Anatomic, Transepiphyseal Anterior Cruciate Ligament Reconstruction

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Introduction

Our technique for physeal-sparing, anatomic anterior cruciate ligament (ACL) reconstruction reliably produces femoral tunnels that are of adequate length and that safely avoid the femoral physis without the addition of time-consuming surgical methods or substantial utilization of fluoroscopy.

Physeal-sparing, anatomic ACL reconstruction may now be the preferred technique for skeletally immature patients. The number of ACL reconstructions performed on skeletally immature patients is growing. This growth is believed to be secondary to increased participation in cutting and pivoting sports, a more intense level of training and competition among youth athletes, as well as improvements in diagnosis with the use of magnetic resonance imaging (MRI)¹⁻⁴.

Currently, the most common techniques utilized for these reconstructions are nonanatomic and/or transphyseal⁵⁻⁸. Thus, they do not reproduce normal knee kinematics and may lead to an increased rate of meniscal and chondral injury⁹⁻¹². With anatomic ACL reconstructions, the native knee kinematics are reproduced and compartmental forces in the joint are significantly less than those in a knee with a non-anatomically reconstructed ACL¹³. Theoretically, this improvement in knee kinematics and joint forces could decrease the rate of degeneration of the joint in the future, which should be an important factor to consider in the younger population. Another concern with most current techniques is the potential for causing physeal growth disturbances and/or angular deformity, especially with transphyseal reconstructions.

In order to avoid these complications, we developed an anatomic femoral-sided, transepiphyseal ACL reconstruction technique. A transphyseal tunnel is used on the tibial side because we believe that physeal growth arrest is less of a concern in that location as a result of the fact that the tunnel is centrally located, it has a small diameter, we avoid fixation at the physis, and overall there is less growth at the

proximal part of the tibia than at the distal part of the femur.

We utilize preoperative MRI as well as easily identifiable extra-articular and intra-articular landmarks to produce uniform, anatomic femoral tunnels that safely avoid the femoral physis and cartilage cap. These landmarks were shown to be consistent in their relationship to both the femoral physes and cartilage caps in our previous study¹⁴. Our technique, which provides an anatomic reconstruction without violating the femoral physis, is performed in seven steps:

Step 1: Preoperative planning

Step 2: Patient setup, portal placement, and graft harvest

Step 3: Prepare ACL footprint and establish far anteromedial portal

Step 4: Identify extra-articular landmarks and prepare femoral tunnel

Step 5: Prepare tibial tunnel

Step 6: Fix graft

Step 7: Postoperative care

Step 1: Preoperative Planning

Obtain radiographs and MRI of the knee as well as an anteroposterior radiograph of the hand (to obtain a bone age).

- Take a thorough history, perform a complete physical examination, and obtain radiographs and MRI of the knee as well as an anteroposterior radiograph of the hand (to obtain a bone age). Using this clinical and radiographic information, determine the Tanner stage and bone age.
- While this technique can be utilized in any skeletally immature patient, we think it should be considered for patients in Tanner stage 3 or lower. For patients in Tanner stage 4 or higher, we employ our standard transphyseal recon-

struction with the use of a far anterior medial portal.

- Estimate femoral tunnel length and diameter using our previously described method based on computer-generated MRI measurements¹⁴.

Step 2: Patient Setup, Portal Placement, and Graft Harvest

The affected knee must be able to flex at least 90° with the end of the operative table lowered, in order to properly visualize the anatomy of the ACL femoral footprint.

- With the patient under general anesthesia, document the results of an examination of both the affected and the unaffected knee. Apply a pneumatic tourniquet to the affected thigh. With the patient supine, place the unaffected extremity into a lithotomy leg-holder.
- With the knee flexed 90° with the end of the operative table lowered, delineate pertinent anatomic sites with a sterile surgical marker. Outline the inferior pole of the patella, patellar tendon, tibial tubercle, fibular head, and lateral femoral epicondyle.
- Place the knee into the figure-four position; palpate and outline the lateral collateral ligament (LCL) from its insertion on the fibular head to its origin on the lateral aspect of the femur. The LCL origin closely correlates with the lateral epicondyle.
- With the knee in 90° of flexion, move just slightly distal and anterior from the lateral femoral epicondyle (or LCL origin) to palpate and mark the popliteal sulcus, which corresponds with the insertion of the popliteal tendon.
- Draw two important safety lines on the lateral part of the knee. The first is a horizontal line from the lateral epicondyle extending along the posterior aspect of the femur. The second line is perpendicular to the first line, traveling in the anterior direction from the lateral epicondyle (Fig. 1). No incision or tunnel should be made proximal to the perpendicular line because of its close proximity to the physes.
- Use three portals for the arthroscopic procedure: anterolateral, anteromedial, and far anteromedial (Fig. 2). Perform diagnostic arthroscopy using the anterolateral portal for visualization and the anteromedial portal as a working portal. The ACL tear is confirmed, and concomitant intra-articular pathology should be identified and treated accordingly.
- Our preferred graft choices are the hamstring tendons (gracilis and semitendinosus). Harvest

these tendons in a standard fashion, employing a tendon stripper, and then prepare them on the back table. Utilize a four or five-limb construct by folding each tendon onto itself, suturing them together, and looping them over the cortical fixation device to ensure a 7.5 to 8-mm graft diameter. The finished graft length should be between 7 and 9 cm. In the following description of our technique, the ACL TightRope RT (Arthrex, Naples, Florida) is utilized, but this technique will also work well with use of other femoral fixation methods.

Step 3: Prepare ACL Footprint and Establish Far Anteromedial Portal

Maintain soft-tissue remnants at both the femoral and the tibial footprint in order to individualize the anatomy.

- Place the arthroscope in the anterolateral portal, and debride the torn ACL using the shaver. Care should be taken to leave both footprints of the femoral origin and tibial insertion undisturbed. Utilize this portal to visualize the proper placement of the far anteromedial portal.
- We usually leave at least 5 mm of tissue over each of the footprints for aid in identifying intra-articular anatomy.
- Create a far anteromedial portal while looking from the anterolateral portal and visualizing the medial femoral condyle, medial meniscus, and anteromedial aspect of the capsule. Use an 18-gauge needle to mark the far anteromedial portal. It should travel tangentially along the medial femoral condyle at a point where the needle finds an unobstructed path to the center of the femoral footprint. Once this point is chosen, use a number-11 blade to create a 5-mm horizontal portal through the capsule.
- Move the arthroscope from the anterolateral portal to the anteromedial portal. This allows direct visualization of the femoral ACL insertions rather than the obstructed view one gets with the arthroscope in the anterolateral portal.
- To ensure proper identification of the ACL femoral footprint, which is vital for an anatomic reconstruction, the knee must be in 90° of flexion. Identify the center of the ACL femoral footprint and mark it with an intra-articular cautery device. The central portion of the soft-tissue footprint should correlate with the mid-point of the bifurcate ridge.
- Use an awl to mark a position 2 mm proximal and 2 mm anterior to the ablation mark. This awl hole will mark the central portion of the femoral ACL tunnel (Fig. 3) (Video 1). This

maneuver moves the center of the tunnel into the distal portion of the ACL anteromedial bundle footprint. This is very important because the final graft will lie in the distal aspect of the tunnel, which places it closer to the true point between the two bundles of the ACL origin. Thus, offsetting this tunnel placement is essential to retain a central position in the footprint.

Step 4: Identify Extra-Articular Landmarks and Prepare Femoral Tunnel

Visualize and palpate your previously marked popliteal sulcus and lateral epicondyle; these landmarks are the crucial extra-articular points for establishing a safe femoral tunnel.

- Make a small 2-mm incision with a number-11 blade at this point, which is just distal and anterior to the lateral epicondyle. In our previously published study¹⁴, we determined that this anatomic point along with the awl hole made on the intra-articular femoral footprint consistently yields a tunnel length between 23 and 33 mm and this tunnel's central portion is at least 8 mm from the physes at its nearest point. (The shortest tunnel and the tunnel closest to the physes were seen in six-year-old patients in our study.)
- Palpate the lateral epicondyle and the popliteal sulcus.
- We previously explained the method to preoperatively determine tunnel length and the distance from the physes to the center of the femoral tunnel on the basis of preoperative MRI¹⁴. However, this method is not always necessary since use of the anatomic points mentioned above predictably yields a tunnel of sufficient length as well as a safe distance from the physes for tunnels ≤ 10 mm in diameter.
- With the starting and ending points of the femoral tunnel identified and marked, the tunnel is ready to be drilled. The drilling can be performed in an antegrade or retrograde fashion, with use of a variety of devices. In this article, we describe the technique as employing retrograde drilling with the FlipCutter II (Arthrex), but other proprietary devices can be used in the same manner. There are several advantages to these systems: (1) the small 3.5-mm entry hole can be made near the tendinous attachment of the LCL or popliteus without damaging these structures, (2) the lateral cortex and ligamentous attachments remain in-

tact with the creation of any size of tunnel, and (3) the small diameter of the drill allows it to be easily redirected if the surgeon does not like its placement.

- To drill the femoral tunnel, move the arthroscope to the far anteromedial portal, which allows direct visualization of the femoral footprint. Then place the FlipCutter guide through the anteromedial portal. Place the point of the guide into the previously made awl hole, which secures the guide within the femoral footprint (Figs. 4-A and 4-B). Then place the FlipCutter bullet guide into the previously made skin incision over the popliteus insertion. The angle of the guide is easily adjusted to fit any size of knee. Finally, drill the FlipCutter pin through the guide and into the knee joint, under arthroscopic visualization.
- A single anteroposterior fluoroscopic image can then be obtained to ensure proper placement of the FlipCutter pin (Fig. 5). We suggest employing this step during the early implementation of our technique to verify physeal safety. When the exact position is confirmed, drive the bullet guide into the cortex. The bullet guide recesses 7 mm into the lateral cortex and acts as a "stop" for the retrodrill; thus, it ensures that the drill will not violate the lateral femoral cortex as it is pulled out of the joint. As a side note, on fluoroscopic imaging, it often appears that the bullet guide is not seated on the osseous cortex, but you must take into account the cartilage cap thickness, which can be several millimeters thick, especially in Tanner stage-1 and 2 patients.
- While holding the bullet guide in place, advance the FlipCutter 2 mm into the joint. Then remove the guide, leaving the bullet guide and FlipCutter. Next, deploy the FlipCutter with a probe and lock the cutter into place. While steadily holding the bullet guide in place, trigger/run the FlipCutter (Video 2). While the device is running, pull back until the deployed blade engages the cortical bone of the footprint (Fig. 6). Then slide the rubber grommet down the FlipCutter shaft until it engages with the bullet guide. The grommet will be used to measure the length of the tunnel after drilling. Hold the bullet guide in place, start the FlipCutter drill on forward, and then pull retrograde until it engages the tip of the bullet guide. (This point will be 7 mm from the lateral border of the femur.) Using the rubber grommet, you can then determine the length of the tunnel. Again, holding the bullet guide in place, push the FlipCutter back into the joint, undeploy the cut-

ter with a probe, and remove the device retrograde from the knee.

- Place a looped suture through the bullet guide into the joint and then remove it out of the far anteromedial portal. Remove the femoral bullet, and snap the sutures together. This suture loop will be used for graft passage. From the far anteromedial portal, use the arthroscope to visualize the inside of the femoral tunnel and confirm that the lateral cortex remained intact and that no evidence of the femoral physis is visible (Fig. 7).

Step 5: Prepare Tibial Tunnel

The tibial tunnel can be safely drilled in a transphyseal manner in skeletally immature patients.

- In a previous publication from our laboratory, we showed that approximately 3% of the physeal volume is removed with an 8-mm tunnel¹⁵. In animal studies, the volume of physeal removal that led to a growth disturbance was 7%¹⁶. Also, the tibial tunnel is drilled in the central portion of the physes, which is less likely to lead to an angular growth deformity.
- Move the arthroscope back to the anterolateral portal. Multiple landmarks are used to determine the tibial footprint. They are static and constant, and do not change with injury to the knee (posterior cruciate ligament injury, etc.). First identify the tibial soft-tissue footprint. The medial and lateral tibial spines define the medial and lateral borders of the footprint. The center of the footprint between the anteromedial and posterolateral bundles correlates with the posterior aspect of the anterior horn of the lateral meniscus.
- Our goal is to place the tunnel in the center of the tibial footprint. Thus, using an ablation device, identify the posterior aspect of the anterior horn of the lateral meniscus. Use the ablator and move medially to a position centered between the medial and lateral tibial spines. Then move the ablator 2 mm anteriorly, and mark this spot in the tibial footprint. This point signifies the guidepin placement. The reason we choose to move slightly anterior to the center of the footprint is to compensate for the tibial tunnel obliquity.
- Set the tibial tunnel guide (ConMed Linvatec, Largo, Florida) between 45° and 60° and place it through the anteromedial portal into the previously marked footprint point (Fig. 8). Previous work from our laboratory demonstrated that the angle of the tibial tunnel has minimal effect on the physeal volume removed¹⁵. Place

the bullet through the anteromedial tibial skin incision that you previously used for the hamstring tendon harvest. Drill the Kirschner wire through the bullet guide. Remove the guide and extend the knee to visualize that the guidepin is in the center of the femoral notch. Place a curet through the anteromedial portal over the guidepin in order to protect against reamer-induced chondral injury. Select the correct size of drill on the basis of the graft size, and then drill over the pin. Use a shaver to clean and smooth the intra-articular portion of the tunnel. No dilator is used on the tibial side, secondary to a potentially deleterious effect on the physes^{16,17}.

- Finally, place a grasper through the anteromedial tibial tunnel into the knee joint. The looped end of the suture can then be grabbed from the femoral tunnel and pulled out of the tibial tunnel. The graft is ready to be passed and fixed into place.

Step 6: Fix Graft

Use the Arthrex ACL TightRope RT for femoral fixation.

- The major advantage of the Arthrex ACL TightRope RT for femoral fixation, compared with a “closed loop” button, is that it allows the maximal amount of graft to be placed in the femoral tunnel.
- Place the sutures from the button through the suture loop, which is used to draw the graft up through the tibia and into the femoral tunnel. Because the tunnels are perpendicular to each other, graft passage can be difficult. In order to compensate, switch the arthroscope to the far anteromedial portal to directly visualize the femoral tunnel. It is very important to watch the button go through the 3.5-mm hole in the cortex. This will ensure that the button will both “flip” on the outer cortex of the femur and not be pulled through the skin (Video 3). Once the button has been adequately deployed on the lateral cortex, pull the tightening suture to advance the graft into the tunnel aperture. Apply slight counter pressure to the distal end of the graft while it is pulled into the femoral tunnel. A trocar placed through the anterolateral portal is helpful to guide the graft from the tibial tunnel through the 90° turn into the femoral tunnel.
- Pull the graft into the femoral tunnel until it is bottomed out, or the desired amount of graft resides in the tunnel. A very young athlete many have a shorter tunnel; thus, maximizing the amount of graft in the femoral tunnel is

crucial for tendon-bone healing. Pull hard on the distal sutures from the tibial tunnel to test the fixation. Then move the arthroscope back to the anterolateral portal and visualize the graft with the knee fully flexed and extended (Video 4). The knee should have a full range of motion, and there should be no signs of graft impingement. Repeat this motion approximately twenty times, to remove any laxity and to accommodate for creep from the graft construct.

- Finally, place the knee between 0° and 30° and tie the graft over a screw and washer, while applying gentle internal rotation and posterior drawer (Figs. 9-A and 9-B). The distance from the tibial cortex to the physes has been <2 cm in most of our cases. Thus, interference screw fixation is dangerous and should be avoided, due to the risk of physeal arrest¹⁷.

Step 7: Postoperative Care

As a skeletally immature athlete differs from a more mature athlete in several important ways, alter the postoperative protocol accordingly.

- Postoperative stiffness of the knee is uncommon in the pediatric population, so an immediate range of motion is not necessary. However, noncompliance with regard to activity restriction is a major problem. Thus, we commonly apply a locked knee brace or knee immobilizer, allowing weight-bearing as tolerated with crutches for the first three to four weeks after surgery.
- After three to four weeks, apply a functional ACL brace and allow a 0° to 90° range of motion. The functional ACL brace is used for only the first three months. While it is not our standard protocol to use functional knee braces after ACL reconstructions, we do so for these patients, primarily to remind them (and their peers) of their knee injury and hopefully help with their compliance with the postoperative plan.
- At six weeks, initiate a standard ACL rehabilitation protocol. The initial phase consists of closed-chain exercises for strengthening and controlled stretching to improve range of motion. Running is restricted until four months postoperatively, and the patient must have at least 80% of the muscular strength on the contralateral limb before resuming running. Sport-specific exercises and proprioceptive training begin at six to eight months. On average, patients return to sports activity between ten and

twelve months and only after completion of functional testing.

Results

Our clinical experience has corresponded to our MRI-based findings from our original study¹⁴, and we have not observed any physeal or chondral injuries leading to growth disturbances from our femoral tunnels. Also, we have not seen any reruptures at the time of the latest follow-up, and all subjects have returned to athletics. Figures 10-A and 10-B show examples of preoperative three-dimensional (3D) MRI templates of our proposed femoral tunnel made with our previously described technique¹⁴. Figures 10-C, 10-D, and 10-E are one-year postoperative computed tomography (CT) scans demonstrating that, for this particular patient, our described technique produced a successful anatomic, physeal-sparing ACL reconstruction.

What to Watch For

Indications

- In our practice, we treat all skeletally immature athletes with an ACL tear surgically, rather than delaying reconstruction until skeletal maturity.
- Our described technique is utilized in children whose development falls within Tanner stages 1 and 2.
- Tanner stage-3 patients are also candidates for this technique, to eliminate any chance of a femoral physeal disturbance.
- This technique will result in a viable anatomic ACL reconstruction in individuals of any age and is a useful alternative for revision ACL surgery.

Contraindications

- This, or any, ACL reconstruction is contraindicated in patients who cannot comply with the postoperative protocol or who lack parental support.
- The procedure is contraindicated in any child who has a medical comorbidity that precludes surgical intervention.

Pitfalls & Challenges

- The discussion of femoral footprint anatomy pertains to a knee in 90° of flexion. The femoral portion of this surgery must be performed with the knee at 90° so that the anatomic directions are consistent and the femoral footprint anatomy can be accurately identified. Otherwise, nonanatomic placement of the

femoral tunnel, as well as potential injury to the physes, will occur.

- Viewing the femoral ACL footprint through the anterolateral portal, rather than the anteromedial portal, makes it difficult if not impossible to identify the landmarks to delineate the anatomy of the ACL footprint.
- When identifying the surface anatomy of the lateral aspect of the knee, it is vital that one can palpate the LCL, its origin from the lateral epicondyle, and the popliteal sulcus just distal and anterior. This ensures proper tunnel placement, length, and distance from the physes.
- Holding the femoral bullet guide in place while drilling in a retrograde fashion ensures that the guide does not back out and that no breach of the lateral femoral cortex occurs.
- A single anteroposterior c-arm image after FlipCutter placement ensures proper placement and verifies that no injury to the physis has occurred. This step may become optional

as one becomes more experienced with the technique.

- Using a trocar through the anterolateral portal while viewing through the anteromedial portal to help the graft into the femoral tunnel is important to ensure that the graft passes without the need to forcefully pull on the sutures, which could lead to breakage or pullout through the lateral skin.

Clinical Comments

- Are there any consequences to drilling a femoral tunnel near, or into, the epiphyseal-cartilage cap junction?
- There may be increased force at the graft-femoral tunnel junction, due to the acuity of the turn that the graft makes as it enters the femoral tunnel. If this is the case, should the post-operative course be lengthened before the patient returns to sports?

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Figures

Fig. 1

Preoperative markings are made to delineate the fibular head, lateral epicondyle, popliteal insertion, axis of the femoral shaft, and a line perpendicular to the axis from the lateral epicondyle. The area proximal to the lateral epicondyle and anterior to the femoral axis is not safe for introduction of the femoral tunnel pin because of the likelihood that this trajectory will encroach on the femoral physis. Use of the area posterior to the femoral axis line will increase the likelihood of cartilage cap injury and/or creation of a very short femoral tunnel.

Fig. 2

Illustration of the three described portals used with this technique. The far anteromedial portal is labeled as the *accessory anteromedial portal*.

Fig. 3

An awl has been utilized to mark the central portion of the femoral footprint, which we utilize for a single-bundle anatomic reconstruction. The arthroscope is visualizing the lateral intercondylar wall from the anteromedial portal, while the awl is placed through the far anteromedial portal.

Fig. 4-A

Photograph depicting the extra-articular placement of the FlipCutter at a point between the popliteal tendon's insertion and the lateral epicondyle.

Fig. 4-B

The intra-articular (arthroscopic) placement of the FlipCutter's guide. This guide is placed into the previously created awl mark.

Fig. 5

A single fluoroscopic view is obtained to ensure that the FlipCutter pin is placed in the correct, epiphyseal position prior to proceeding with the FlipCutter drill.

Fig. 6

The FlipCutter drill has entered the knee joint at the predetermined femoral footprint. A probe is then used to flip the blade of the drill into position, thus allowing the device to drill in a retrograde manner.

Fig. 7

When the femoral tunnel is drilled correctly there will be no evidence of the femoral physis or any signs of femoral tunnel blow-out.

Fig. 8

The tibial footprint in addition to the posterior portion of the anterior horn of the lateral meniscus are both used to place the tibial tunnel guidepin in the central portion of the tibial footprint for a single-bundle ACL reconstruction.

Fig. 9-A

Postoperative anteroposterior radiograph showing that, with our described technique, the femoral tunnel is transepiphyseal. The graft is suspended in the femoral tunnel, and the tibial side is tied over a screw and washer (to avoid placing an interference screw near the tibial physis).

Fig. 9-B

Postoperative lateral radiograph.

Fig. 10-A

Preoperative 3D MRI template, lateral view.

Fig. 10-B

Preoperative 3D MRI template, posterior view.

Fig. 10-C

Comparison of this lateral, sagittal CT image with the preoperative 3D MRI template shows a well-placed femoral tunnel that is transepiphyseal and does not encroach onto the femoral physis.

Fig. 10-D

This intercondylar, sagittal CT image depicts accurate recreation of the femoral tunnel anatomy.

Fig. 10-E

Posterior, coronal CT image.

Fig. 1

Fig. 2

Fig. 3

Fig. 4-A

Fig. 4-B

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9-A

Fig. 9-B

Fig. 10-A

Fig. 10-B

Fig. 10-C

Fig. 10-D

Fig. 10-E