All-Inside, All-Epiphyseal Autograft Reconstruction of the Anterior Cruciate Ligament in the Skeletally Immature Athlete

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Introduction

We present an all-inside, all-epiphyseal anterior cruciate ligament (ACL) reconstruction technique with use of a hamstring autograft for skeletally immature athletes.

Numerous reports have indicated that nonoperative management of pediatric and adolescent ACL tears leads to poor outcomes, marked by recurrent instability resulting in a high rate of dropout from sports^{1,2}. Progressive meniscal and cartilage damage is also a concern, with Fairbanks radiographic changes having been reported in up to 61% of knees³⁻⁵. Previously, concern about physeal damage, growth arrest, and subsequent sequelae, including angular deformity and leg-length discrepancy, led some surgeons to delay surgical management until the patient reaches skeletal maturity. Numerous studies have indicated, however, that waiting until skeletal maturity to perform ACL reconstruction in adolescent athletes leads to chondral injury and irreparable meniscal tears^{2,6,7}.

The reluctance to drill a tunnel across an open physis has led to the development of numerous reconstruction techniques for use in skeletally immature athletes. These reconstructive techniques can be categorized into three groups: extraphyseal, partial or complete transphyseal, and all epiphyseal. We believe that all of these various approaches have appropriate applications in the treatment of ACL injury, given the wide spectrum of skeletal development in young athletes. The iliotibial band (modified MacIntosh) reconstruction is an extraphyseal technique that combines intra-articular and extra-articular reconstruction components⁸. We utilize this technique in the youngest, prepubescent patients. Complete transphyseal techniques are used in older adolescents with minimal growth remaining. Partial transphyseal

techniques utilize a transphyseal tunnel in the tibia only, which is less prone to growth disturbance, with soft-tissue grafts used in a central location^{9,10}. In young athletes with more than two years of growth remaining, we prefer to utilize an all-epiphyseal reconstruction, which can restore the anatomic footprint of the ACL without crossing the physeal plate^{11,12}.

Anderson¹¹ first described all-epiphyseal ACL reconstruction in children with use of suspensory fixation in the femoral epiphysis and an epiphyseal tibial tunnel with tibial fixation over an extraphyseal post in the tibial metaphysis. Lawrence and Ganley et al.¹² modified this technique by using interference fixation on both sides of the graft, with intraoperative computed tomography scanning to confirm tunnel placement. We further modified these all-epiphyseal techniques by using suspensory fixation, in both the tibia and the femur, and utilizing mini-C-arm fluoroscopy to confirm socket placement. We employ blind-ended sockets, rather than tunnels, in both the femoral and the tibial epiphysis, with all fixation limited to the epiphyses.

The procedure described here is an all-inside, all-epiphyseal technique that employs a four-strand hamstring autograft and suspensory fixation. This procedure is performed in patients who have three to six years of growth remaining. Intraoperative fluoroscopy is used to confirm guidewire placement prior to socket drilling. Suspensory fixation is used in both the femoral and the tibial sockets. We prefer this method because it facilitates anatomic restoration of the ACL footprint without crossing either physis and it does not rely on interference fixation, which may harm the soft-tissue graft and has unknown fixation strength in pediatric epiphyseal bone. Furthermore, this all-inside technique is versatile and is easily adapted for use for partial and complete transphyseal reconstructions. A preliminary version of this technique has been previously described¹³; however, we describe several key

modifications used in our current technique as well as early clinical results.

These reconstructions are performed with the following six steps:

Step 1: Identify Subcutaneous Landmarks

Identify and mark subcutaneous landmarks to aid with anatomic orientation throughout the operation and to assist with socket placement (Fig. 1).

- Position, prepare, and drape the patient in a standard fashion for ACL reconstruction, according to your preference. Do not use a leg-holder as it obscures images made with mini-c-arm fluoroscopy.
- Mark the skin, identifying the following landmarks:
 - A 2-cm longitudinal incision for hamstring harvest at the posteromedial border of the tibia at the hamstring insertion. Alternatively, if you prefer, you can perform a posterior hamstring harvest.
 - The position for placement of the distal femoral drill guide near the insertion of the popliteus tendon posterolaterally, proximal to the joint line and distal to the distal femoral physis.
 - The inferior pole of the patella.
 - The tibial tubercle.
 - The planned medial and lateral arthroscopic portal sites.
 - The medial and lateral joint lines.

Step 2: Harvest the Hamstring Graft

Harvest a hamstring autograft to create a four-strand autograft in the standard fashion or, if you prefer, perform a posterior hamstring harvest.

- Place the knee in a figure-of-four position (60° of knee flexion with the hip in maximal external rotation).
- Make a 2-cm longitudinal skin incision proximal and medial to the posterior border of the tibia at the level of the pes anserinus. Carry the dissection down sharply through the sartorius fascia (layer 1) and identify and isolate the semitendinosus and gracilis tendons (running between layers 1 and 2)¹⁴.
- Alternatively, if you prefer, you can perform a posterior hamstring harvest as previously described¹⁵. While the posterior harvest technique may provide a better cosmetic

appearance and less risk of damage to the infrapatellar branch of the saphenous nerve, the primary advantage (avoiding an anterior approach) is negated by the fact that we utilize the anterior incision to palpate the proximal tibial physis as a reference for placement of the drill guide.

- Use a tendon harvester to harvest the semitendinosus, which alone may be sufficient to create the four-strand autograft in larger children. If this does not provide enough graft material (>8 mm in diameter and >55 mm in length when quadrupled), also harvest the gracilis at this time, and use both tendons to prepare the autograft as outlined in Step 3.

Step 3: Prepare the Graft

Prepare a four-strand hamstring autograft using suspensory cortical fixation devices—a reverse-tensioning button (ACL TightRope RT; Arthrex, Naples, Florida) on the femoral side and an attachable button system (ACL TightRope ABS, Arthrex) on the tibial side (Fig. 2).

- To allow preparation of a graft with a reverse-tensioning button for suspensory cortical fixation on the femoral side, use an appropriate graft preparation board. This will facilitate graft preparation, sizing, and tensioning.
- Place a reverse-tensioning button on the end of the graft preparation board corresponding to the femoral side of the graft. On the tibial side of the graft, place the loop suture for an attachable button system. The metal implant will be secured to the loop after graft docking in the tibial tunnel and just prior to graft tensioning. Set the loop ends of the fixation devices at a distance equal to 10 mm less than the desired final length of the graft.
- Pass the graft through the suture loops such that the graft consists of a total of four strands (either a quadrupled semitendinosus or a doubled semitendinosus and gracilis, as described in Step 2). The free graft ends should be oriented toward the tibial (ABS button) fixation. Use a FiberLoop (Arthrex) in a whipstitch to combine the four tendon ends.
- Pass the whipstitch suture through the looped tendon to bury the end, and bundle this suture with the ABS button fixation loop. This suture will assist in passing and dunking the graft into the tibial socket, and will eventually be tied down over the ABS button after graft tensioning, serving as a secondary fixation suture.
- Pretension the graft to 20 lb (89 N) for at least five minutes.

- Depending on the size of the patient, the length of the graft is typically between 55 and 65 mm, derived from the socket depth and intra-articular distance. If the graft is too long, it may bottom out in one of the sockets; if it is too short, there may not be sufficient graft within the tunnel for biologic fixation.
- Using a number-0 FiberWire (Arthrex) and a “buried knot” technique (Video 1), suture the graft limbs together (Fig. 2). Repeat this process for a total of two stitches on each end, 15 mm and 20 mm from the end of the graft.
- Mark on the femoral side (RT button) suture loop the length of the socket to the lateral femoral cortex, once it is known from the femoral tunnel preparation. This will assist with initial button passage through the lateral femoral cortex (as outlined in Step 5).
- Determine the diameter of the graft on each end by using the appropriate graft sizer. The goal is a graft diameter of between 8 and 11 mm. While the graft diameter is typically symmetrical on each end, in the event that one end has a larger diameter, one advantage of this technique is that the larger diameter may be on either the femoral side or the tibial side.

Step 4: Prepare the Femoral and Tibial Sockets

Create blind-ended intra-articular sockets in the femur and tibia using the center-center footprint positions while avoiding the physeal plates (Video 2).

- To clearly identify the footprints for the ACL, completely remove the remaining stump on the femur and the tibia using a shaver and electrocautery.
- A 70° arthroscope is ideal to better view the femoral footprint from the anterolateral portal, but you can use a 30° arthroscope from the anteromedial portal as an alternative.
- Create the femoral socket first with a femoral ACL guide placed at the center of the footprint. Perform this step while viewing from the anteromedial portal. Seat the guide adjacent to the popliteus tendon insertion¹⁶ through a 5-mm incision. Drill the appropriately sized retrograde reamer (FlipCutter, Arthrex) from outside-in and verify the position distal to the pysis using fluoroscopy. You may use a smaller drill pin to assess placement fluoroscopically first.
- Once the position of the tunnel is acceptable, mallet the stepped drill guide down to the cortex to ensure that a bone bridge of at least 7

mm between the end of the socket and the lateral cortex will be present after reaming. Flip the retrograde reamer into position (orienting the reamer perpendicular to the axis of the drill) and ream the blind-ended socket from an inside-out direction to approximately 20 to 25 mm in length as determined by the length of the graft and femoral anatomy (Fig. 3). Tag this socket with a suture passed through the tunnel from outside-in using a small-diameter suture-passing instrument (FiberStick, Arthrex) and deliver it out the anteromedial portal for later graft passage. Use of soft cannulas (PassPort, Arthrex) facilitates suture management, graft passage, and switching of the arthroscope and instruments between the medial and lateral portals.

- Debride the tibial footprint with a radiofrequency probe while viewing through the anterolateral portal with a 70° lens. Place the tibial ACL guide through the medial portal and approximately 1.5 cm medial to the tibial tubercle. Palpate the tibial pysis through the previously made hamstring graft harvest incision, pass the appropriately sized retrograde reamer through the stepped drill guide, and verify the position proximal to the tibial pysis using fluoroscopy. Once again, a smaller-diameter drill pin is used to assess placement first. Activate the retrograde reamer and ream from an inside-out direction to create a socket approximately 15 to 20 mm in length with a bone bridge of at least 7 mm from the cortex (Fig. 4). Pass a suture through the socket for later graft passage.
- Evaluate the sockets arthroscopically to ensure that no physeal cartilage is visible within the sockets and visualize that the back wall of the socket is intact.

Step 5: Pass and Secure the Graft

Pass the hamstring autograft through the anteromedial portal and dock it in the femoral and tibial sockets; engage the cortical button on the femur, dock the graft, and then perform final fixation on the tibial side (Fig. 5).

- Retrieve the shuttle suture from the femoral socket out of the anteromedial portal, and then pass the graft cortical button sutures through the femoral socket and out of the skin laterally. Then advance the hamstring autograft into the knee through the anteromedial portal and pass the reverse-tensioning button through the lateral femoral cortex while visualizing the button

advancing through the socket using the 70° arthroscope.

- Once the previously made mark is seen at the femoral socket, flip the button to engage the cortex and confirm placement with fluoroscopy. It is important not to pass the button through the soft tissues; pass it only as far as the marking on the implant loop suture that was made corresponding to the tunnel depth. This ensures contact between the button and the periosteum without interposed soft tissue.
- Partially advance and dock the graft in the femoral socket by shortening the ACL Tight-Rope RT loop under direct arthroscopic visualization until there is at least 1.5 to 2 cm of graft within the femoral socket. Be careful not to bottom out the graft.
- Using a suture retriever, pass the tibial end of the graft into the tibial socket using the second shuttle suture, making sure to direct the graft sutures to the center of the socket with a suture retriever in order to prevent the creation of a tract into the soft metaphyseal bone anteriorly. Then dock the distal end of the graft in the tibial socket, and attach the ABS button to the button loop.
- Complete the tibial fixation tensioning, cycle the graft, and lock the suspensory cortical fixation device on the tibia in approximately 20° to 30° of knee flexion. The sutures from the FiberLoop that accompany the ABS button sutures are tied down to the ABS button as well, as an augmentation suture. Ensure appropriate graft tension and absence of graft impingement during the final arthroscopic examination.
- Obtain final fluoroscopic images to ensure appropriate positioning of cortical buttons, and subsequent standing radiographs during follow-up (Fig. 6).

Step 6: Postoperative Rehabilitation

The patient's age and maturity level dictate the progression of rehabilitation, and parents and caregivers are encouraged to regularly participate in the child's rehabilitation regimen.

- Apply a knee brace locked in extension, and instruct the patient to maintain partial weight-bearing with crutches. Weight-bearing restrictions are altered in the event of a concomitant meniscal repair or restorative cartilage procedure.
- During the first four postoperative weeks, physical therapy goals are (1) passive and active ranges of motion of 0° to 90°, (2) improved

quadriceps strength, and (3) implementation of a home exercise program. At home, continuous passive motion can be used within the range-of-motion restrictions with frequent cryotherapy.

- During weeks four to eight, the patient is weaned off of crutches, increases the range of motion to 125° of knee flexion, and works on normalizing gait while weight-bearing as tolerated. The patient should work to improve core and lower-extremity strength with the goal of performing a single-leg stance.
- In weeks eight to sixteen, the patient should obtain a full knee range of motion, improve quadriceps and eccentric control, and improve core strength.
- In weeks sixteen to twenty, the patient should focus on maximizing strength, flexibility, and endurance, and then proceed to running, proper dynamic control with jumping and landing, and an independent gym program by week twenty-eight.
- Finally, sport-specific training is begun with the goal of returning to play. Seven to twelve months postoperatively and prior to sports participation, evaluate the athlete's readiness to return to play in a sports performance center. The athlete must demonstrate successful performance during this evaluation before being cleared to return to sports^{17,18}. An ACL injury prevention program should continue until one year postoperatively in order to continue to teach and reinforce neuromuscular training. If desired, functional bracing can be prescribed.

Results

Research is ongoing to evaluate the clinical and radiographic outcomes following ACL reconstruction in skeletally immature athletes with use of this technique¹⁹. To date, the preliminary one-year clinical follow-up data are promising. In a cohort of twenty-one adolescents (mean age, 12.7 years) who underwent either an all-epiphyseal (fourteen) or a partial transphyseal (transtibial physis) ACL reconstruction (seven), the mean International Knee Documentation Committee (IKDC) and Lysholm scores were 93.3 ± 5.9 and 97.8 ± 3.8 , respectively, in the all-epiphyseal group¹⁹. Those who underwent partial transphyseal reconstruction had scores of 87.7 ± 3.5 and 96 ± 3.2 . While the Lysholm scores were equivalent, the IKDC score was significantly better in the all-epiphyseal group compared with the partial transphyseal group ($p = 0.033$). The clinical relevance of this difference is not known, however, given the excellent results seen in this cohort as a whole.

There have been no graft failures to date and no cases of fracture, articular surface violation, or osteonecrosis. With use of physseal-specific spoiled gradient recalled echo (SPGR) magnetic resonance imaging (MRI) sequences and physseal mapping to evaluate physseal violation, tibial physseal violation was found to be common but minor. Thirteen of fourteen patients treated with all-epiphyseal ACL reconstruction exhibited some tibial physseal violation; however, only 1.7% of the physseal plate was affected on average¹⁹. Distal femoral physseal violation was much less common, with one of the fourteen patients having involvement of 1.5% of the distal femoral physis. In all instances, this was considerably less than the 7% disruption of physseal volume that potentially increases the incidence of growth disturbance²⁰. Furthermore, no leg-length discrepancies or angular deformities have been noted as measured on full-length 51-in (129.5-cm) standing radiographs, although longer follow-up is required in order to discover any clinically relevant growth disturbances.

What to Watch For

Indications

- ACL tear in a skeletally immature patient
- Three to six years of growth remaining according to radiographic growth estimates²¹
- Three to six years of growth remaining based on bone age

Contraindications

- Skeletal maturity
- Epiphyseal dysplasia, lateral condyle hypoplasia
- Marked osteopenia
- More than six years of growth remaining (epiphyses too small for socket reaming, in which case a modified MacIntosh procedure preferred)⁸

Pitfalls & Challenges

- It is important not to use a leg-holder as it obscures images made with mini-c-arm fluoroscopy.

- High-quality image intensification (e.g., c-arm or mini-c-arm fluoroscopy) is vital to ensure guidewire placement away from the physes prior to socket reaming.
- Suture management can be aided with the use of soft button cannulas (PassPort, Arthrex), which facilitate easy camera switching and suture passage without suture shuttles by creating a free path through the soft tissues at the anterior arthroscopic portals.
- The 70° degree arthroscope is ideal for placing, visualizing, and evaluating the femoral socket.

Clinical Comments

Question: When passing the reverse-tensioning button and graft into the femoral socket, what measures should you take to ensure that there is no soft-tissue interposition between the button and the femoral cortex/periosteum?

Answer: We suggest marking the suture loop at a distance from the reverse-tensioning button equal to that of the length of the femoral socket to the lateral femoral cortex. Pass the button under direct visualization by using the 70° arthroscope to view up the tunnel, and do not advance further than the marking on the suture loop. This will prevent passage of the button through the iliotibial band and the subsequent interposition of soft tissue between the button and the lateral femoral cortex.

Question: Is there a substantial learning curve for the operating-room staff and surgical technicians for this technique?

Answer: No. Due to the great versatility inherent to this technique, the same instrumentation can be used for all-epiphyseal, partial transphyseal, and complete transphyseal reconstructions. The all-epiphyseal technique is indicated for children with three to six years of skeletal growth remaining. When there is less than three years of remaining growth, a partial transphyseal technique may be chosen, and when growth is nearly complete, a complete transphyseal technique may be used. In any event, the procedural steps are identical and the same implants and graft may be used at the discretion of the surgeon.

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Figures

Fig. 1

Osseous landmarks and cutaneous markings on an anterior view of the surgical site. The markings are at the inferior pole of the patella (P), tibial tuberosity (T), medial (M) and lateral (L) portals, and a 2-cm graft harvest incision (G). The planned location for

the posterolateral distal femoral drill guide is also marked (arrow), slightly proximal and anterior to the palpable popliteus insertion.

Fig. 2

Graft preparation. The four-strand autograft is created by looping the two tendons through the attachable button system loop (ABS) and then passing all four strands back through the reverse-tensioning button loop (RT). A FiberLoop is used in a whipstitch to combine the four tendon ends (arrowhead) (**Fig. 2-A**). The tail of the whipstitch is then passed through the looped tendon in order to bury the end (**Fig. 2-B**). The graft is then placed in 20 lb (89 N) of tension (**Fig. 2-C**). A number-0 FiberWire (Arthrex) is passed from inside-out (**Fig. 2-D**), looped twice around the graft, and passed from outside-in (**Fig. 2-E**). The knot is tied and laid inside the graft (**Fig. 2-F**) and is passed again from inside-out, which buries the knot (**Fig. 2-G**). This is repeated so that four sutures are placed in the tendon, two at each end at 15 mm (arrows) and 20 mm (arrowheads) from the end of the implant strands (**Fig. 2-H**).

Fig. 3

Femoral socket preparation. A FlipCutter guide with a 7-mm step-off (arrow) is used to ensure 7 mm of cortical buttress (**Fig. 3-A**). After debridement of the femoral footprint and performance of a limited notchplasty, a guidewire is passed from the popliteal hiatus to the femoral footprint (**Fig. 3-B**) and is checked with fluoroscopy (**Fig. 3-C**). The guidewire is then replaced with a FlipCutter, which is checked again with fluoroscopy and deployed (**Fig. 3-D**). The 7-mm step guide is malleted down to the lateral cortex (**Fig. 3-E**). After reaming in a retrograde direction, a FiberStick is used to tag the femoral socket and is inspected with the 70° arthroscope (**Fig. 3-F**). These tagging sutures will be used to pass the graft.

Fig. 4

Tibial socket preparation. The tibial socket is prepared with a technique similar to that used to prepare the femoral socket. After debridement of the tibial footprint, palpation through the graft harvest site reveals the level of the physal plate and a safe starting point proximally in the epiphysis is chosen (**Fig. 4-A**). After a guidewire is placed and its position is checked with fluoroscopy, the FlipCutter is drilled into position (**Fig. 4-B**), deployed (**Fig. 4-C**), and checked again with fluoroscopy (**Fig. 4-D**). The 7-mm step guide is malleted into position and can be seen on the fluoroscopic image (arrow). The socket is then reamed in a retrograde direction.

Fig. 5

Graft passage, tensioning, and fixation. A suture retriever is used to retrieve the femoral socket tagging suture, and the suture from the reverse-tensioning (RT) button is advanced through the femoral socket and out of the lateral distal femoral incision. A marking pen is used to mark the RT suture loop at a distance from the button equal to the socket depth (white arrow, **Fig. 5-A**). This prevents excessive advancement of the RT button through the iliotibial band. The graft is passed until the marking is seen arthroscopically at the socket entrance (black arrow, **Fig. 5-B**), indicating that the button has passed sufficiently through the lateral femoral cortex. The RT button is provisionally tensioned. A suture retriever is similarly used to pass the tibial end of the graft sutures through the tibial socket. A suture retriever is used to direct the sutures below the graft (**G**) into the tibial socket (TS), so that they do not create a tract into the softer tibial metaphysis (TM) when passed (**Fig. 5-C**). The ABS button is placed on the fixation loop (arrow, **Fig. 5-D**), tensioned (**Fig. 5-E**), and tied down after final tensioning of both femoral and tibial fixation. The graft is evaluated arthroscopically, revealing notch impingement in extension (**Fig. 5-F**).

Fig. 6

Final anteroposterior (**Fig. 6-A**) and lateral (**Fig. 6-B**) standing radiographs reveal the all-epiphyseal position of the graft and suspensory fixation.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6