 36, 103–106].

In addition, increased body mass relative to height (BMI) may be a risk factor for ACL injuries [36]. For female athletes older than 8 years, BMI is a significant risk factor for increased knee injury risk [107]. Myer et al. found that increased BMI was strongly related to the potential for increased ACL injury [37–40]. Lastly, reports indicate that increased knee-laxity measures and other joint laxity measure are associated with increased risk of ACL injury [51].

Step Two: Exercise Selection

Exercise selection to decrease risk of ACL injury should comprehensively address modifiable risk factors. The rehabilitation or strength and conditioning professional must understand the types of exercise, exercise technique experience, and equipment availability.

Exercise Type

Although there are hundreds of exercises to select from when designing a program, those involved in ACL injury prevention focus on one of four areas, alignment, force dissipation and application, strength, endurance.

Alignment refers two primary components: the position of the knees in relation to the feet and the position of the upper body in relation to the center of gravity. Specifically, when moving (e.g., running, jumping, landing, cutting) athletes should be instructed to keep each knee aligned over the second and third toes in the frontal plane (Fig. 24.1). Dynamic valgus is one of the known risk factors of ACL injury. In addition to knee alignment, position of the trunk relative to the lower body is important [108]. When the trunk does not lie within the base of support, then posture is unstable (Fig. 24.2a) [109]. Athletes experiencing a noncontact ACL injury tend to display a landing position with their trunks more posterior to their bases of support in comparison with

Fig. 24.1 Athletes should align knee over second and third toes to prevent dynamic valgus position

Fig. 24.2 (**a**, **b**) When landing, the trunk should lie within the base of support to improve stability. When the trunk is lateral to (**a**) or posterior to (**b**) the athlete's base of support, noncontact ACL injuries are more likely

uninjured athletes (Fig. 24.2b). In addition, the distance from the trunk to the base of support is larger in female, as compared with male [110]. If the distance of the center of gravity to base of support is too great, then recovery is difficult and a fall is likely.

Force dissipation is the ability to absorb and adequately distribute forces when impacting the ground when running, landing, or cutting. In contrast **force application** is the ability to produce higher ground reaction forces to the ground when running, landing, or cutting. Being able to both absorb and apply more force to the ground improves sprinting performance [111–113]; however, these higher ground reaction forces, especially when experienced by those with reduced training age or experience [114], also increase an athlete's risk of ACL injury during stop-jump tasks [68, 87, 89, 115]. Unfortunately, while training athletes to better dissipate ground reaction forces when landing does indeed work [79, 116, 117], it might actually worsen performance [118].

To address these contradicting goals, we recommend a two-step process when designing ACL injury prevention programs: (1) First learn to dissipate force by improving shock absorption through deceleration; (2) Learn to properly apply force to the ground when running, jumping/landing, and cutting. This approach can help athletes optimize force absorption when decelerating and enhance force generation performance needed for success in sports.

Strength of certain muscle groups must be adequately addressed when designing an ACL injury prevention program. While several muscles—like hip extensors, abdominals, and even those acting at the ankle—play a role in controlling lower extremity alignment and control, the primary muscle groups that play key roles in reducing the risk of ACL injury are the hamstrings, hip abductors, and quadriceps [33, 48, 50, 51, 74–76, 79–84]. As a review, Hamstrings help to reduce anterior tibial shear [119]; strength of this muscle group is well known in its ability to reduce ACL injury rate [48, 50, 51, 76, 79–84, 120]. Hip abductors and external rotators help to resist hip adduction, a primary component of the position associated with ACL injury, dynamic valgus [74]. The quadriceps are active eccentrically to dampen or control knee flexion. If insufficient quadriceps strength exists, it is likely that athletes will avoid knee flexion positions that rely on those muscles for control. The importance of quadriceps strength appears to be more of a factor for secondary or re-injury versus primary or initial ACL injury [121, 122].

The last component to consider when choosing the type of exercise is **endurance**, which includes both cardiovascular and muscular components. Establishing an adequate endurance base is an important part of reducing risk of ACL injury [90, 91, 93, 97, 123, 124].

There are several exercises that target the aforementioned variables and therefore may be used in an ACL injury prevention program. Table 24.1 provides a list of exercises that decrease an athlete's risk of ACL tear. At the end of the chapter, a description and figure for each of these exercises is provided.

Table 24.1 Common ACL injury prevention exercises

Warm Up	Strength	Plyometric
Skipping	Deadlift	Vertical Jump
Walking Hamstring Stretch	Squat (Bilateral)	Squat Jump
Ankle Hop	Squat (Single Leg)	Standing Long Jump
Tuck Jump	Lunge—Forward and Lateral	Jump to Box
Stability Hop—Front and Lateral	Step Up	Jump from Box
	RDL (Bilateral)	Single Leg Box Push-Off
	RDL (Single Leg)	Vertical Jump (Single Leg)
	Nordic Hamstring Curl	Standing Long Jump (Single Leg)
	Knee Extension (Single Leg)	Jump over Object/Hurdle
		Drop Jump (Bilateral)

Exercise Technique Experience

Athlete training status and experience performing exercises is an essential part of exercise selection, especially for pediatric and adolescent female athletes [37, 38, 114]. Given their age and the need to improve movement quality, it is best to spend considerable time with each athlete to ensure that correct technique is used, even with those exercises that are relatively easy to perform. If the athlete uses incorrect technique, comprehensive, age-specific instruction should be provided to reduce aberrant movements that increase injury risk. The role of instruction to break the cycle of high risk movements is critical to avoid training the reinforces bad movement strategies [82, 125].

Equipment Availability

The availability of training equipment must be considered when choosing exercises for ACL injury prevention programs. Many such programs do not use equipment, primarily to make participation more convenient, with capacity to perform in conjunction with sport (e.g., soccer field, basketball court), and thereby improve compliance. For example, the depth (or drop) jump requires the use of a box to land from before jumping again (Fig. 24.3). The absence of plyometric boxes would therefore preclude this exercise. Or a single leg Romanian Deadlift might need to be substituted for a stability ball hamstring curl if a stability ball is unavailable. In most cases, ACL injury prevention programs can

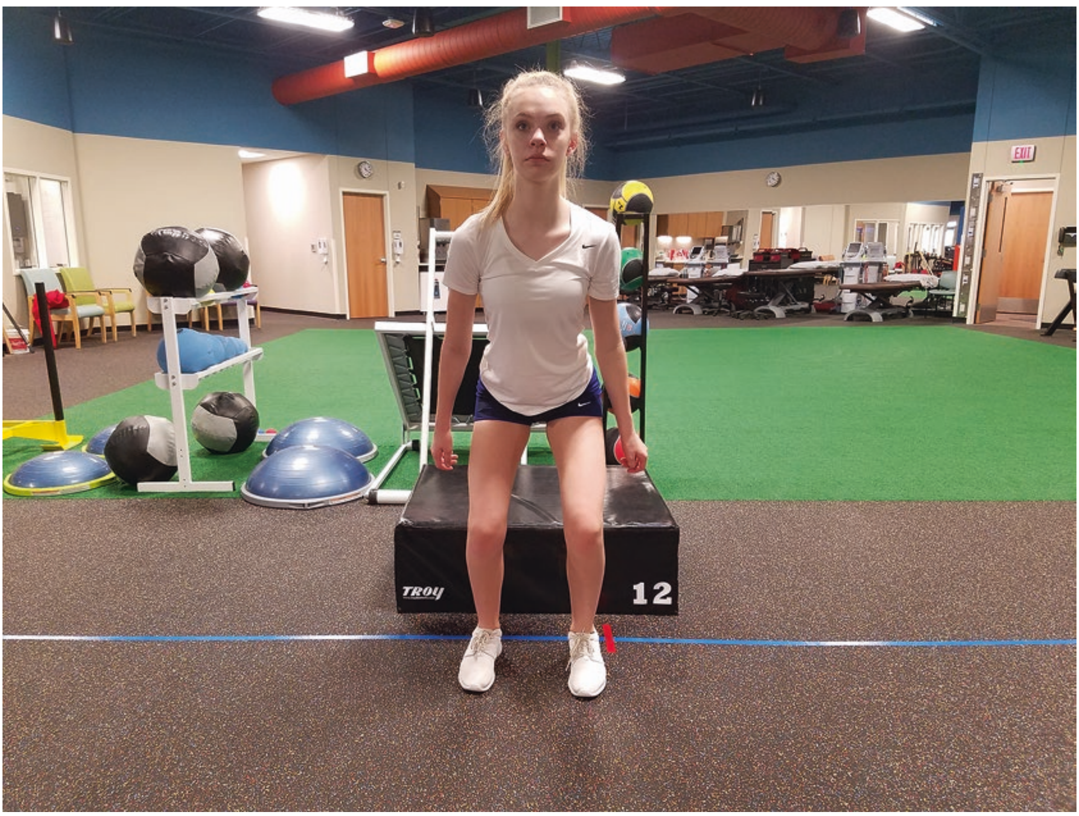


Fig. 24.3 Equipment is often necessary when performing exercises to prevent ACL injury. Here, a 12 in. box is used during a depth (or drop) jump

be implemented with little if any equipment as exercise selection and instruction can help overcome any limitations with available equipment.

Step Three: Training Load and Volume

Load most simply refers to the amount of weight assigned to an exercise and is one of the most critical aspects of an ACL injury prevention program. However, it must be noted that initially the complexity and novelty of some exercises may necessitate that no external resistance be used to allow the athlete to properly control the movement. As with any athlete beginning a training program, motor learning is an important initial occurrence prior to actual muscle fiber hypertrophy and strength. Bodyweight may initially provide sufficient demands during early participation in ACL injury prevention programs. Once technique has been mastered, either exercise complexity can be increased or external resistance can be added. To keep the stimulus to level needed for adaptive response the intensity—or load—of exercise must be progressed to avoid plateaus in strength and motor control development [126]. When training with sufficient load (>80% 1 repetition maximum), healthy individuals can increase strength [127, 128] and power within 3 to 6 weeks [129].

Exercise volume (dose) can be defined using a variety of equations. For our purposes, we will consider volume to be related only to the total number of repetitions performed during a workout session [130–132]. A set is defined as a group of repetitions performed sequentially before an athlete rests [130]. There is an inverse dose-response indicating that the higher the neuromuscular training volume, the greater the prophylactic effectiveness of the training program relative to increased benefit in ACL injury reduction among female athletes [96, 133]. A meta-analysis examining dose-response determined programs more than 30 minutes per session in duration demonstrated 26% lower risk of ACL injury compared to programs performed 15 min or less [95, 96]. Thirty minutes is a relatively short amount of time to perform exercise each week and should be deemed the minimum time spent on this activity [96].

Step Four: Training Frequency

Training frequency refers to the number of training sessions completed in a given time period, typically the number of training sessions per week. Program emphasis, and therefore training frequency, may vary depending on time within a training cycle. While there are several methods to divide a training cycle, we will focus on three distinct cycles, preseason, in-season, and off-season. Each cycle, or season, has a specific goal and with that goal, a recommended ACL injury prevention training frequency. While each season has importance it should be noted that programs that incorporate both preseason and in-season programming have the greatest positive impact on biomechanics and injury reduction [32, 134–136].

Preseason

The preseason is used to prepare the athlete for the upcoming competition season. The goal of the preseason is to maximize the athlete's performance prior to competition. There is strong evidence that general preseason preparatory conditioning reduces overall injury risk. Likewise neuromuscular training implemented in as part of preseason conditioning is critical to alter high injury risk biomechanics and improve performance [49, 137–139]. In-season only ACL prevention strategies are limited in their potential to provide the adequate dosage and intensity to alter high risk biomechanics. Specifically, an intensive preseason ACL intervention reduced deficits points during the tuck jump assessment but no similar reductions were noted in an in-season only program [134–136]. These results are further supported by the data indicating that in-season only neuromuscular training program reduced ACL only in second half of season [32]. The concept of needed preseason ACL prevention is logical as it would not be expected prophylactic effect at the start of the season when risk is highest without adequate dosage that can be provided prior to initiation of competitive play.

In-season

In-season training scheduling presents logistical challenges such as limited practice time (NCAA restrictions) to dedicate to injury prevention versus sport skill development and training. Traditionally, three workouts per week are recommended by the majority of programs currently in place [43, 46, 57, 140], though some are performed five to six times per week by integrating into practice settings [34]. The loads and majority of these programs have athletes perform the assigned exercises before practices and/or games. With more experienced (intermediate or advanced) athletes, pre-practice or pre-game training can be augmented by using a split routine. Specifically, different muscle groups, movements, and exercises are trained on off days. Athletes training multiple times per week—as might occur as part of a sport-specific warm-up—demonstrated a 27% lower risk of ACL injury as compared to those training one time per week [133, 141].

Off-season

Often overlooked is what to do during the time athletes are not participating in formal practices or games. By definition, off-season lasts from the end of the season to the beginning of preseason. During these times, the authors advocate continuing to focus on alignment and technique while simultaneously training to improve muscular strength and endurance. Because preseason focuses so much on technique and alignment and in-season focuses on maintenance, off-season is when the majority of strength gains are made. Previously discussed was strength of the quadriceps, hamstrings, and hip abductors. Off-season is an ideal time to maximize the strength of those individual muscle groups while also using those muscles during more functional activities, like running and landing and jumping.

Step Five: Exercise Timing

In the context of ACL injury prevention, exercise timing refers to the placement of the assigned ACL injury prevention exercises when training. Although there are many ways to arrange exercises, decisions are invariably based on both convenience and how one exercise affects the quality of effort of other training sessions. Two primary approaches exist: performing the program combined with another training session (e.g., activity preparation/warm-up) or as a standalone training program.

Most ACL injury programs are performed in combination with other training sessions, specifically *prior to practice or games*, and have been shown to increase compliance [59]. Fatigue is a risk factor of ACL injury [90, 91, 93–98], therefore, performing exercises right *after other training sessions* is another option to consider. Learning and understanding how to properly move and land when fatigued is an important component of injury prevention and might be an option when considering the timing of ACL injury prevention programming. Therefore, while it should not be every session, purposeful performance of an ACL injury prevention program after other training sessions is recommended.

Another option is incorporating ACL injury prevention as a standalone program, especially during the off-season. Doing this will allow the athlete to better address strength and endurance at levels that are more conducive to the sought after gains [126]. Ultimately the most critical factor related to timing is when the season and schedule allow to get the best quantity and quality dosage of exercise targeted to reduce ACL injury risk factors [59, 96, 133, 141].

Conclusion

Well-designed ACL injury prevention programs are based on determined risk factors for injury and application of program design principles to minimize risk. Once those exercises are chosen, selecting the load and volume of those exercises is considered next. Finally, the training frequency, exercise order, and timing are done. Table 24.2 provides a sample program to reduce ACL injury risk.

Table 24.2 Putting it all together: Sample Program

<table>
<tr><th rowspan="2">Preseason</th><th rowspan="2">In-Season</th><th>Off-season</th></tr>
<tr><th>Two parts</th></tr>
<tr><td>GOAL
To prepare the athlete for the upcoming competition season by using sport-and movement-specific exercises</td><td>GOAL
To maintain the strength and movement quality developed during the preseason</td><td>GOAL
To increase strength and power while continuing to focus on proper movement quality</td></tr>
<tr><td rowspan="2">EXERCISES
Deadlift
Stability Hop
Single Leg RDL
Standing Long Jump
Single Leg Squat
Drop Jump
Nordic Hamstring Curl</td><td rowspan="2">EXERCISES
Stability Hop
Single Leg RDL
Standing Long Jump
Single Leg Squat
Drop Jump</td><td>EXERCISES—Plyometric
(Choose 4 for Part I, Choose other 4 for Part II)
Jump to Box
Jump From Box
Squat Jump
Single Leg Push Off
Standing Long Jump (SL)
Vertical Jump (SL)
Jump Over Object/Hurdle
Drop Jump</td></tr>
<tr><td>EXERCISES—Strength
(Choose 4 for Part I, Choose other 4 for Part II)
Deadlift
Double Leg Squat
Single Leg Squat
Double Leg RDL
Nordic Hamstring Curl
Lunge—Forward
Lunge—Lateral
Step Up</td></tr>
<tr><td>FREQUENCY
3×/week</td><td>FREQUENCY
2×/week</td><td>FREQUENCY
4×/week</td></tr>
<tr><td>SETS PER EXERCISE
3</td><td>SETS PER EXERCISE
2</td><td>SETS PER EXERCISE
4</td></tr>
<tr><td>REPETITIONS PER SET
10</td><td>REPETITIONS PER SET
8</td><td>REPETITIONS PER SET
8–15 (Depending on the Off-season phase)</td></tr>
</table>

Appendix:

1. Warm Up Exercises

- Skipping
  - Preparatory position
    - Athlete lifts leg to approximately 90° of hip and knee flexion.
  - Step One
    - Athlete jumps up and forward on one leg. Athlete's opposite leg should remain in the starting flexed position until landing. As one leg is lifted, athlete lifts opposite arm.
  - Step Two
    - Athlete lands on the same leg and immediately repeats the skip on the other side.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).

- Walking Hamstring Stretch
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete lowers torso by flexing the hips and lifts opposite leg backward while maintaining neutral lumbar alignment.
    - Athlete holds stretch position for one second, then steps backward while stretching.
  - Step Two
    - Athlete returns to preparatory position by extending the hips.
  - *Note*: This exercise can also be performed with a barbell or two dumbbells for resistance. With a barbell, the position described with the deadlift exercise is used and care must be used to ensure bar remains close to the athlete's thighs. With dumbbells, the dumbbells to hang at arm's length in front of the body throughout the exercise.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).

- Ankle Hop
  - Preparatory position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete hops up, with most of the motion occurring at the ankle joint.
  - Step Two
    - Athlete lands and immediately repeats the hop.
  - Alignment Cues
    - Minimal horizontal or lateral movement should occur.
    - Knees should not move inward (dynamic valgus).


- Tuck Jump
  - Preparatory position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete jumps up and pulls the knees to the chest. Athlete quickly grasps the knees with hands, and then releases.
  - Step Two
    - Athlete lands and immediately repeats the tuck jump.
  - Alignment Cues
    - Minimal horizontal or lateral movement should occur.
    - Knees should not move inward (dynamic valgus).


- Stability Hop—Front and Lateral
  - Preparatory position
    - Athlete assumes a comfortable, standing position on one foot. The athlete holds the non-jumping leg in a stationary position with the knee flexed.
  - Step One
    - Athlete performs a countermovement and explosively jumps forward and up; athlete may use both arms to assist.
  - Step Two
    - Athlete lands on the opposite leg and repeats the jump.
  - *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps is not the focus).
  - *Note*: This may also be performed to the side.
  - Alignment Cues
    - Knee should not move inward (dynamic valgus).

2. Strength Exercises

- Deadlift
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
    - Athlete squats down and grasps the bar with a closed, pronated grip. Athlete places hands on the bar slightly wider than shoulder-width apart with the arms outside the knees and elbows fully extended.
    - Athlete places positions the bar approximately 1 inch in front of the shins.
    - Athlete positions the body with the back flat, chest held up, head in line with the spine, weight balanced between the balls and heels of the feet; athlete looks straight ahead.
  - Step One
    - Athlete lifts the bar off the floor by extending the hips and knees.
    - Athlete maintains a flat-back position with elbows fully extended.
    - Athlete keeps the bar as close to the shins as possible.
    - Athlete moves the hips forward as the bar rises just above the knees.
    - Athlete continues until the body is fully erect.
  - Step Two
    - Athlete flexes the hips and knees to slowly lower the bar to the floor.

    - Athlete maintains a flat-back position with elbows fully extended.
    - Alignment Cues
      - Knees should not move inward (dynamic valgus).
      - Lumbar lordosis should remain.
      - Bar should not move too far forward.
      - Elbows should remain extended.

- Squat (Bilateral)
  - Preparatory Position
    - Athlete grasps the bar with a closed, pronated grip and steps under the bar and position the feet parallel to each other.
    - Athlete place the bar across the posterior deltoids and positions the body with chest held up, looking straight ahead.
    - Position the feet shoulder- to hip-width apart.
  - Step One
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete lowers body by flexing the hips and knees while maintaining a flat-back position, the heels on the floor, and the knees lined up over the second and third toes.
    - Athlete continues lowering until one of the following occurs:
      - The thighs are parallel to the floor.
      - The trunk begins to round forward.
      - The heels rise off the floor.
      - The knees move out of alignment.
  - Step Two
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete extends the hips and knees at the same rate with the heels on the floor and the knees properly aligned until the body is fully erect.
    - Alignment Cues

        - Knees should not move inward (dynamic valgus).
        - Lumbar lordosis should remain.
        - Knees should not move forward past the athlete's feet.

- Squat (Single Leg)
  - Preparatory Position
    - Athlete assumes a comfortable, standing position on one foot. The athlete places the other leg in a stationary position either in front or to the back on a bench.
  - Step One
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete lowers body by flexing the hips and knees while maintaining a flat-back position, the heel on the floor, and the knee lined up over the second and third toes.
    - Athlete continues lowering until one of the following occurs:
      - The thighs are parallel to the floor.
      - The trunk begins to round forward.
      - The heels rise off the floor.
      - The knees move out of alignment.
  - Step Two
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete extends the hip and knee at the same rate with the heel on the floor and the knee properly aligned until the body is fully erect.
    - Alignment Cues
      - Knee should not move inward (dynamic valgus).
      - Lumbar lordosis should remain.
      - Knee should not move forward past the athlete's feet.
      - Pelvis should remain level.

- Lunge—Forward and Lateral
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete takes one big step forward with the lead leg.
    - Athlete keeps the trailing foot in the starting position with the trailing knee slightly flexing.
    - Athlete plants the lead foot on the floor with the lead knee lined up over the second and third toes.
    - Athlete continues to lower the body until the trailing knee is 1–2 in. above the floor (trailing knee is not to contact the floor).
  - Step Two
    - Athlete maintains a position with the back flat and the chest up and forcefully pushes off the floor with the lead leg until the lead foot is next to the trailing foot.
  - *Note*: This exercise can also be performed with a barbell or two dumbbells for resistance. With a barbell, the position described with the squat exercise is used. With dumbbells, the dumbbells to hang at arm's length alongside the body throughout the exercise.
  - *Note*: This exercise can also be performed laterally by taking a big step to the side instead of forward during Step One.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Lumbar lordosis should remain.
    - Knees should not move forward past the athlete's feet.

- Step Up
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart in front of a box.
  - Step One
    - Athlete step up onto the box with the lead leg and places the entire foot on the top of the box.
    - Athlete maintains a position with the back flat and the chest up.
    - Athlete extends the lead hip and knee to move the trailing leg and body to a standing position on top of the box.
    - Athlete minimizes push off or hop up with the trailing leg or foot.
  - Step Two
    - Athlete step off the box with the same trailing leg. Athlete maintains a position with the back flat and the chest up.
    - Athlete places the trailing foot on the floor approximately 12 in. from the box.
    - Athlete shifts the body weight to the trailing leg when the trailing foot is in full contact with the floor.
    - Athlete steps off the box with the lead leg and brings the lead foot back to a position next to the trailing foot.

- *Note*: The box used should be 12–18 in. high so that a 90° knee angle occurs when the foot is on the box.
- *Note*: This exercise can also be performed with a barbell or two dumbbells for resistance. With a barbell, the position described with the squat exercise is used. With dumbbells, the dumbbells to hang at arm's length alongside the body throughout the exercise.
- Alignment Cues
  - Knees should not move inward (dynamic valgus).

- RDL (Bilateral)
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete flexes the knees to approximately 30° and keeps them in this position throughout this exercise.
    - Athlete lowers torso by flexing the hips and moving them backward while maintaining neutral lumbar alignment.
    - Athlete continues lowering until hands are level with bilateral patellar tendons or until moving lower changes lumbar position.
  - Step Two
    - Athlete returns to preparatory position by extending the hips.
  - *Note*: This exercise can also be performed with a barbell or two dumbbells for resistance. With a barbell, the position described with the deadlift exercise is used and care must be used to ensure bar remains close to the athlete's thighs. With dumbbells, the dumbbells to hang at arm's length in front of the body throughout the exercise.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Knees should not flex more than 30°.
    - Lumbar lordosis should remain.

- RDL (Single Leg)
  - Preparatory Position
    - Athlete assumes a comfortable, standing position on one foot. The athlete holds the non-exercising leg off the floor and it remains off the floor during the exercise.
  - Step One
    - Athlete flexes the knee of the exercising limb to approximately 30° and keeps them in this position throughout this exercise.
    - Athlete lowers torso by flexing the hips and moving them backward while maintaining neutral lumbar alignment.
    - Athlete continues lowering until hands are level with bilateral patellar tendons or until moving lower changes lumbar position.
    - Athlete allows non-exercising leg to move backward/posteriorly during this initial step.
  - Step Two
    - Athlete returns to preparatory position by extending the hips of the exercising leg and allowing the non-exercising leg to return to a position next to the exercising leg.
  - *Note*: This exercise can also be performed with a barbell, two dumbbells, or a kettlebell for resistance. With a barbell, the position described with the deadlift exercise is used and care must be used to ensure bar remains close to the athlete's thighs. With dumbbells, the dumbbells to hang at arm's length in front of the body throughout the exercise. With kettlebell, the athlete typically grasps the kettlebell in the contralateral hand.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Knees should not flex more than 30°.
    - Lumbar lordosis should remain.

- Nordic Hamstring Curl
  - Preparatory Position
    - Athlete kneels on the floor or foam pad with the feet held against the floor by a partner or machine.
  - Step One
    - Athlete leans forward by allowing knees to extend.
    - Athlete continues forward lean until holding such a position cannot be maintained or until the athlete touches the ground with the torso.
  - Step Two
    - Athlete returns to the preparatory position by activating the hamstring to flex the knees.
  - Alignment Cues
    - Maintain straight line from knees to shoulders (i.e., hips should neither flex nor extend).

- Knee Extension (Single Leg)
  - Preparatory Position
    - Athlete sits in the machine with the back held against the back pad and the anterior aspect of the ankles behind and in contact with the roller pad, and knees lined up with the axis of the machine.
  - Step One
    - Athlete lifts the roller pad by fully extending the knees.
  - Step Two
    - Athlete returns the knees to the preparatory position by allowing the knees to flex.
  - Alignment Cues
    - The back pad or the roller pad may need to be adjusted to properly position the legs.
    - Do not allow the hips to lift off the seat during the exercise.
    - Keep the torso erect and the back firmly pressed against the back pad.

3. Plyometrics

- Vertical Jump
  - Preparatory position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete performs a countermovement and explosively jumps up reaching for a target; athlete may use both arms to assist.

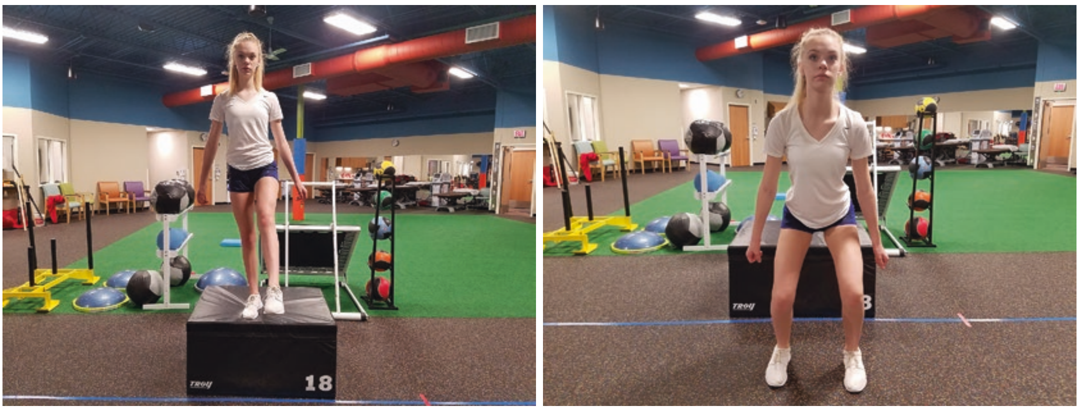
- Step Two
  - Athlete lands in the starting position and repeats the jump.
- *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps is not the focus).
- Alignment Cues
  - Knees should not move inward (dynamic valgus).
  - Minimal horizontal or lateral movement should occur.

- Squat Jump
  - Preparatory position
    - Athlete assumes a squat position with feet shoulder- to hip-width apart. Athlete places hands behind head.
  - Step One
    - Athlete explosively jumps without countermovement; because the hands are placed behind the head, athlete may neither reach for a target nor use the arms to assist.
  - Step Two
    - Athlete lands in the squat position and immediately repeats the jump.
  - *Note*: Athlete should not recover between jumps (i.e., speed between jumps and minimizing upper extremity involvement are the foci).
  - *Note*: Minimal horizontal or lateral movement should occur.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Minimal horizontal or lateral movement should occur.

- Standing Long Jump
  - Preparatory position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete performs a countermovement and explosively jumps forward and up; athlete may use both arms to assist.
  - Step Two
    - Athlete lands on both feet and repeats the jump.
  - *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps is not the focus).
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).

- Jump to Box
  - Preparatory Position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart in front of a plyometric box.
  - Step One
    - Athlete performs a countermovement and explosively jumps up and onto the top of the box using both legs; athlete may use both arms to assist.
  - Step Two
    - Athlete lands on both feet in a half squat position; athlete then steps down from the box and repeats.
  - *Note*: Intensity may be increased by increasing the height of the box. Begin with a height of 6 in.; boxes up to 42 in. high may be used.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).

- Jump from Box
  - Preparatory position
    - While on a plyometric box, athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete steps from box.
  - Step Two
    - Athlete lands on the floor with both feet and quickly absorbs the impact upon landing; athlete then steps back onto the box and repeats.
  - *Note*: Intensity may be increased by increasing the height of the box. Begin with a height of 12 in.; boxes up to 42 in. high may be used.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus) when landing.
    - When stepping from the box, step straight out. Athlete should not first jump up or step down, as these adjustments will change the height from which the exercise is performed.

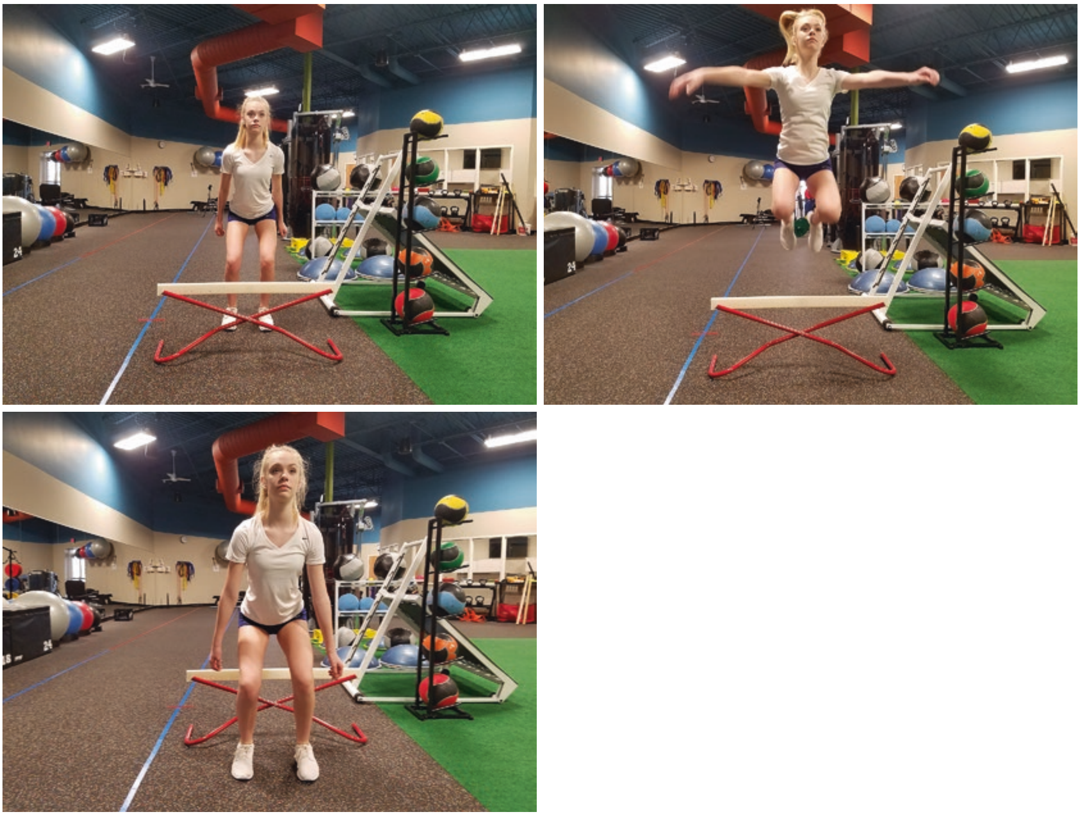


- Single Leg Box Push-Off
  - Preparatory position
    - Athlete stands next to a plyometric box with one foot on the ground and one foot on the box.
  - Step One:
    - Athlete jumps up using the foot on the box to push off.
  - Step Two
    - Athlete lands with the same foot on the box and immediately repeats the jump; the foot on the box should land just before the foot on the ground.
  - *Note*: Intensity may be increased by increasing the height of the box. Begin with a height of 6 in.; boxes up to 18 in. high may be used, depending on the athlete's height (i.e., taller athletes require taller boxes).
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Focus will be on height, assuming knee is properly aligned.

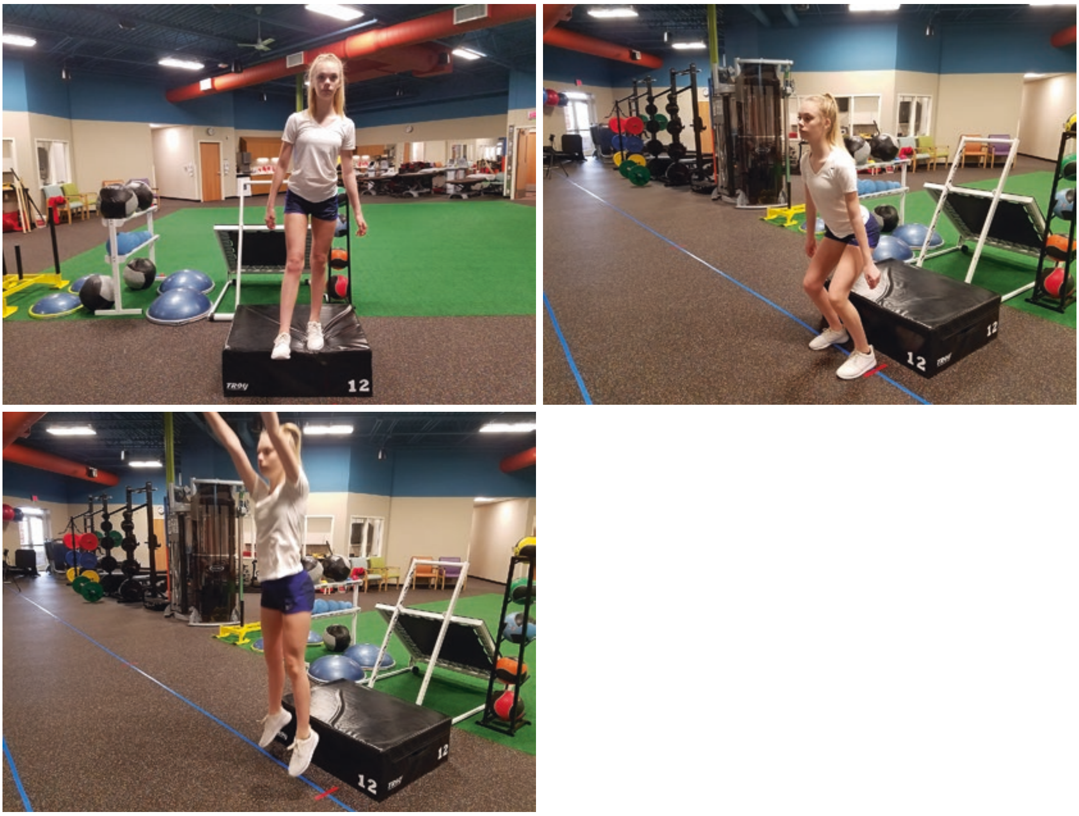
- Vertical Jump (Single Leg)
  - Preparatory position
    - Athlete assumes a comfortable, standing position on one foot. The athlete holds the non-jumping leg in a stationary position with the knee flexed during the exercise.
  - Step One
    - Athlete performs a countermovement and explosively jumps up reaching for a target; athlete may use both arms to assist.
  - Step Two
    - Athlete lands on the same leg in the starting position and repeats the jump.
  - *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps is not the focus).
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Minimal horizontal or lateral movement should occur.

- Standing Long Jump (Single Leg)
  - Preparatory position
    - Athlete assumes a comfortable, standing position on one foot. The athlete holds the non-jumping leg in a stationary position with the knee flexed during the exercise.
  - Step One
    - Athlete performs a countermovement and explosively jumps forward and up; athlete may use both arms to assist.
  - Step Two
    - Athlete lands on the same leg and repeats the jump.
  - *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps.
  - Alignment Cues
    - Knee should not move inward (dynamic valgus).

- Jump over Object/Hurdle
  - Preparatory position
    - Athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart in front of a barrier (e.g., cone or hurdle).
  - Step One
    - Athlete performs a countermovement and explosively jumps over a barrier with both legs, using primarily hip and knee flexion to clear the barrier.
  - Step Two
    - Athlete lands on both feet and repeats the jump.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - Keep the knees and feet together without lateral deviation.
  - *Note*: The height of the barrier should be progressively increased (e.g., from a cone to a hurdle).
  - *Note*: Athlete should briefly recover between jumps (i.e., speed between jumps is not the focus).



- Drop Jump (Bilateral)
  - Preparatory position
    - While on a plyometric box, athlete assumes a comfortable, standing position with feet shoulder- to hip-width apart.
  - Step One
    - Athlete steps from box.
  - Step Two
    - Athlete lands on the floor with both feet and immediately jumps up as high as possible; athlete then steps back onto the box and repeats.
  - *Note*: Intensity may be increased by increasing the height of the box. Begin with a height of 12 in.; boxes up to 42 in. high may be used.
  - Alignment Cues
    - Knees should not move inward (dynamic valgus).
    - When stepping from the box, step straight out. Athlete should not first jump up or step down, as these adjustments will change the height from which the exercise is performed.
    - Upon landing, time on the ground should be kept to a minimum and minimal horizontal or lateral movement should occur.
    - Knees should not move forward past the athlete's feet.



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25 New Horizons in ACL Surgery

Charles T. Mehlman

Introduction

Nonsurgically treated anterior cruciate ligament (ACL) ruptures convey a significant long-term risk of osteoarthritis of the knee as well as future need for total knee replacement surgery [1]. Surprisingly, ACL injury prevention programs [2, 3] and ACL surgical reconstruction [4] may only have a questionable impact on these long-term outcomes. In recent years this has led to renewed efforts at primary ACL repair and enhancing the healing process. These concepts are not new to orthopedic surgery.

Efforts at primary repair of the anterior cruciate ligament (ACL) have rather deep roots in the literature. In 1903 Mr. Mayo Robson (Leeds, England) reported delayed primary repair (36 weeks) of both cruciate ligaments in a 41-year-old coal miner [5]. In the first edition of Rockwood and Green (1975) Robert L. Larson stated in the author's preferred method of treatment section, "My opinion is that if satisfactory stabilization can be accomplished after suturing the acutely ruptured cruciate or cruciates, then nothing more need be done" [6]. Later studies of primary repair yielded disappointing results in both adults and children [7–10] and these techniques were subsequently all but abandoned in favor of a host of alternative reconstructive procedures. In recent years there has been renewed interest in primary repair of the ACL [11].

Enhanced Healing with Growth Factors

Several basic science studies have focused on enhancing the healing process following ACL reconstruction with ligament grafts. Targeted growth factors are felt to carry more promise than platelet rich plasma [12]. Bone marrow-derived mesenchymal stem cells have been shown to foster bone-tendon healing following ACL reconstruction [13, 14]. Basic science data focusing on the tendon-bone healing time period indicate that graft tensioning is associated with increased Indian Hedgehog signaling pathway as well as enhanced healing with local administration of growth factors [8, 15]. Recently a sheet of tendon derived stem cells has been shown to speed intra-articular graft healing in an animal model [16].

Navigation and Tunnel Placement

Based on advanced imaging techniques the accuracy of tunnel placement in ACL reconstructions has been questioned in recent years, with nearly 70% of grafts showing unfavorable placement [17, 18]. This has led to computer assisted and

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navigation supported approaches to tunnel placement [19, 20]. In the setting of revision ACL surgery Plaweski and colleagues showed statistically significant improvements in tunnel placement using this approach [17]. Other authors have questioned the value of such computer assisted ACL methods [21].

Intra-articular Environment Following Injury

In its natural state the ACL is intra-articular yet extra-synovial as it is simply enveloped by the synovial membrane [22]. This anatomic relationship is altered by injury in that the torn ligament becomes exposed to the synovial environment. Ruptured ligaments require stable fibrin clot formation in order to initiate healing, and this does not occur due to what Harrold termed "the defect of blood coagulation in joints" [23]. In contrast to the medial collateral ligament, repair associated growth factors (transforming growth factor beta) and key scar matrix proteins (collagen III) do not increase following ACL injury [24, 25]. A notable lack of tissue bridging and a strong tendency towards tissue retraction at the ACL rupture site has also been identified [26, 27]. It has been said that "the presence of a gap, even one less than 1 millimeter wide, can result in the failure of the suture repair" of the ACL [11].

Early Efforts at Primary Repair

In 1895 Robson used "catgut ligatures" for delayed primary repair of his patient's torn ACL and PCL [5]. After approximately 3 weeks of monitored wound healing a plaster of Paris cast was applied for an additional 4 weeks [5]. At 5 year follow-up the patient was said to be "perfectly strong," to walk without a limp, and to be working full 8 h days as a coal miner [5]. Don O'Donoghue, a giant in the history of sports medicine, had a busy orthopedic surgery practice where he began to surgically treat a large number of injured athletes. He used trans-osseous Number 3 twisted silk or number 10 cotton sutures to perform early primary repair of the ACL, often within a couple days of injury [28, 29]. This was a significant departure from the nonoperative treatment approaches of the day.

O'Donoghue's results were carefully documented and return to sporting activity was his main reported functional outcome [see Table 25.1]. The reaction of O'Donoghue's peers changed from initial disagreement to embracing these new aggressive concepts in ligament repair and this became the surgical standard over the next several decades [20, 28, 29]. O'Donoghue studied the results of primary ACL repair both in the predominately young Oklahoma athletic population that he treated as well as within the context of his dog research. In 1966 O'Donohue (and co-author Charles Rockwood) showed that primary ligament healing occurred in dogs provided there was no gap in the repaired tissue [30]. Long-term follow-up (up to 4 years) of these canine surgeries showed high rates of degenerative changes (65%) in the primary repair animals while iliotibial band reconstruction restored stability in others [31].

Primary Repair Embraced Then Rejected

In 1979 sports medicine researchers from the Hospital for Special Surgery reported their primary ACL repair technique (Fig. 25.1) [32]. This technique was aggressively used and by 1982 these same authors reported an average of just over 2 year follow-up on 70 primary repair patients and concluded "that primary repairs of mid-substance tears are technically possible and recommended in an athlete" [33]. Further follow-up was humbling. When a group of 52 primary repair patients were reported at over six and a half years average follow-up, a 17% failure rate and 42% abnormal laxity rate were identified and it was declared "an unpredictable operative procedure" [10]. Many other sports medicine centers reported similar disappointing results of primary repair [7, 9, 10, 34]. Subsequently enthusiasm soared for reconstructive techniques.

Table 25.1 Don O'Donoghue's series of primary knee repairs reported in 1950

Knee	Age	Sex	Side	Sport	Injury	F/U	Repair Ligament	Outcome
1	19 years	M	?	Football	Triad	10 years	Yes	Football at 9 months, norm knee at 10 years
2	?	M	Left	Football	MCL	1 year	Yes	Football at 6 months
3	Same pt		Right	Football	Triad	10 months	No	Football at 10 months, "bothered him"
4	19 years	M	Right	Football	Triad	7 years	Yes	Returned to football
5	Same pt		Left	"Injury"	ACL Med men	?	No	Pain and instability
6	16 years	M	?	Football	MCL Med men	2 years	Yes	Returned to football
7	18 years	M	?	Football	MCL Med men	3 years	Yes	Championship college football
8	22 years	M	Right	Football	Triad	3 years	Yes	All American
9	20 years	M	?	Football	MCL Med men	2 years	Yes	Basketball, baseball, football
10	24 years	M	?	Football	Triad	2 years	Yes	Football at 6 months, PRO football
11	20 years	M	?	Football	Triad	1 year	Yes	Championship football
12	20 years	M	?	Football	Triad PCL	1 year	Yes	Champion high jumper
13	24 years	M	?	Football	Triad PCL	1 year	Yes	PRO football
14	16 years	M	?	Football	MCL Med men	1 year	Yes	Returned to football
15	22 years	M	?	Football	Triad	1 year	Yes	"Normal activity"
16	23 years	M	?	Wrestling	Triad	10 months	Yes	Returned to wrestling
17	18 years	M	Right	Football	ACL MCL Lat men	9 months	Yes	ADLs OK, no football
18	19 years	M	Right	Football	Triad	?	Yes	ADLs OK, no football
19	30 years	M	?	Baseball	Triad	1 year	No	OK to work, no sports
20	16 years	M	Left	Football	ACL LCL Lat men	4 years	Yes	College and PRO basketball
21	24 years	M	?	Worker's Comp	Triad	?	Yes	Poor ROM, bad outcome
22	42 years	M	?	Worker's Comp	MCL	?	Yes	Poor ROM

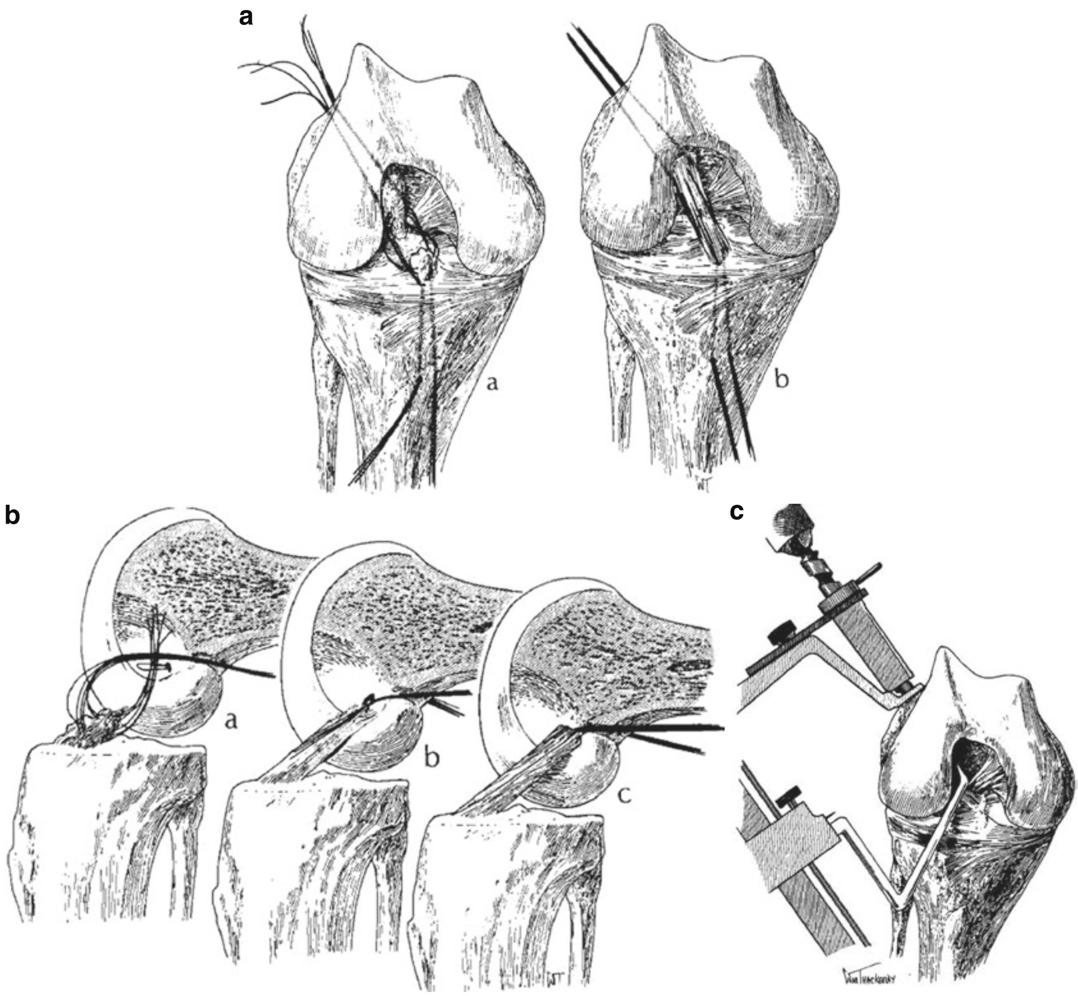

Fig. 25.1 Hospital for Special Surgery Primary Repair Technique. (**a**) Bidirectional suture technique aimed at approximating ligament tissue. (**b**) Attention to proper tension and anatomic placement. (**c**) Drill guide used for suture drill holes

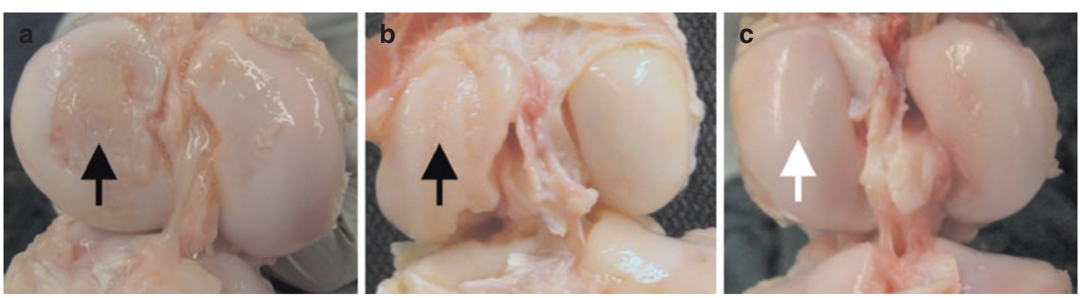

Fig. 25.2 Early porcine arthritic changes in three different settings at 1 year follow-up. (**a**) *Solid dark arrow* points to significant loss of articular cartilage following untreated ACL rupture. (**b**) *Solid dark arrow* points to detectable loss of articular cartilage following anterior cruciate ligament reconstruction. (**c**) *Solid light arrow* points to normal appearing articular cartilage following bio-enhanced primary anterior cruciate ligament repair

Contemporary Research Focused on Primary Repair

A new era of interest in primary ACL repair has been stimulated by disappointing results of injury prevention programs [2, 3], concern for increasing rates of ACL injury in children [35], and long-term outcomes following typical ACL surgical reconstruction techniques [4]. A series of basic science publications led by Martha Murray have incrementally demonstrated the feasibility of primary ACL repair in a porcine model [36–42]. Similar promising results have been found using a goat model [43, 44], and in a dog model [45]. Some of the most compelling animal data involve the 1 year comparison of untreated, conventional reconstruction, and bio-enhanced ACL repairs regarding early arthritic changes (Fig. 25.2) [46–48]. Applications of these concepts to humans (i.e., translational research) are still pending [49, 50].

Conclusion

This chapter has highlighted a diverse collection of research on the horizon aimed at improving the results of ACL surgery. Improving existing reconstructive techniques may be possible via computerized tunnel placement and growth factor enhanced graft healing. The case for primary repair of the ACL revolves around the noble concept of further improving results obtainable with current reconstructive techniques. The positive results of animal research have yet to be translated to the human setting. Abundant orthopedic examples exist that illustrate the dangers of early adoption of unproven techniques, so we must look upon these evolving techniques with an appropriately critical eye [51].

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