Anterior Cruciate Ligament Injury in the Skeletally Immature Patient: Diagnosis and Treatment

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Abstract

Significant intra-articular knee injuries, including tears of the anterior cruciate ligament (ACL), are now being recognized more frequently in skeletally immature patients. Previously reported data on ACL tears in this age group are sparse, and studies have been of limited quality. Improvements in diagnostic techniques (e.g., physical examination signs, arthrometric testing, magnetic resonance imaging, and arthroscopy) have facilitated identification of such injuries. Hemarthrosis must be regarded as a herald of a major intra-articular injury. Surgical reconstruction options vary according to the specific diagnosis and the stage of maturity, and the available options for the very skeletally immature patient are limited. Therefore, treatment must be predicated on assessment of maturity, as determined on the basis of chronologic, radiologic, and physiologic criteria. An ACL injury in this age group is not a surgical emergency; therefore, time for discussion with the patient and his or her parents is available, so that all appropriate options can be considered.

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A major effort has recently been made to analyze the normal function of the anterior cruciate ligament (ACL), as well as the sequelae of its injury. In the past decade more has been written about this relatively small (11 mm × 30 mm) bundle of collagen than about any other musculoskeletal structure. Information about ACL injuries and treatment has been widely disseminated to the general public because of such injuries among high-performance, celebrity athletes.

The introduction of new techniques to evaluate ACL integrity, including magnetic resonance (MR) imaging, arthrometry, and arthroscopy, has led to a heightened awareness of the frequency of ACL injury, particularly when associated with hemarthrosis. More specific findings obtainable during the history and physical examination (Lachman and pivot-shift tests) have also been emphasized. With the evolution of arthroscopic techniques, ACL reconstruction can now be performed with low morbidity and consistently reproducible good results.

Despite this wave of interest in ACL function and reconstruction, relatively little has been written on the diagnosis and treatment of ACL injury in the skeletally immature patient. Much of what has been published has been lacking in quality, definition of maturity, patient numbers, and duration of follow-up.

The true incidence and prevalence of acute and chronic ACL injuries in skeletally immature patients are unknown. In the past, cases of very young children with ACL injuries were reported as curiosities, and most cases of ACL injuries in the early or middle adolescent years were incorporated into adult series, making their data and results difficult to separate. Recent series that have addressed the "skeletally immature patient" suffer from a variety of inadequacies in study design, including lack of specificity of diagnosis and lack of documentation of skeletal immaturity. It is nevertheless clear that trauma due to sports-related and motor-vehicle accidents has certainly increased the number of these injuries in children. Stanitski et al,[1] Angel and Hall,[2] and others[3-9] have documented a significant number of cases in which skeletally immature patients sustained ACL injuries, either partial or complete, independent of tibial eminence fractures.

Developmental Considerations

In children, the ACL is attached to a perichondral cuff of the proximal tibial and distal femoral chondro-

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epiphyses. With maturity, this junction progresses to the fibrocartilage-bone attachment seen in adults. In children and young adolescents, the blood supply to the ACL is through its perisynovial sheath and the terminal elements of the tibia and femur.

Guzzanti et al[10] recently presented experimental data on the effects of intra-articular ACL reconstruction on physeal growth in rabbits. In their lapin model, semitendinosus reconstruction was done through 2-mm-diameter tibial and femoral tunnels. Histologic examination of specimens obtained up to 6 months postoperatively showed no evidence of premature epiphysiodesis. Cross section of the femoral physis showed 11% involvement in the frontal plane and 3% involvement in the anteroposterior plane, but no alteration in growth or axial deviation was noted. Tibial cross section showed 12% involvement in the frontal plane and 4% involvement in the anteroposterior plane. Two tibiae developed valgus deformities, and one tibia became shortened. This elegant research points out the need to evaluate the percentage of potential physeal closure before attempting intra-articular reconstruction of the ACL. The safe threshold percentage of tibial and femoral physeal transgression in humans is as yet unknown.

Natural History of ACL Injury

There have been few natural history reviews of isolated acute ACL injury in skeletally immature patients. As stated earlier, many previous reports suffer from a multitude of deficiencies in study design, including small patient numbers, mixed ages and genders, varied athletic demands and treatment protocols, inadequate definition of mechanism of injury (contact versus noncontact) and duration, differing methods of data collection (prospective versus retrospective), varied evaluation criteria, and lack of defined control groups. A major deficiency of most studies is the lack of diagnosis specificity, particularly with associated injuries (e.g., articular, meniscal, and other ligamentous injuries). Researchers have attempted to explain the four- to sixfold greater incidence of acute ACL injuries in the female population,[11] including adolescent girls, on the basis of their more generalized ligamentous laxity and/or morphologic differences in the femoral notch (Fig. 1). The cause of this high frequency of injury has still not been determined.

With the use of phone and mail questionnaires, Angel and Hall[2] retrospectively studied the data on 27 children with arthroscopically documented acute ACL injuries. The study was conducted an average of 51 months after injury. The mean patient age at initial injury was 14.5 years (range, 8 to 18 years), and the mean age at follow-up was 19.2 years. Eighteen patients had partial tears. Twenty-five patients were treated with a physical therapy program, no immobilization, and no activity limitations or bracing. At follow-up, 15 of the 27 patients reported giving way with mild pain, 11 returned to full sports activity, 7 returned to lower-level play, and 9 were unable to participate; this pattern is similar to that seen in adults. Eleven of 12 patients under 14 were not satisfied with their knee function.

Graf et al[4] assessed 12 reportedly skeletally immature patients with intrasubstance ACL tears. Arthroscopy confirmed eight meniscal tears (four medial and four lateral) in 6 of the 12 patients, who ranged in age from 11 to 16 years. There was no

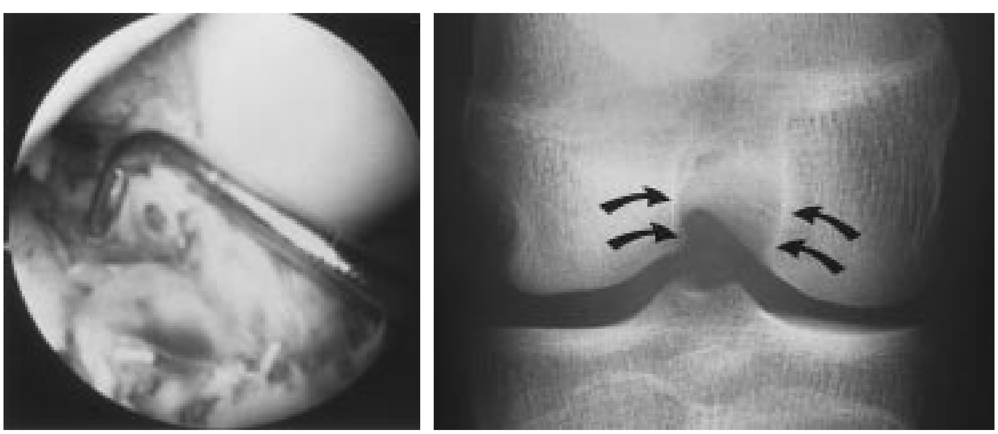

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Fig. 1 **A,** Arthroscopic view of a complete acute ACL tear in a premenarchal 13-year-old female basketball player with a very narrow femoral notch. **B,** Radiograph of same patient shows diminished notch configuration (arrows).

specific mention of the amount of physeal closure or the degree of physiologic maturity. Two patients underwent extra-articular ligament reconstruction, and 2 had an over-the-top semitendinosus intra-articular repair. Of the 8 patients who did not undergo initial reconstruction and for whom neither rehabilitation nor activity modifications were prescribed, 7 had evidence of new meniscal tears with recurrent episodes of instability during the mean follow-up period of 15 months.

The question remains, "How many patients do not seek care at the time of the initial or repeat injury (either a partial or a complete tear)?" It has been suggested that instability and dysfunction usually occur within the 6 months after the acute primary injury. Over the past decade, it has been fairly well agreed that if a patient has a compromised ACL, return to high-demand sports will cause recurrence of symptoms, persistent feelings of instability, and progressive damage to articular cartilage and other intra-articular structures, the so-called ACL syndrome.[9,12]

The fate of the knee with a partially torn ACL is a subject for debate.[13,14] Buckley et al[14] reviewed the cases of 35 young adults with arthroscopically documented partial ACL tears. A nonoperative program of protected early weight-bearing and range-of-motion and strengthening exercises had been prescribed. At an average follow-up of 41 months, 86% of the patients were minimally symptomatic, and 40% had returned to their preinjury level of performance. With minimal anterior translation and no rotatory instability, partial ACL injuries with intact secondary restraints appeared to do well 3 to 4 years after injury. The amount of acute or repetitive injury required to convert a partial tear with an attenuated ligament to a complete tear has not been ascertained, nor has the percentage of damage to each bundle been quantitated to allow classification of partial and complete tears (Fig. 2).

Functional complaints are diminished in patients who alter the intensity of sport demands. Follow-up studies of skeletally immature patients who elected such changes in sports activity have, unfortunately, been limited in both population size and duration of follow-up. Alteration of participation is often a self-selection process chosen for reasons totally unrelated to knee function. It is not uncommon for a joint to function well in the pediatric age range and longer in the face of instability (e.g., developmental dysplasia of the hip). Symptom onset is commonly delayed until the third or fourth decade.

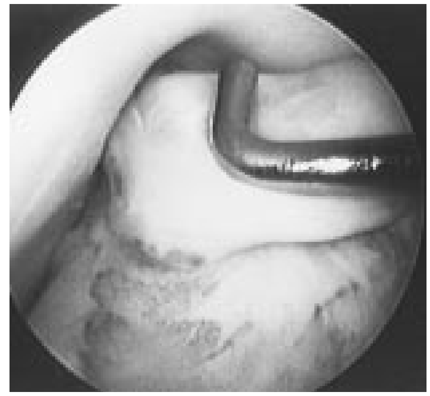


Fig. 2 "Partial" ACL tear with loss of 90% of the posterior lateral bundle (behind probe).

Diagnosis of ACL Injury

History

Harvell et al,[15] Angel and Hall,[2] and others[5] found that, compared with arthroscopic assessment, even the best attempts at obtaining an accurate history and a thorough physical examination correlated poorly with a correct preoperative diagnosis, especially in the acute injury setting. I characterize the mechanism of injury and its severity on the basis of whether there has been contact and whether there is a deceleration or rotation component to the injury; in general, injuries without an element of contact, deceleration, or rotation are less likely to be associated with an ACL tear. Injuries are temporally characterized as being acute if present for less than 3 weeks, subacute if present for 3 to 12 weeks, and chronic if present for more than 12 weeks. Sports risks and demands should also be assessed (Table 1).

Table 1
Demands on the ACL in Various Sports

High demand
Football
Hockey (ice or field)
Basketball
Lacrosse
Gymnastics
Wrestling
Volleyball
Moderate demand
Baseball
Softball
Track
Tennis
Low demand
Swimming
Crew
Jogging

Physical Examination

Physical examination is difficult in the acute phase because of limited patient cooperation. Range of motion; tenderness at the collateral ligament and/or joint line, the femoral or tibial physis, or the patellar retinaculum; and presence of an effusion should be noted. Physiologic laxity, which may be significant in children, particularly girls, must be assessed in all planes. The motion and laxity of the opposite knee are used as a baseline if there was no previous injury to that knee. Translation and rotation tests should be assessed not only for magnitude but also for the quality of the end point. Use of arthrometers may provide baseline uniplanar information and side-to-side comparison, which may vary with age.

Imaging

Imaging evaluation of the knee begins with a routine four-view radiographic series (anteroposterior, lateral, skyline, and tunnel views). Routine films can be used to assess malformation in the tibial spine and / or femoral notch, which is commonly seen in patients with congenital absence of the ACL (Fig. 3). In the case of an acute contact injury, comparison and stress views are needed if tibial and / or femoral epiphyseal fractures are suspected. The amount of tibial and femoral physeal closure can be noted on routine radiographs (Fig. 4). Computed tomographic scans and tomograms may also be used to assess the structure of the notch and the degree of epiphyseal closure. Physeal mapping may be done when skeletal maturity is in question.

Magnetic resonance imaging is commonly overused. Many children undergo MR imaging studies before physical examination and routine radiography. Magnetic resonance images are also commonly overread, with supposed "degenerative" meniscal changes in young patients often reported. Unless the study is properly done, tears of the ACL may be difficult to visualize with MR imaging, which is extremely dependent on the specificity, shape, and thickness of the individual sections. This is particularly true in trying to identify partial ACL tears. Limitation of range of motion may cause difficulties with patient positioning for optimal imaging. An MR study can be useful for assessing the status of maturity of the femoral and tibial epiphyses (Fig. 5).

Kloeppel-Wirth et al[5] evaluated the clinical and arthroscopic findings in 35 children aged 4 to 15 years. Seven patients had a complete ACL tear, and 2 had a partial tear. The clinical and arthroscopic findings correlated in only 12 of the 35 cases.

Stanitski et al[1] reported on 70 patients with hemarthrosis who underwent arthroscopy. Of the preadolescents (aged 7 to 12 years), 47% had meniscal tears, and 47% had ACL tears. Of the 55 adolescent patients (equally divided between 13- and 15-year-olds and 16- and 18-year-olds), 45% had meniscal tears, and 65% had ACL tears. Osteochondral injuries accounted for 7% of the lesions. In the preadolescent group, 58% of the ACL tears were partial, with the loci of injury equally divided among proximal, middle, and distal sites. In adolescents with ACL tears, 60% were partial, with proximal, middle, and distal tears equally represented. Eighteen percent of the adolescents had a combination meniscus-ACL tear. The ACL tear was the source of the hemarthrosis in 63% of the 70 cases. Sixty-five percent of all ACL tears were partial. The diagnosis of a partial ACL tear is difficult without arthroscopic verification.

Angel and Hall[2] retrospectively reviewed the findings in 202 children who underwent knee arthroscopy. They found tears of the ACL in 2 preadolescents and 25 adolescents. The frequency of meniscal injury was higher in the adolescent group. Of the 27 ACL injuries, 18 were partial.

Assessment of Maturity

Physical maturity is a dynamic process. The path of skeletal growth

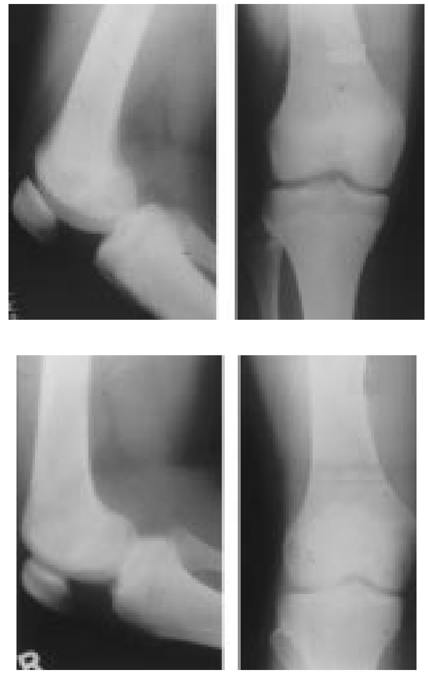
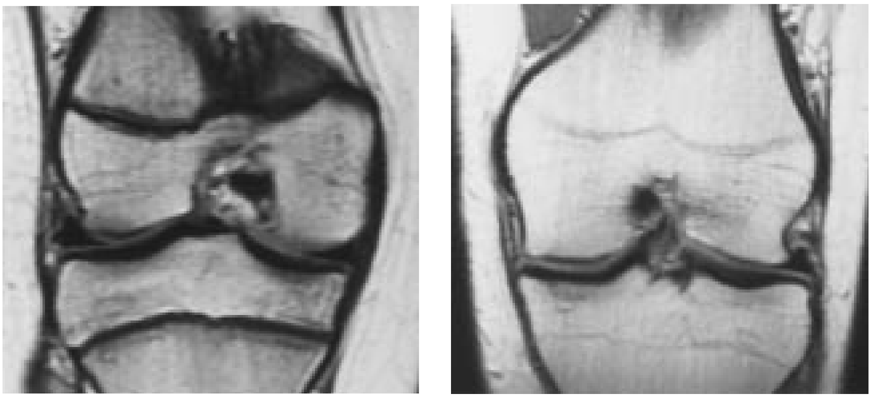


Fig. 4 Radiographs of two skeletally mature girls, aged 10 years 11 months **(top)** and 13 years 7 months **(bottom)**.

Fig. 3 Anteroposterior radiograph of an 8-year-old boy with fibular hemimelia. Note the flat notch and underdevelopment of the tibial spines in the right knee (seen at left). Left knee is normal.



A B

Fig. 5 Magnetic resonance images used to evaluate tibial and femoral physeal closure. **A,** Immature subject. **B,** Mature subject.

toward epiphyseal closure and adulthood is marked by variance of growth in terms of its onset, duration, rate, and magnitude. Maturity is evaluated on chronologic, physiologic, and radiologic bases. Chronologic and skeletal age usually follow a very concordant path.[16,17]

Family height is an index of growth potential and ultimate adult height. A rough guide to adult height is provided by ascertaining the child's height at the age of 2 years in girls and 2.5 years in boys. Doubling that height gives one an estimate of adult height. This anthropometric determination is less accurate at the extremes of the growth curve.[16]

Tanner and Davies[17] reported on normal growth curves in North American children in 1985. They noted that the adolescent growth spurt begins at an average of 10.5 years in girls and 12.5 years in boys and that peak height velocity occurs at 11.5 years in girls and 13.5 years in boys. Cessation of changes in shoe size is a useful indicator of growth deceleration since feet reach approximately 95% of their adult size by age 12.5 years in girls and 14 years in boys.[16] Menarche is preceded by the period of peak height velocity, with rapid growth diminution following menarche. In girls involved in long-term, high-demand athletics, menarche may be significantly delayed. Clinical examination allows one to assess aspects of physical maturity on the basis of the Tanner grading scale of development of secondary sexual characteristics.[17] Development of pigmented axillary and pubic hair in boys is approximately equivalent physiologically to the onset of menarche.

The use of imaging techniques to establish maturity suffers from potential inaccuracies because of the wide range of normal values. This is particularly true of bone-age determination, in which standards are based on the fairly uniform genetic pool used for estimation almost 50 years ago. Whether those standards hold true for the multicultural society of America today is unknown.

Tibial Eminence Fracture

Fractures of the tibial eminence are a special type of injury to the ACL complex (Fig. 6). Most preadolescent patients with such fractures have been injured in bicycle accidents.

Baxter and Wiley[19] examined 45 patients in whom tibial eminence fractures had been diagnosed 3 to 10 years previously. Fractures that had been partially or completely displaced were associated with ACL laxity, with positive Lachman and anterior drawer tests on arthrometric studies. Type III injuries were much more common in children over the age of 11, but the mean results of instrumented laxity testing in this group were not different from those in younger patients. No patient complained of instability, although 51% of them had clinical and arthrometric evidence of positive anterior drawer tests. None of the patients had a pivot shift. The functional demands of the patients were not assessed. Associated injuries (medial collateral ligament and / or meniscal) were not addressed. The lack of a pivot shift suggests that the secondary restraints were intact despite abnormal anterior translation in the sagittal plane.

Arthroscopically guided fracture reduction and fixation and evaluation of other intra-articular disorders has become popular. Mylle et al[20] report use of screw fixation for an eminence fracture in an 11-year-old girl in whom growth asymmetry and a hyperextension deformity subsequently developed. The authors now recommend using an arthroscopically guided screw that does not cross the physeal line (Fig. 7).

Almost all patients with eminence fractures demonstrate evidence of some residual laxity in the sagittal plane as indicated by either Lachman or anterior drawer tests, but most authors have not evaluated rotatory instability either preoperatively or at follow-up. In general, if the patients had no evidence of rotatory instability, sagittal-plane instability remained asymptomatic.

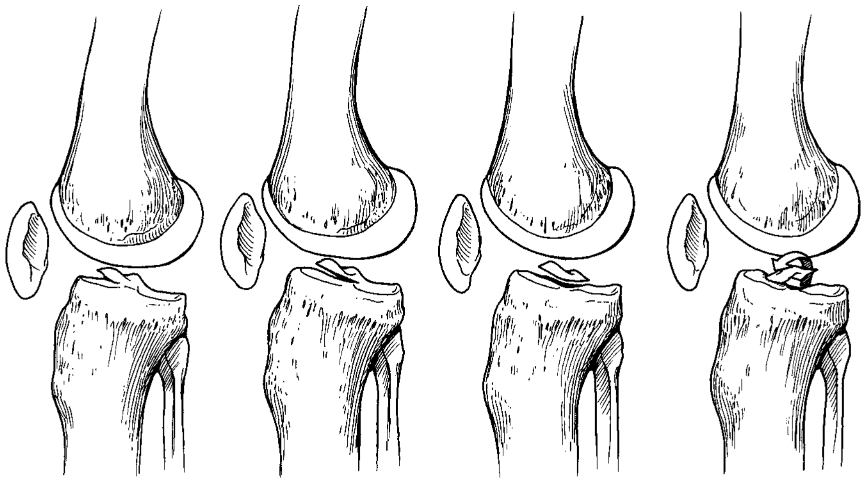


Fig. 6 The tibial eminence fracture classification developed by Zaricznyj.[18] A type III fracture is characterized by a displaced and rotated fragment and may be comminuted.

Anterior cruciate ligament injuries may be seen in other fracture patterns about the knee in the skeletally immature patient. Bertin and Goble[21] reviewed the data on 16 boys who had suffered a distal femoral physeal fracture at a mean age of 12 years. Six had positive Lachman and anterior drawer tests. Five of 13 patients with fractures of the proximal tibial epiphysis had positive Lachman and anterior drawer tests. No data were given concerning rotatory instability. Ligament stability should be checked in patients with femoral and tibial fractures so that a ligamentous lesion is not missed in the urgency of physeal injury management.

Treatment

The treatment of ACL injuries in the child and young adolescent remains controversial. No consensus has been reached because of the paucity of data that are accurate, objective, and sufficient in length of follow-up. The initial 30% plastic deformation of the ligament before rupture sets the stage for absorption. Inflammatory changes and degeneration of the ends begin within 48 hours after injury. This rapid inflammatory challenge, coupled with the attenuation of the ligament, dooms any direct repair. The presence of hostile metalloproteases and cytokine-mediated inflammatory factors also affects the healing potential of acute direct ligament repair. Transcartilaginous avulsions that are not visualized radiologically may also occur.

The role of functional braces to control instability following ACL injury continues to be debated. Patients with mild laxity under low-load conditions appear to gain the greatest improvement from bracing. The mechanism of brace efficacy is unknown. Improved proprioceptive feedback while using the orthotic device has been suggested. Proper fit of a functional brace is often difficult in young patients because of their lesser leg length and girth. Customized braces may be required. Use of a functional brace in conjunction with a comprehensive rehabilitation program may allow temporization until the patient becomes more skeletally mature, at which time a complete transphyseal reconstruction can be done. The high cost of functional braces makes them prohibitive for some.

An ACL injury is not a surgical emergency. Unfortunately, many children use professional athletes as their role models and commonly expect and demand immediate return to play when it is prejudicial to long-term knee function. The patient and his or her family must understand the rehabilitation effort and the time necessary for any of the treatment options.

An accurate initial diagnosis is imperative so that proper treatment can be outlined. From a combina-

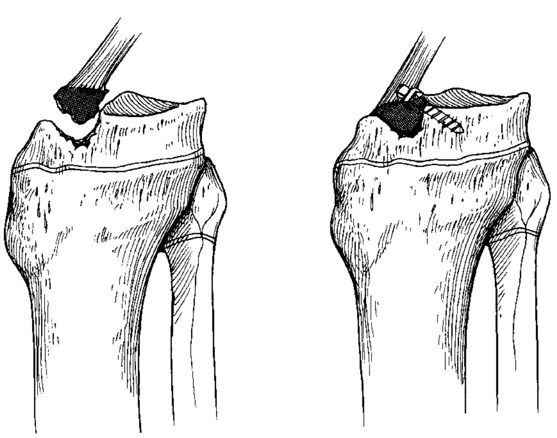


Fig. 7 Technique for internal fixation of a tibial eminence fracture, in which the displaced fragment **(left)** is reduced anatomically and fixed without physeal invasion **(right)**.

tion of data from the history, physical examination, and imaging studies (Table 2), an informed decision can be made, and an appropriate treatment program can be outlined, be it operative or nonoperative. Diagnostic arthroscopy can be added to the evaluation if diagnostic doubts still exist.

Table 2
Considerations in Diagnostic Evaluation of Suspected ACL Injury*

History
Presence of a “pop”
Mechanism of injury
Effusion onset
Ability to return to play
Previous injury and treatment
Physical examination
Range of motion
Stability testing
Effusion
Patellar signs
Joint-line tenderness
Imaging
Knee radiographs (four views)
MR imaging
CT/tomography
Diagnostic arthroscopy
Examination under anesthesia: stability tests
Articular injury
Meniscal injury
ACL status
MCL/LCL status

*Abbreviations: CT, computed tomography; LCL, lateral collateral ligament; MCL, medial collateral ligament.

Nonoperative Management

Nonoperative management of acute ACL tears consists of a three-phase program:

Phase I includes crutch-protected weight-bearing; daily active, active-assisted, and passive range-of-motion exercises; and use of a knee immobilizer for comfort. This phase normally lasts 7 to 10 days. The patient and the parents are also counseled about the treatment options, which include the need for activity modification, with reduction and/or elimination of sports that place high demands on ACL function (e.g., rapid acceleration/deceleration and change in direction with or without contact).

Phase II is an objectively monitored and documented rehabilitation effort to restore normal muscle balance to the lower extremity, with particular emphasis on normalization of the quadriceps-hamstring strength ratio and attainment of complete range of motion. This phase normally lasts up to 6 weeks.

Phase III consists of use of a functional brace and continued maintenance rehabilitation. Return to low- and moderate-demand sports is allowed when knee range of motion is full and lower-extremity strength is equal to that on the uninjured side. There is no unanimity of opinion on the timing of use of functional braces (e.g., only during sport participation versus full-time). The goal of treatment is to prevent recurrent injury so as to avoid intra-articular damage and premature degenerative arthrosis.

Operative Management

Operative management options include intra-articular reconstruction and intra-articular plus extra-articular procedures. Intra-articular reconstructions include physis-sparing and partial or complete transphyseal procedures. Isolated extra-articular reconstructions are not recommended.

Reapproximation of femoral or tibial ACL avulsion by direct suturing, with avoidance of the physis, is an example of a physis-sparing technique. Autograft tendon augmentation with the use of patellar tendon or hamstring grafts brought in continuity for an over-the-top repair also eliminates physeal invasion (Fig. 8). A disadvantage of this type of physis-sparing procedure is lack of isometry.

In partial transphyseal procedures, hamstring or patellar tendon grafts are brought in continuity through a drill hole in the central tibial physis and placed in an over-the-top femoral position (Fig. 9). An example of complete transphyseal surgery is placement of a hamstring or patellar tendon-bone complex through a tibial and femoral tunnel (Fig. 10).

In 1963, Jones reported 11 cases of transfer of the central third of the patellar tendon, which was left attached to the tibial tubercle and fixed into a femoral drill hole with a patellar bone plug. Two of his patients were 14-year-old boys. In a follow-up article in 1970, Jones[22] reported the data on 46 patients at an average follow-up of 110 weeks. Included in his patient group were 14 adolescents (3 aged 14 years and 11 aged 15 through 17 years) with an average follow-up of 7 months. Jones stated that “the possibility of early closure was considered, but did not prove to be significant.” No documentation of physiologic or radiologic skeletal maturity was mentioned. All patients were reported to be doing well.

Lipscomb and Anderson[6] reported their experience with intra-articular semitendinosus and gracilis tendon autograft reconstructions combined with extra-articular procedures in 24 patients aged 12 to 15 years, with an average follow-up of 35 months. These patients represented a subset of 710 patients who underwent ACL reconstruction during the same 6-year period. Although 11 of the patients reportedly had completely open physes, they were not specifically identified by age or sex; neither were the 13 patients characterized as having partly open physes. No further assessment of skeletal maturity was reported. Ten were treated for acute injuries and 14 for chronic injuries; reconstruction was performed

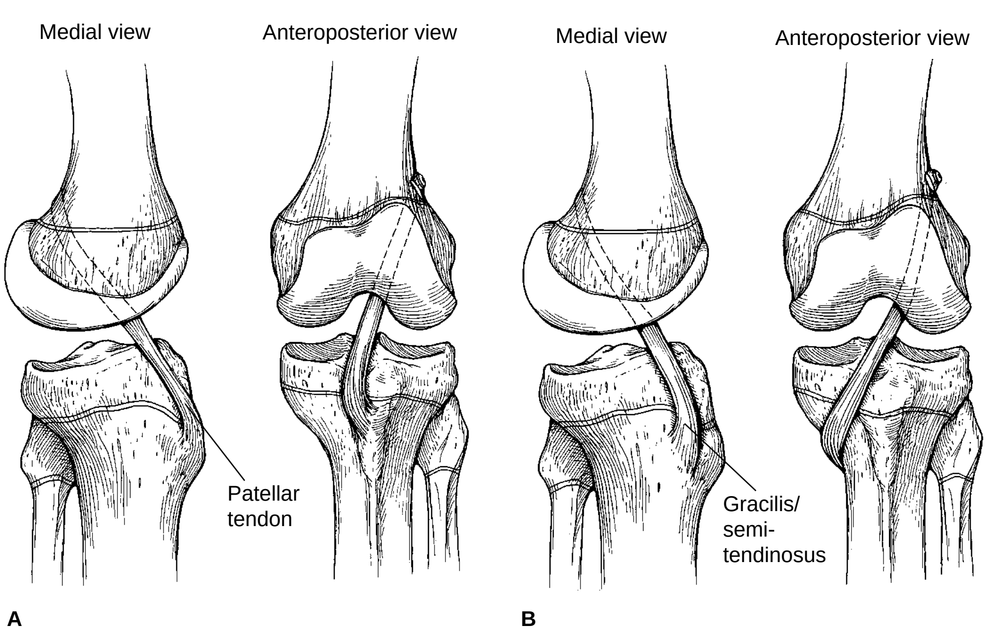


Fig. 8 Nontransphyseal ACL reconstruction using a patellar tendon **(A)** or a semitendinosus/gracilis autograft **(B).**

through a 16-mm tibial tunnel. Nineteen menisci were excised, and four were repaired. Postoperative objective testing showed good to excellent results in most patients. In one case the involved limb was shortened by 2 cm, which was attributed to direct stapling of the femoral and tibial epiphyses during an open (nonarthroscopic) procedure. At follow-up, 68% of the patients had evidence of Fairbank's radiographic changes.

Brief[23] recently reported on the use of a semitendinosus-gracilis tendon combination as an intra-articular in-continuity graft passed under the anterior meniscal horns and coronary ligament and brought to an over-the-top femoral position. An iliotibial-band tenodesis was also performed. Of the nine patients, five were younger than 16 years. No documentation of skeletal maturity was given. Data from five of the patients analyzed objectively at various times during the 36-month follow-up period suggested that the grafts underwent additional excursion between the 6th and 18th months postoperatively, with no further laxity seen over the subsequent 18 months.

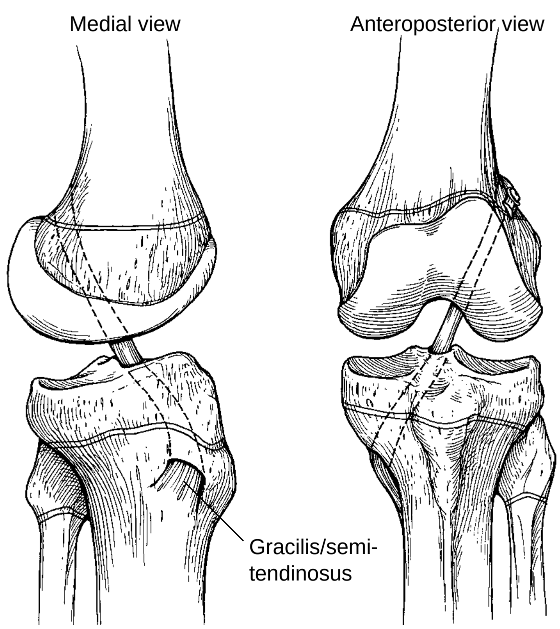


Fig. 9 Partial transphyseal ACL reconstruction in which a central patellar or hamstring tendon graft is fixed in the over-the-top femoral position.

Fowler[8] reported on intra-articular reconstruction using in-continuity hamstring or patellar-quadriceps tendon in 29 patients under the age of 14 years (some were as young as 8 years old). A well-directed, nonoperative treatment program had proved a failure for all patients. The reconstruction was done through a 6-mm tibial tunnel placed somewhat more vertically than usual to improve isometry. Femoral fixation

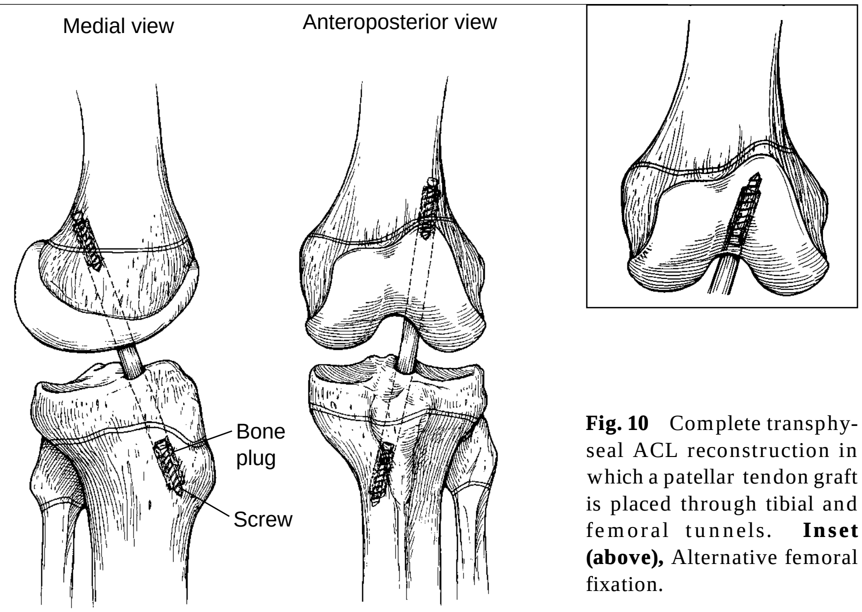


Fig. 10 Complete transphyseal ACL reconstruction in which a patellar tendon graft is placed through tibial and femoral tunnels. **Inset (above),** Alternative femoral fixation.

was in an over-the-top position (Fig. 11). All returned to preoperative activities without reported limb-length deficiencies or deformity.

In a recent article by Parker et al,[24] six patients underwent ACL reconstruction using in-continuity hamstring-tendon grafts placed in a groove across the anterior tibia and brought into an over-the-top femoral position without violation of the physes. In an attempt to improve the isometry of the transferred hamstring tissue, the over-the-top position was augmented with a groove in the femoral metaphysis, with care taken to avoid the physeal line. Three of the six patients also underwent direct repair of the ACL. At follow-up averaging 32 months, four of five patients evaluated had returned to maximum preinjury levels of sports participation. Objective testing demonstrated excellent anatomic and functional results. All patients had previously undergone rehabilitation according to a vigorous nonoperative protocol. The patients ranged in age from 10.3 to 14.1 years preoperatively and had open distal femoral and proximal tibial physes. No physiologic characterization of maturity was reported. In the short follow-up, no evidence of untoward effects on the physes was seen.

Fig. 11 Postoperative MR image of a 10-year-old boy who underwent ACL reconstruction with use of a 6-mm semitendinosus graft passed through a transphyseal tibial tunnel and fixed in the over-the-top femoral position. (Courtesy of Peter Fowler, MD, London, Ontario, Canada.)

Andrews et al[25] recently reported on the use of a 7-mm fascia lata or Achilles tendon allograft placed through a tibial drill hole and fastened in the over-the-top femoral position. This is the initial report on use of allograft tissue for ACL reconstruction in skeletally immature patients. The eight patients in this series ranged from 10 to 15 years of age and were reported to have evidence of open growth plates on routine radiographs. At an average follow-up of 58 months, objective and subjective analysis showed six excellent results and one good and one fair result. Preoperatively, the authors evaluated skeletal maturity by radiologic bone-age assessment and physiologic maturity by Tanner scoring of secondary sex characteristics. Unfortunately, they did not correlate these factors with chronologic age, either pre- or postoperatively. Before hardware removal, one patient required arthroscopic management of a flexion contracture that caused patellofemoral symptoms. One graft reruptured 4 years postoperatively when the patient engaged in vigorous athletic activity.

McCarroll et al[7] reported on 40 patients under the age of 14 years who were treated for ACL insufficiency. Twenty-four patients underwent surgery (14 intra-articular and 10 extra-articular procedures). The end-point analysis was the ability to return to athletics, which was achieved by all 24 surgical patients. In contrast, of the 16 patients treated nonoperatively, only 7 returned to their sport. In this retrospective review of an uncontrolled series of patients, no documentation of maturity by physiologic or radiologic criteria was given. Only 37% of the patients in the nonoperative group had arthroscopically documented pathologic changes. Intra-articular lesions other than the ACL tear may have been responsible for treatment failure in the nonoperative group, in which the criteria for inclusion were not as well defined as in the operative group.[26]

In a more recent study, McCarroll et al[27] reported the data on 58 skeletally immature patients who were followed up for an average of 4.3 years after treatment of acute, arthroscopically documented complete ACL midsubstance tears. The 38 patients who were classified as being in Tanner stage 1 or 2 were initially treated nonoperatively. The 20 more mature patients underwent complete transphyseal primary reconstructions with patellar tendon grafts through 10-mm tunnels. Symptomatic meniscal tears developed in 27 of the initial 38 patients in the nonoperative group. All underwent complete transphyseal reconstruction at further maturity for persistent activity-related instability. Ninety percent of the patients returned to prior levels of sports activity. None had radiographic or clinical evidence of abnormal femoral or tibial growth. This study assessed a homogeneous group of patients with documented pathologic changes who were ultimately treated in a standard manner. The authors emphasize the need for avoidance of high-risk sports if the nonoperative course is chosen. In very immature patients, they suggest postponement of ACL reconstruction until an adult-type complete transphyseal procedure can be done.

Some surgeons use extra-articular repair alone or in combination with intra-articular procedures as a means of buying time in skeletally immature patients.[4,8] The overall results of extra-articular reconstruction alone in young adults have not been particularly good, with decreased ratings with increased duration of follow-up. Although the hamstring tendons (i.e., gracilis and semitendinosus) have approximately 70% to 80% of the strength of the normal ACL ligament, they apparently function well in an intra-articular reconstruction, especially when placed as a conjoint graft, with more than adequate strength to replace the torn ACL (Fig. 12). Augmentation with use of a synthetic device has been advocated to provide initial stability through the device and progressive stability through neoligament formation of the transplanted tendon.

Use of allografts for reconstruction may be required if host tissue is inadequate. The advantage of allograft use—lessened donor-site morbidity—must be balanced against the potential for transmission of disease, particularly hepatitis and human immunodeficiency virus infection.[28] Freeze-drying and ethylene-oxide sterilization of bone-patella-tendon-bone allografts may cause significant changes in the mechanical properties of the graft.

Prosthetic ligament substitutes have been developed from a variety of materials. Some are designed for use in primary replacement, and others are used to augment biologic graft reconstruction. Many patients undergoing synthetic augmentation of an allograft also undergo extra-articular reconstruction as part of the procedure. The role of prosthetic ligaments as the sole replacement in the skeletally immature patient is of concern because of questions about graft longevity, intra-articular reaction to the foreign body and its degradation products, and the effects of chronic synovitis on growth.

Meniscal injury at the time of ACL rupture seems to occur at a lower frequency in children and young adolescents than in older adolescents and adults.[2-4] This difference may reflect the magnitude of inciting trauma. Not all meniscal injuries require surgical reconstruction. If unstable meniscal tears exist, management is indicated, according to the same criteria used for adult meniscal injury.

Postoperative Management

Over the past decade, in addition to surgical technique development, a significant evolution has occurred in postoperative management to eliminate effects of misuse, disuse, and abuse. Current programs incorporate the biologic principle of progressive, physiologically tolerable stress by allowing earlier motion, weight-bearing, and muscle strengthening. The emphasis on rehabilitating the entire lower extremity with use of isometric, isotonic, and isokinetic exercises (both concentric and eccentric) has contributed to rapid rehabilitation. The rehabilitative program must be customized to accommodate the patient's size and the available equipment. Current isokinetic testing and rehabilitation machines can be used with most patients older than 10 years of age. If the patient is too small for such devices or if such equipment is not readily available, free weights can be used with modified protocols to accommodate limited arcs of motion (i.e., ones that do not initially involve extension beyond –30 degrees). Return to full activity is not expected until full range of motion has been achieved, with normal restoration of hamstring-quadriceps strength ratios on concentric and eccentric isokinetic testing. Sport-specific tasks must be done at full speed before a return to full participation.

Complications following ligament reconstruction primarily involve loss of motion, usually diminished extension, with secondary infrapatellar contractures, arthrofibrosis, and anterior knee pain requiring surgical intervention. Other problems have to do with graft or insertion-site morbidity. Patellofemoral pain and contractures have been seen in as many as 20% of patients and can be attrib-

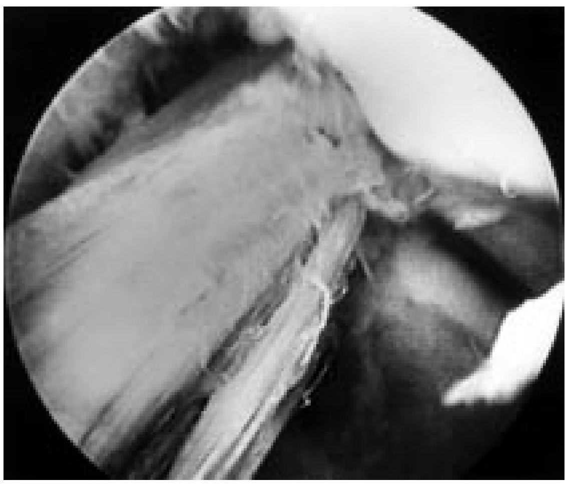


Fig. 12 Images of the knee of a Tanner stage 2 premenarchal girl who underwent partial transphyseal ACL reconstruction with use of a hamstring (semitendinosus) graft. **Top,** Preoperative views. **Center,** Intraoperative arthroscopic view. **Bottom,** Views obtained 12 months after surgery.

uted to prolonged postoperative casting in flexion and / or inappropriate graft position. The infrapatellar contracture is seen more commonly after acute repairs (within the first 3 weeks of injury), especially in patients with limited preoperative motion, and may reflect an augmented inflammatory response to the acute injury and subsequent surgery. In the skeletally immature patient, there is the potential for limb-length inequality and / or angular and rotational deformities following transphyseal reconstructions. Too few truly skeletally immature patients have been followed up for a sufficient time for there to be adequate specific data concerning the prevalence of these conditions after surgical reconstruction.

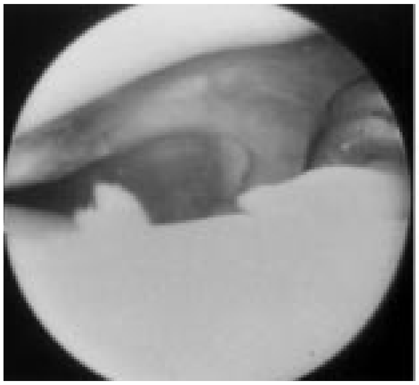
Author's Recommendations

The diagnostic approach to a possible ACL injury in a skeletally immature patient should begin with classification of the injury mechanism and duration. Associated injuries to other ligaments, menisci, and articular surfaces should also be assessed (Fig. 13). Maturity is evaluated on the basis of the patient's chronologic age; various physiologic factors, such as family height, the patient's projected height, and estimation of sexual development; and radiographic findings in the knee, hip (Risser sign), or hand and wrist (bone-age study). Preoperative and postoperative physical examinations (Lachman, anterior drawer, and rotatory instability tests) document the type and amount of instability. Functional scale assessment is also used. The effects of transphyseal procedures on growth are best assessed on standing full-length orthoroentgenograms. If questions remain about the status of the femoral and tibial physes, polytomography or MR imaging is used to assess the extent of physeal closure.

Physis-sparing procedures are done in Tanner stage 1 patients. Reconstruction with partial transphyseal techniques is used in Tanner stage 2 patients. Complete transphyseal reconstructions are done in patients who are approaching skeletal maturity (Tanner stage 3 adolescents, postmenarchal girls, and boys who demonstrate pigmented axillary and pubic hair and who have had no significant change in shoe size in the recent past).

Summary

Anterior cruciate ligament injury in children is being recognized with



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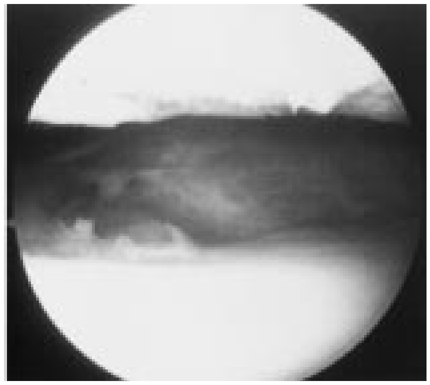

B

Fig. 13 Arthroscopic views illustrating injuries associated with ACL tears. **A,** Lateral meniscal flap tear (retracted). **B,** Patellar osteochondral injury

greater frequency because of improved diagnostic techniques as well as a heightened awareness of the condition. Unfortunately, the diagnosis is still missed because the attitude persists that children do not suffer ligamentous injuries. Treatment by cast immobilization and a temporizing "wait-and-see" approach without specific diagnosis are all too common, especially in patients with a major hemarthrosis.

The basic principles of diagnosis and the treatment goals in the skeletally immature patient are the same as those in the adult patient The natural history of partial ACL injuries in skeletally immature patients is currently unknown. Because of the special characteristics of the skeletally immature patient, the orthopaedic surgeon must act as a "knee counselor" by attempting to identify at-risk patients, particularly those who abuse their knees for any of a variety of reasons. Compared with a mature elite athlete whose livelihood is dependent on sports performance, a 10-year-old patient with an ACL tear presents a more difficult treatment decision, since future vocational and avocational demands are unknown. The nonoperative treatment principles are the same as those in an adult, although brace fitting may be difficult because of the patient's size.

The surgical options are restricted in the truly skeletally immature patient because of concern about procedures that violate the tibial and / or femoral physis. The threshold ratio of physeal area to graft (tunnel) size that is safe is currently unknown. With surgical reconstructions, questions still remain about the ability of the transplanted tissue, with its uniplanar orientation, to act in the same manner as the normal ACL, with its multifunctional-bundle structure. Questions about tolerance of lack of isometry with a variety of reconstructive procedures will be answered only with longer follow-up. Whether youth and diminished graft size allow more rapid maturation of the transferred neoligament is unknown. A 6- to 7-mm graft may be appropriate and proportional for the patient's size at the time of the reconstruction. It is unknown whether such a graft will, with growth, hypertrophy in its intra-articular segment and take on the size and mechanical properties of an adult ACL.

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