All-Epiphyseal, All-Inside Anterior Cruciate Ligament Reconstruction Technique for Skeletally Immature Patients

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Abstract: Anterior cruciate ligament (ACL) injuries are an increasingly recognized problem in the juvenile population. Unfortunately, outcomes with conservative treatment are extremely poor. Adult reconstruction techniques are inappropriate to treat skeletally immature patients because of the risk of physeal complications, including limb-length discrepancy and angular deformities. "Physeal-sparing" reconstruction techniques exist, but their ability to restore knee stability is not well understood. We describe an all-epiphyseal ACL reconstruction for use in skeletally immature patients. This is an all-inside technique with the femoral tunnel drilled retrograde and the tibial tunnel drilled retrograde; both tunnels are entirely within the epiphysis. Fixation of the hamstring autograft is achieved with soft-tissue buttons on both the femur and tibia. We present case examples for 2 patients who underwent the all-inside, all-epiphyseal reconstruction and our postoperative rehabilitation protocol. We present a novel surgical technique for an all-inside, all-epiphyseal ACL reconstruction in skeletally immature patients.

Anterior cruciate ligament (ACL) injuries are common in active, young patients and are increasingly being treated in skeletally immature patients. The increase in the incidence of these injuries in children and adolescents results in part from Title IX, which has doubled the denominator by including female persons in athletics; in addition, there has been a proliferation of competitive sports at younger ages, as well as a surge in the level of competition within these age groups, and improved recognition of these injuries by athletic trainers and orthopaedic surgeons. The surgical treatment of ACL injuries in this age group has risen because of the increased injury rate and as a result of literature documenting the poor natural history of nonoperative treatment.

The true incidence of midsubstance ACL rupture in children is unknown, but ACL injury has been reported in 10% to 65% of pediatric knees with acute hemarthrosis. Shea et al. found that ACL injuries accounted for 6.7% of total injuries and 30.8% of all knee injuries in soccer players aged 5 to 18 years in the United States. Bony ACL avulsions are more likely to occur in preadolescents, whereas adolescents are more prone to ACL substance tears. Historically, ACL reconstruction in skeletally immature patients was not recommended because of potential iatrogenic physeal injury resulting in growth arrest, limb-length discrepancies, and angular deformities. Left untreated, chronic ACL deficiency can lead to instability, meniscal damage, chondral damage, osteoarthritis, and decreased activity levels. Previous data have shown that between 21% and 100% of pediatric patients have a concomitant meniscal injury at the time of the ACL injury.

The increased recognition of these injuries and the need for treatment acutely rather than delaying treatment until skeletal maturity have led to the emergence
of a variety of surgical procedures for ACL reconstruction.29 “Physeal-sparing” alternative techniques have been developed, including over-the-top reconstructions of the femur and tibia, transtibial over-the-top femur reconstructions, and iliotibial band reconstructions.23,24,30-36 These reconstructions, however, distort the intra-articular anatomy. A recently described all-epiphyseal reconstruction aims to restore the intra-articular anatomy while minimizing the risk of physeal injury.37,38 There is no consensus yet on the optimal surgical technique to best re-create the biomechanics of the native ACL.39-41 Kocher et al.4 reported that 78% of surgeons surveyed had performed an ACL reconstruction in a skeletally immature patient but that no single technique predominated.

We describe a novel all-inside, all-epiphyseal technique for ACL reconstruction. This technique restores the intra-articular anatomy better than the other physeal-sparing techniques and minimizes the risk of physeal injury by placing both the femoral and tibial sockets, as well as fixation, exclusively within the epiphysis.

**SURGICAL TECHNIQUE**

Our reconstruction technique is demonstrated in Video 1. The autologous hamstring graft is prepared first. The semitendinosus is harvested by the standard technique with a 2-cm vertical incision over the distal insertion of the hamstring tendon. The knee is positioned at 60° of flexion with the hip externally rotated. To achieve a quadrupled graft of the appropriate length and diameter, the semitendinosus alone is most commonly harvested while the gracilis is maintained. If the diameter of the graft is determined to be insufficient (<7 mm), the gracilis is then harvested as well. The graft is prepared by the GraftLink technique (Arthrex, Naples, FL) with 2 TightRope RT suture buttons (Arthrex) for fixation on the tibia and femur (Fig 1). The graft length is between 50 and 55 mm, with a diameter between 7 and 8 mm. The graft is tensioned at 20 lb for 5 minutes.

Standard diagnostic knee arthroscopy is performed through the anteromedial and anterolateral portals. All chondral and meniscal pathology is addressed appropriately. The intrasubstance ACL tear is identified, confirmed, and debrided to show the tibial and femoral insertional footprints. A 70° arthroscope is routinely used to better view the femoral footprint from the anterolateral portal. One can use a 30° arthroscope from the anteromedial portal as an alternative.

The femoral socket is addressed first (Fig 2). The surgeon places an outside-in femoral ACL guide (Arthrex), set at approximately 95°, onto the center of the femoral footprint, approximately 2 to 3 mm from the back wall, through the anterolateral portal, while viewing with a 30° arthroscope from the anteromedial portal. A 1-cm incision is made followed by dissection and seating of the guide just anterior to the lateral epicondyle. The appropriate size FlipCutter (Arthrex) is then used to drill from the lateral cortex to the guide on the footprint. The positioning distal to the physis is verified by fluoroscopy. Once the position is confirmed, the drill sleeve is malleted through the cortex; this ensures a bone bridge of at least 7 mm between the end of the tunnel and the lateral cortex. The FlipCutter is then deployed and used to drill the femoral socket retrograde to approximately 20 to 25 mm. The FlipCutter is advanced into the joint, closed, and removed through the lateral cortex. A FiberStick (Arthrex) is advanced through the guide, delivered out the anterolateral portal, and tagged for later graft passage.

The tibial socket is then addressed (Fig 3). The tibial ACL guide, set at approximately 50°, is placed through the medial portal. The guide is placed approximately 1.5 cm medial to the tibial tubercle. The appropriate size FlipCutter is then drilled through the guide. Again, positioning is verified by fluoroscopy to avoid physeal damage. The FlipCutter is drilled retrograde within the tibial epiphysis to establish a socket of approximately 15 to 20 mm, again with a bone bridge of at least 7 mm. A FiberStick is then advanced through the socket, retrieved through the anterolateral portal (to
FIGURE 2. (A) The femoral footprint is debrided while the surgeon is viewing with arthroscopes using both 70° and 30° lenses from the anterolateral portal. This is a view using the 70° lens. The tunnel is planned for the center of the femoral footprint, approximately 2 to 3 mm from the back wall. (B) The tunnel is drilled by first placing the outside-in femoral guide through the anterolateral portal. Once the appropriate position is verified by fluoroscopy, the FlipCutter is opened and the tunnel is drilled retrograde while the surgeon is viewing with either a 30° or 70° arthroscope from the anteromedial portal. (C) The tunnel, viewed from the anterolateral portal, with a bone bridge to the lateral cortex of at least 7 mm, is tagged with a FiberStick for later graft passage.
avoid complication with the femoral FiberStick), and tagged for later graft passage.

The 2 blind sockets are then evaluated arthroscopically to ensure appropriate position and the absence of physeal damage. The graft is passed retrograde through the anteromedial portal. By use of the previously passed FiberStick, the femoral side is passed first. The button is engaged on the lateral cortex and deployed to dock at least 1 cm of the graft inside the femoral socket. The tibial-side FiberStick is then shuttled from the anterolateral portal to the anteromedial portal, and the tibial side of the graft is docked into the tibial socket. The suture button is engaged on the cortex and deployed to dock the graft in the tunnel. Viewing the graft arthroscopically

FIGURE 3. (A) The tibial footprint, as viewed through the anterolateral portal with a 70° arthroscope, is debrided. The tunnel is planned for the center of the tibial footprint. Again, the FlipCutter is drilled from outside in completely within the epiphysis. Once appropriate position is confirmed by fluoroscopy on the anteroposterior and lateral views, the FlipCutter is opened and the tunnel is drilled antegrade. (B) Views of the tibial tunnel from the anterolateral portal using a 70° arthroscope. The guide is malleted through the cortex to ensure a bone bridge of at least 7 mm between the graft and the suture button.
(Fig 4) and with the knee placed in extension, the femoral and tibial TightRope RT devices are both tensioned until tight (Fig 5). The incisions are irrigated thoroughly and closed according to standard protocol. The knee is dressed with sterile dressings and placed in a hinged knee brace locked in maximal extension. Patients in this age group are generally admitted to the hospital for 1 night and undergo cryotherapy in the postanesthesia care unit. Physical therapy is begun on postoperative day 1, and patients are weight bearing as tolerated unless meniscal repair or treatment of articular cartilage injury dictates otherwise.

**CASE REPORTS**

Two case examples are presented. Both patients and their parents gave consent to having their cases presented.
Patient 1 is a healthy 11-year-old boy who sustained an acute noncontact twisting injury of the left knee 10 days before presentation. His physical examination was notable for no effusion, a grade 2B Lachman test, and a 2+ pivot-shift test, and range of motion (ROM) lacking 5° of extension. A magnetic resonance imaging (MRI) study confirmed the presence of an acute, complete rupture of the ACL with characteristic lateral-compartment transchondral fractures. Knee radiographs showed open physes, and a hand radiograph showed a bone age of 12 years 6 months. The patient completed a short course of physical therapy focusing on regaining full ROM. He underwent an all-inside, all-epiphyseal ACL reconstruction with hamstring autograft as described earlier. At 6 months postoperatively, he has full knee ROM and negative Lachman and pivot-shift examinations. He is on target with the rehabilitation protocol described earlier.

Patient 2 is a healthy 10-year-old boy who sustained a contact injury of the right knee while ski racing 4 months before presentation. His physical examination was notable for no effusion, a grade 2B Lachman test, a 2+ pivot-shift test, and full ROM. Knee radiographs showed open physes. An MRI study showed a complete ACL intrasubstance tear with no bone edema but with anterior tibial translation. The patient underwent an all-inside, all-epiphyseal ACL reconstruction with hamstring autograft as described earlier. At 6 months postoperatively, he has full knee ROM and negative Lachman and pivot-shift examinations. He is ahead of schedule with the rehabilitation protocol and is already progressing to agility and side-to-side training.

DISCUSSION

Because of the fear of physeal injury in skeletally immature patients presenting with complete ACL ruptures, several techniques for physeal-sparing ACL reconstruction have been developed and described. One of the first techniques was reported by Micheli et al. and Kocher et al. and it is a nonanatomic, extra-articular reconstruction that involves harvesting a strip of iliotibial band. The strip is left attached to the Gerdy tubercle; passed around the lateral femoral condyle, through the notch, and secured in the over-the-top position on the femur; and then passed under the transverse meniscal ligament and sutured to the periosteum of the anterior tibial plateau distal to the physis. This is an anatomy-distorting procedure and is technically demanding. Kocher et al. reported on 44 skeletally immature patients with a mean follow-up of 5.3 years. There were 2 failures, normal Lachman examinations in 23 patients, nearly normal Lachman examinations in 18 patients, normal pivot-shift examinations in 31 patients, and nearly normal pivot-shift examinations in 11 patients. There were no angular deformities or clinically apparent growth disturbances. Recent biomechanical reports suggest that this extra-articular reconstruction technique may overconstrain the knee, especially with regard to rotational stability, which is concerning in this very young age group.

Another physeal-sparing technique, described by Guzzanti et al., involves a small, centrally located and vertical femoral tunnel combined with an all-epiphyseal but eccentric proximal tibial tunnel. The autograft hamstrings are left attached distally, brought into the tibial tunnel and through the femoral tunnel. With the knee in 30° of flexion, the graft is fixed to the femur proximal to the physis. Among 14 patients, 10 were asymptomatic and fully active in sports at skeletal maturity with no significant leg-length or angular deformities. Another physeal-sparing technique, described by Anderson, involves all-epiphyseal tunnels on both the femur and tibia. The tibial tunnel is eccentric. Fixation on the femur is achieved with a washer and an EndoButton (Smith & Nephew Endoscopy, Andover, MA), whereas fixation on the tibia is achieved with a post and suture distal to the physis. There were no failures among 12 patients with a mean follow-up of 4.1 years.

The most recently described technique, reported by Lawrence et al., involves all-epiphyseal tunnels in both the femur and tibia. The femoral tunnel is parallel to the epiphysis and fixed with an interference screw. The tibial tunnel is drilled with a RetroDrill (Arthrex), which places it in a more anatomic location than the eccentric tunnels advocated in the techniques described earlier. The RetroDrill requires placement of a 3-mm guide pin across the tibial physis. Fixation on the tibial side is with a RetroScrew (Arthrex); however, the tibial tunnel length must be at least 20 mm to accommodate the RetroScrew, thereby excluding smaller knees. There is cause for concern regarding the use of a RetroScrew in this setting. First, placement of a RetroScrew may cause damage to the autograft, especially the intra-articular portion, during placement. In addition, the use of biologically active screws that are intended to provide strong initial fixation may cause physeal growth disturbance if they are placed too close to the physis or across the physis. Moreover, the proper placement of tunnels in this technique requires the use of an intraoperative computed tomography scan, as advocated by Lawrence et
The technique described in this report is novel in several ways. The graft is a hamstring autograft but requires only harvesting of the semitendinosus with maintenance of the gracilis in some cases. This may improve the postoperative lower extremity knee flexor and internal rotator strength as compared with harvesting both the semitendinosus and gracilis tendons, which can be deficient even at 2 years postoperatively.\textsuperscript{46-58} This technique is less anatomy distorting than the iliotibial band reconstruction technique, with lower postoperative morbidity. The sockets used with this technique are all epiphyseal and blind ended with a cortical bone bridge of at least 7 mm. Although research into tendon-to-bone healing is ongoing and, to our knowledge, has not evaluated these particular sockets, these blind sockets may provide a better biological environment for predictable tendon-to-bone healing by excluding the extraosseous environment and not allowing an opening for release of growth factors. Unlike the transtibial tunnels or the tunnels drilled with the RetroDrill, there is no violation of either the tibial or femoral physes. This minimizes risk to the growth plates and does not require intraoperative computed tomography or anything more than several mini C-arm fluoroscopy images. In a recently described study evaluating the clinically identifiable intraoperative landmarks of the popliteus tendon and the center of the femoral footprint, MRI allowed reproducible epiphyseal socket placement and length.\textsuperscript{59} In addition, the fixation method described with this technique is entirely within the physis. Other methods including those that cross the physis are at risk for growth disturbance due to tethering of the physis by the fixation methods.\textsuperscript{60} As a result of this concern, these fixation devices are often removed at 6 months to 1 year, necessitating additional surgery to avoid this type of complication.

Currently, there are sparse descriptions of rehabilitation programs regarding skeletally immature individuals in the literature. The descriptions that do exist limit early weight bearing and ROM.\textsuperscript{64,61,66} It is not recommended to follow adult ACL reconstruction guidelines for patients who have received physeal-sparing ACL reconstruction because of differing fixation technique as well as patient maturity level. Isometric graft placement allows for immediate motion without adverse loads. However, current surgical techniques for epiphyseal ACL reconstruction make it difficult to restore native ACL attachments while keeping graft fixation entirely in the epiphysis.\textsuperscript{38} Therefore the reported guidelines limit ROM to 90° and maintain partial weight bearing postoperatively with a hinged knee brace locked in extension for 4 weeks. If the patient is apprehensive regarding weight bearing, an underwater treadmill is a great modality to unload the extremity. Walking in waist deep water has demonstrated a 40 to 50% reduction in weight bearing.\textsuperscript{63}

Early and appropriate management postoperatively is critical for successful recovery. The reported guidelines progress through criteria-based functional progression and stress the importance of education and the home exercise program (HEP). Frequent reassessment is critical to ensure performance of the HEP as well as improvement of ROM and strength. If the patient is apprehensive and ROM plateaus, the clinician should ensure proper performance of the HEP. A home continuous passive motion unit may be used to prevent arthrofibrosis. Brace education is performed with both the patient and caregiver and is crucial for both graft protection and prevention of ambulation on a bent knee. The clinician should encourage frequent brace checks throughout the day because the brace tends to loosen and slide distally, which may cause knee extension loss. Activity modification and frequent cryotherapy should be emphasized.

The patient’s age and maturity level need to be considered for appropriate management. Compliance tends to be problematic with pediatric athletes. Both patient and caregiver should be involved throughout the rehabilitation process to ensure adherence to precautions, activity modifications, and proper brace use, as well as compliance with the HEP. The clinician should administer 1-on-1 care to ensure safety, proper technique with therapeutic exercises, and performance of the appropriate number of repetitions and sets. The child’s relationship with the clinician is critical in enhancing the child’s confidence with progression through the rehabilitation program. The clinician should be creative and find what motivates the child, create clear tangible goals that the patient can understand, and gain the patient’s trust.

Neuromuscular control is of particular importance, because athletes who return to sports after ACL reconstruction are at increased risk of subsequent ACL injury (either reinjury or injury to the contralateral extremity).\textsuperscript{64-66} The risk of subsequent ACL injury is significantly higher compared with the risk of initial ACL injury, especially in young, active individuals.\textsuperscript{64-66} It is highly recommended that the pediatric athlete participate in an ACL injury prevention program to address neuromuscular control deficits and train for at least 1 year before returning to sports.
Constant communication among the physician, physical therapist, and caregiver is crucial for the success of the surgery and safe return to sports.

Overall, our novel technique for all-epiphyseal ACL reconstruction provides a successful treatment for primary ACL ruptures in skeletally immature patients with minimal risk of physeal disturbance and a protocol for return to sports that takes into account the unique pediatric population.

REFERENCES


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