[ CLINICAL COMMENTARY ]

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# Anatomic Anterior Cruciate Ligament Reconstruction Utilizing the Double-Bundle Technique

**SYNOPSIS:** The goal of every orthopaedic surgeon should be to restore anatomy as close as possible to normal. Intense research on reconstruction of the anterior cruciate ligament (ACL) and an advancing knowledge of the anatomy and function of the 2 primary bundles of the ACL have led to techniques of ACL reconstruction that more closely restore normal anatomy. Restoring the ACL footprint is one of the most important goals of the surgery, and the choice between anatomic single-bundle and double-bundle ACL reconstruction is determined by the anatomical features of each patient. After reconstruction, the graft undergoes a complex, lengthy process of remodeling; therefore, inappropriate (early), aggressive rehabilitation can lead to graft failure and compromise the patient's outcome. The purpose of this article is to provide an overview of the anatomy and function of the ACL, the methods for anatomic single-bundle and double-bundle ACL reconstruction, and our recommendations for postoperative rehabilitation.
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**KEY WORDS:** *ACL, knee, surgery*

SUPPLEMENTAL VIDEO ONLINE

Rupture of the anterior cruciate ligament (ACL) is one of the most common knee ligament injuries, with an annual incidence of 35 per 100 000 people.[26,82] This event occurs primarily in active individuals, and female athletes are 2 to 3 times more likely to have an ACL injury than male athletes.[26,82]

Consequently, ACL reconstruction is one of the most commonly performed orthopaedic surgeries in the United States. Traditional ACL reconstruction, in which a single graft is used to reconstruct the ACL, has been shown to result in normal International Knee Documentation Committee Subjective Knee Form scores in only 61% to 67% of patients after surgery and rehabilitation.[12] Of more concern, however, is the finding that 40% to 90% of patients who undergo ACL reconstruction have radiographic knee osteoarthritis 7 to 12 years after surgery.[52,60] In the last decade, anatomic double-bundle reconstruction of the ACL has gained popularity and become a widely accepted and used method to reconstruct the ACL. Though differences in the outcomes of single-bundle and double-bundle ACL reconstruction comprise a topic of ongoing discussion, it is generally agreed that both methods need to be anatomically performed.[23,38,55] Anatomic ACL reconstruction techniques aim to better restore the normal anatomy and biomechanics of the knee, and are hypothesized to potentially decrease the incidence of osteoarthritis after ACL reconstruction.

In this paper, the different aspects of anatomic ACL reconstruction will be discussed. We will focus on the anatomy, biomechanics, and kinematics of the ACL, methods for anatomic single-bundle and double-bundle reconstruction, and implications for postoperative rehabilitation.

## Anatomy of the ACL

Surgeons in all specialties need to have an in-depth knowledge of anatomy to maximize outcomes for their patients. Based on recent research, knowledge of the anatomy of the ACL is advancing, and this has led to new and different approaches to restore the anatomical structure and physiological function of the ACL.

The ACL consists of 2 functional bundles—the anteromedial (AM) and posterolateral (PL) bundles[4,7,28,59]—named for their position on the tibia (**FIGURE 1**). Recent research has indicated that 2 dis-

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tinct bundles, separated by a septum of vascularized connective tissue,[19] are already in existence in a fetus after approximately 20 weeks of development, which leads one to assume that the 2-bundle anatomy of the ACL is hereditary.

In addition to the ability to identify the remnants of the ACL, detailed knowledge of the specific bony landmarks of the femoral and tibial insertion sites is essential for an anatomic approach to ACL reconstruction. For the femoral insertion site, the prominent landmark is the resident's ridge (lateral intercondylar ridge), which serves as the anterior limit of the ACL in the anatomical position. It is located on the medial wall of the lateral femoral condyle and, in the arthroscopic view of the orthopaedic surgeon with the knee at 90° of flexion, marks the upper border of the ACL (**FIGURE 2**).[18,64] In 80% of all individuals, a second ridge, the bifurcate ridge, can be identified. This ridge separates the origins of the AM and PL bundles and runs perpendicular to the resident's ridge (**FIGURE 2**).[18,64] The footprints of both bundles are larger than the cross-sectional area of the midsubstance of the ACL.[29] In the literature, there is a high degree of intrastudy and interstudy variation in the sizes of the femoral and tibial ACL insertions.[49] In general, the size of the femoral insertion is slightly smaller and of a different shape than the tibial insertion, which needs to be considered when performing anatomic ACL reconstruction.

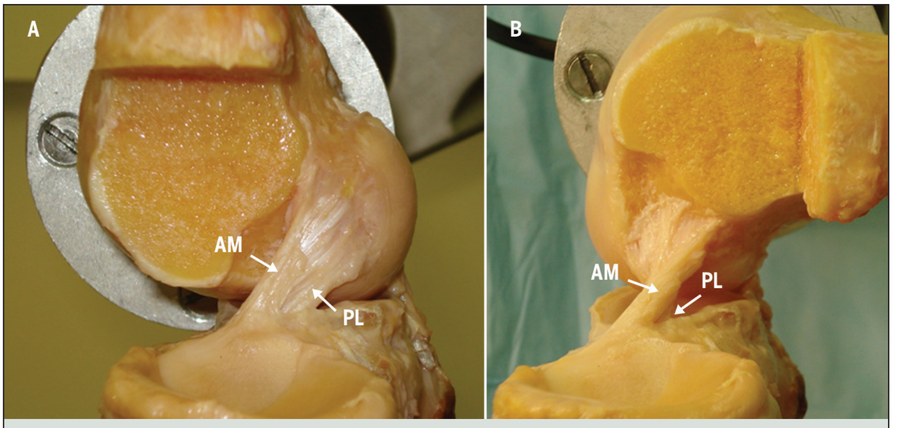


**FIGURE 1.** Right-knee cadaveric specimen showing the 2-bundle anatomy of the anterior cruciate ligament. (A) The knee is in full extension and the AM and PL bundles are parallel to each other. (B) The knee is in flexion, the AM bundle is taut, the PL bundle is looser, and the bundles cross each other. Abbreviations: AM, anteromedial; PL, posterolateral.

## Biomechanics and Kinematics of the ACL and Knee

The femoral footprints of the AM and PL bundles are vertically aligned when the knee is in full extension, and the femoral origin of the AM bundle is located superior to the PL insertion.[93] In this configuration, the 2 bundles are parallel to each other, whereas with the knee in 90° of flexion (ie, the position of the knee during surgery), the 2 bundles cross each other and the femoral insertions are nearly horizontally aligned (**FIGURE 1**).[15,93]

When the knee is in full extension, the AM and PL bundles of the ACL are under tension. When the knee is flexed to 60° to 90°, the PL bundle is lax and allows rotation of the tibia on the femur.[24] The PL bundle also limits anterior translation of the tibia at lower angles of knee flexion (0°-30°). The AM bundle primarily resists anterior translation of the tibia and undergoes less change in length than the PL bundle throughout the range of knee motion. The PL bundle is maximally lengthened when the knee is in full extension, and the AM bundle is under maximum tension when the knee is flexed between 45° and 60°.[15,33,43] This has implications for the angle of knee flexion utilized when tensioning the grafts during ACL reconstruction. The AM and PL bundles do not work individually but rather synergistically to control and limit anterior/posterior translation and axial rotation of the knee.[43,78]

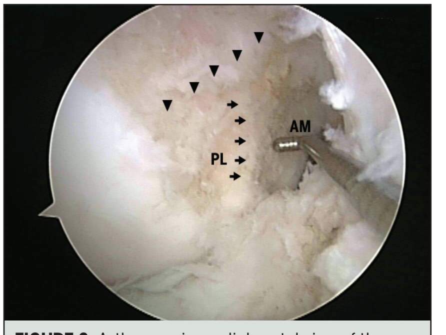


**FIGURE 2.** Arthroscopic medial portal view of the right knee in 90° of flexion, showing the marked native femoral insertion site of the anterior cruciate ligament. Both the lateral intercondylar ridge (triangles) and the lateral bifurcate ridge (arrows) can be seen. Abbreviations: AM, anteromedial; PL, posterolateral.

Generally, traditional single-bundle ACL reconstruction places the ACL in a nonanatomic position. It successfully restores normal anterior/posterior translation but fails to restore normal rotational stability.[84,86] These observations were confirmed by Tashman et al[75] in an in vivo study that used dynamic dual-video fluoroscopy to evaluate the kinematics of the knee during walking and running on a treadmill in patients who underwent traditional, nonanatomic single-bundle reconstruction. Specifically, traditional single-bundle ACL reconstruction restored normal anterior/posterior translation, but the knee was externally rotated by an average of 4° and adducted by an average of 3° compared to the contralateral normal knee. Although the magnitude of the abnormal rotations may seem small, the difference in external rotation is sufficient to move the contact point of the lateral tibial plateau 3.5 mm posteriorly, and the difference in adduction would decrease the medial joint space by 1.3 mm in an average-sized knee. Thus, conventional, nonanatomic single-bundle ACL reconstruction does not appear to restore the normal kinematics of the knee, and it is hypothesized that this inability is one of the factors that may contribute to posttraumatic knee osteoarthritis after ACL injury and surgery.

In contrast, anatomic double-bundle ACL reconstruction appears to better restore rotational stability compared to single-bundle reconstruction.[86,87] In a cadaveric model, Yagi et al[86] demonstrated that reconstructing both bundles of the ACL resulted in more normal restoration of knee kinematics, particularly internal and external rotation of the tibia. However, these better results may be due to the anatomic placement of the ACL and not necessarily the double-bundle technique. Single-bundle ACL reconstruction can also be performed in an anatomic fashion. Yamamoto et al[87] showed that anatomic single-bundle reconstruction with a laterally placed femoral tunnel can restore knee kinematics to a level similar to that achieved by anatomic double-bundle reconstruction when the knee is near full extension; however, double-bundle reconstruction resulted in more normal kinematics when the knee was at higher angles of flexion. The true benefits of anatomic double-bundle reconstruction compared to anatomic single-bundle reconstruction should be the focus of future studies.

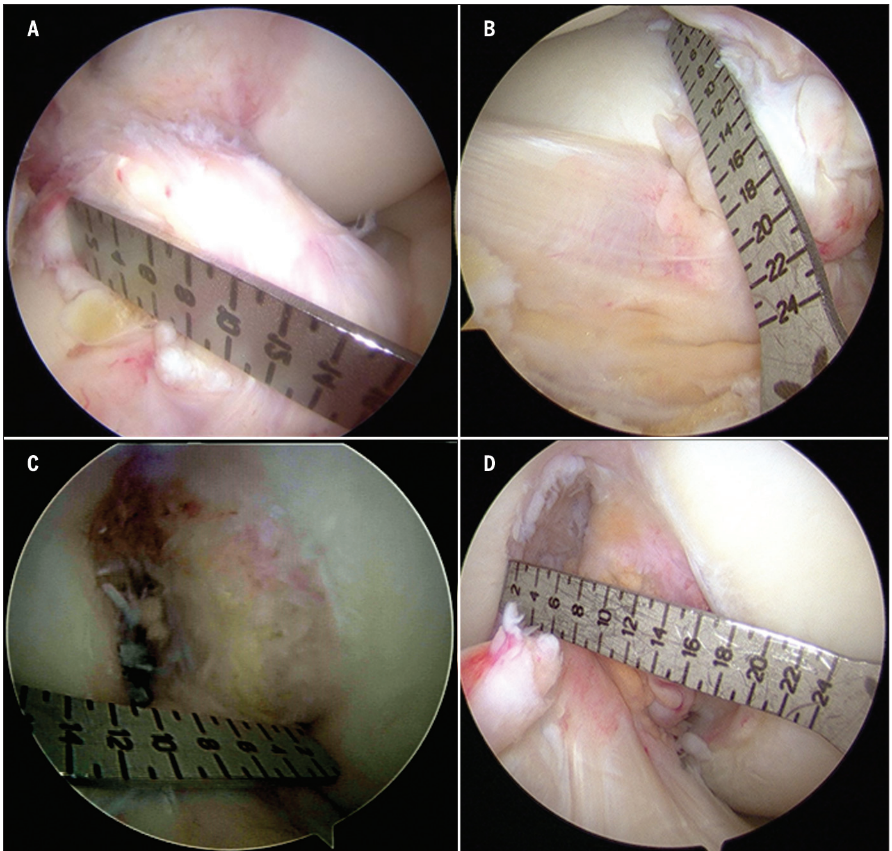


**FIGURE 3.** Arthroscopic view of a right knee in 90° of flexion. (A) Lateral portal view of a 14-mm insertion site. (B) Lateral portal view of a 22-mm insertion site. (C) Central portal view of a 12-mm notch. (D) Central portal view of a 20-mm notch. This figure shows the large variations in tibial insertion site and femoral intercondylar notch size. Online video available at www.jospt.org.

The clinical evidence for double-bundle ACL reconstruction is mounting but is still inconclusive. There have been 16 prospective clinical outcome studies that have compared double-bundle ACL reconstruction to single-bundle ACL reconstruction,[1,3,8,35,40,41,47,57,58,70,74,77,83,85,88,90] of which 10 were randomized clinical trials.[1,3,35,40,41,57,70,74,83,90] A meta-analysis of 4 randomized clinical trials by Meredick et al[55] revealed that double-bundle ACL reconstruction resulted in a significantly smaller side-to-side difference in tibial translation, as measured with the KT1000 Knee Ligament Arthrometer (MEDmetric Corporation, San Diego, CA); there was no difference in the proportion of individuals who had a normal or nearly normal pivot shift test. However, a closer analysis of the data reported by Meredick et al[55] revealed that 88% of patients who underwent double-bundle ACL reconstruction had a normal pivot shift test after surgery, compared to 62% of those who underwent single-bundle reconstruction. This result indicates that a normal pivot shift was more common following double-bundle ACL reconstruction (pooled odds ratio, 3.8; 95% confidence interval: 1.8, 7.8).[38]

Since the meta-analysis by Meredick et al,[55] there have been 6 additional randomized clinical trials comparing double-bundle ACL reconstruction to single-bundle ACL reconstruction.[3,35,70,74,83,90] Three of the trials[3,35,70] demonstrated that double-bundle ACL reconstruction resulted in significantly better side-to-side differences in anterior translation and a significantly higher proportion of normal pivot shift tests. To date, however, none of the studies have demonstrated that double-bundle ACL reconstruction results in better patient-reported outcomes. Most importantly, long-term trials to compare the development and progression of posttraumatic knee osteoarthritis after single-bundle and double-bundle ACL reconstruction are needed to demonstrate the true benefits of anatomic double-bundle ACL reconstruction.

## ANATOMIC ACL RECONSTRUCTION

In the opinion of the authors, there are 4 fundamental principles of anatomic ACL reconstruction. The first 2 principles are to appreciate the native anatomy of the ACL and to individualize surgery to the patient's specific anatomy and functional needs. Because of the high degree of variation in the sizes of the tibial and femoral insertion

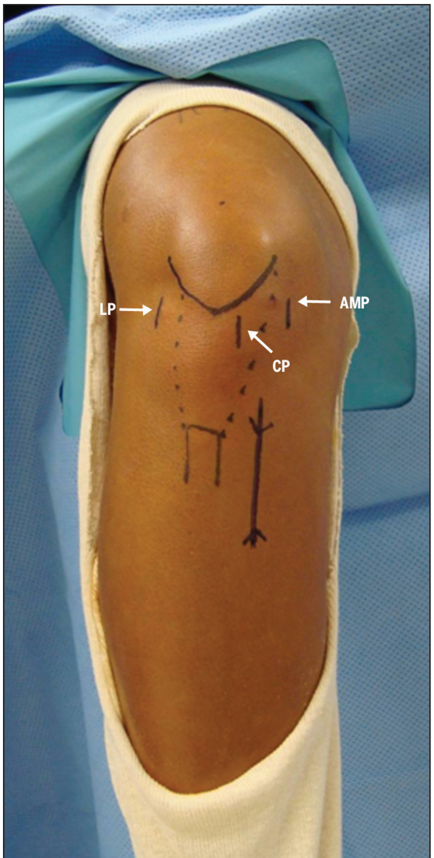


**FIGURE 4.** Three-portal technique marked on a right knee in an operating position of 90° of flexion. The lateral portal (LP), central portal (CP), and accessory medial portal (AMP) are shown.

sites, as well as the sizes of the femoral intercondylar notch, the insertion sites and notch need to be measured to determine whether single-bundle or double-bundle ACL reconstruction best suits the needs of the individual patient (**FIGURE 3** and **ONLINE VIDEO**).[78] A tibial insertion site shorter than 14 mm in length and a notch narrower than 12 mm in width are too small to accommodate double-bundle ACL reconstruction.[79] The third principle is to restore native anatomy by placing the graft in the center of the footprint. The fourth principle is to restore the physiological function of the graft by applying appropriate tension to mimic the native ACL as closely as possible.[5] As such, when anatomic double-bundle ACL reconstruction is performed, the graft for the PL bundle is tensioned with the knee at 0° of flexion and the graft for the AM

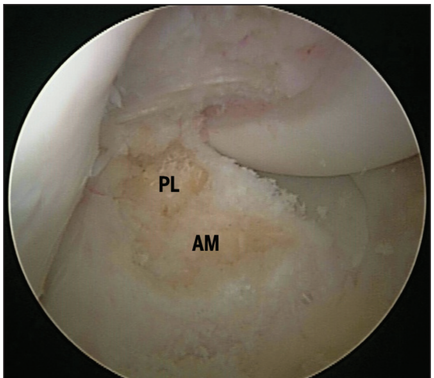


**FIGURE 5.** Arthroscopic lateral portal view of the right knee in 90° of flexion, showing the marked native tibial anterior cruciate ligament insertion site. Abbreviations: AM, anteromedial; PL, posterolateral.

bundle is tensioned with the knee flexed to 45° to 60°. This is consistent with biomechanical evidence that the PL bundle is under maximal tension with the knee in full extension and that the AM bundle is under maximal tension with the knee in 45° to 60° of flexion.[89] For anatomic single-bundle ACL reconstruction, the graft is tensioned with the knee in 10° to 20° of flexion. However, in clinical practice, there is currently no consensus on the optimal knee flexion angles during graft tensioning in both single-bundle and double-bundle approaches.[44,66]

It is our belief that for anatomic single-bundle and double-bundle ACL reconstruction, 3 arthroscopic portals (central, anterolateral, and accessory medial) should be created (**FIGURE 4**).[16] Creation of 3 portals has several advantages compared to the traditional 2-incision technique described in the literature.[6] The creation of a third portal allows for better visualization of the femoral ACL insertion site location, making a notchplasty unnecessary.[6] The anterolateral portal is placed laterally, adjacent to the patellar tendon and the inferior border of the patella. The central portal is located slightly above the medial meniscus and directly adjacent to the medial border of the patellar tendon. With the arthroscope in the central portal, a view along the ACL directly to the femoral ACL footprint is possible. The accessory medial portal is located 2 cm medial to the central portal and is created under arthroscopic visualization, with sufficient space from the medial condyle to avoid damaging the condyle. Placement of the arthroscope in the central portal helps to visualize the lateral wall of the femoral notch and the ACL footprint; therefore, with the accessory portal as a working portal, this technique eliminates the need for notchplasty.

## Anatomic Double-Bundle Reconstruction

After the portals are established and diagnostic arthroscopy of the medial and lateral tibiofemoral and patellofemoral compartments is performed to inspect the menisci and chondral surfaces, focus is turned toward the intercondylar notch to determine the rupture pattern of the ACL. The ACL is most likely to be torn at the femoral site, but there can also be midsubstance tears as well as ruptures at the tibial site. By visualizing and probing the remnants of the ACL, possible single-bundle tears can be diagnosed where 1 bundle remains intact.[91] In addition to the aforementioned bony landmarks, the remnants of the torn ACL can help the surgeon to locate the native tibial and femoral insertion sites. The anterior/posterior and medial/lateral dimensions on the tibia, as well as the proximal/distal and anterior/posterior dimensions on the femur, are measured. Along with measurement of the intercondylar notch width, the measurements are used to determine whether single-bundle or double-bundle reconstruction is preferred for the patient.

After the origins of the 2 bundles on the tibia and femur are marked, 2 tunnels in the tibia and femur are drilled (**FIGURES 2** and **5**). The size of the tunnels is determined by the size of the ACL footprints. To restore the normal size relationship between the AM and PL bundles, the sizes of the graft and tunnel for the AM bundle should be larger than the graft and tunnel for the PL bundle. When drilling the femoral and tibial tunnels, a bony bridge of approximately 2 mm needs to be preserved to prevent coalescence of the tunnels.[81] In the end, the sum of the diameters of the 2 tunnels and the bony bridge between them should be approximately equal to the size of the native footprint.

Either allograft or autograft tissue can be used to reconstruct the ACL, depending on the wishes of the patient and the preferences of the surgeon. Good results are reported for different types of autografts, such as hamstring, bone-patellar tendon-bone, or quadriceps tendon,[66] and allografts.[9] However, recent evidence suggests that graft failure may occur more frequently when an allograft is used to reconstruct the ACL in young, active patients. This may be due to a delayed incorporation of the graft into the tunnel, which leads to inferior biomechanical properties.[14,39,51,53,63,67] As a consequence, the authors believe that the autograft is the best type of graft for young, active athletes, whereas allografts can be used for less active patients because of the lesser amount of postoperative pain secondary to not harvesting a tendon graft during surgery.

The PL graft is passed first, followed by the AM graft. To preserve insertion site integrity, suspensory fixation is used on the femoral side and screw fixation is used on the tibial side, where the screw is placed 1 to 2 cm beyond the joint line. The PL bundle is fixed at 0° to 10° of knee flexion and the AM bundle is fixed at 45° of flexion (**FIGURE 6** and **ONLINE VIDEO**).[5]

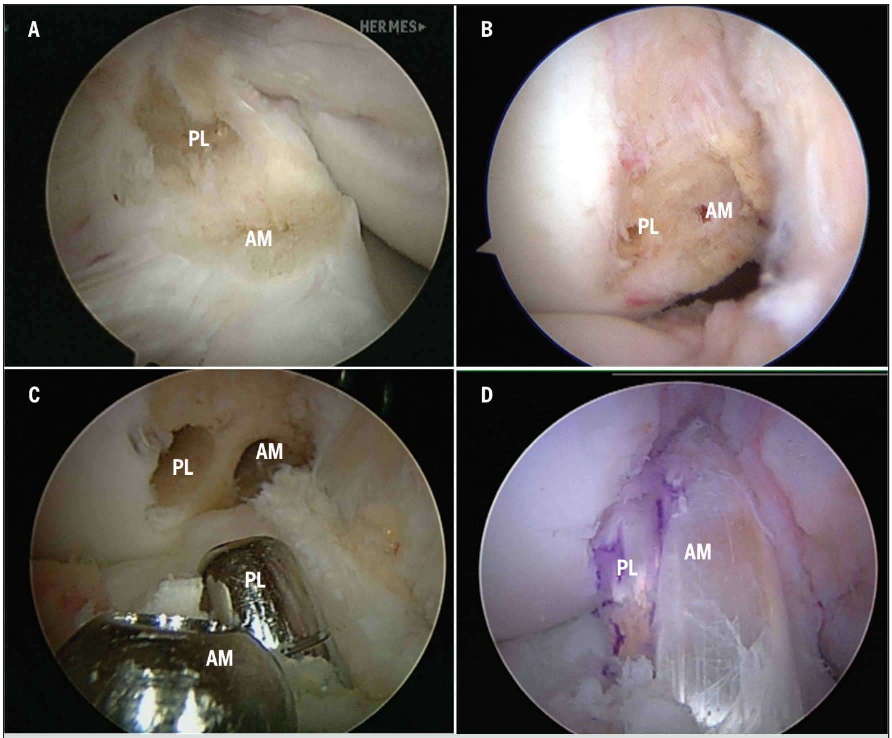


**FIGURE 6.** Arthroscopic view of the anatomic double-bundle reconstruction technique in a right knee. (A) Marking of the tibial insertion site. (B) Marking of the femoral insertion site. (C) The tibial and femoral tunnels are drilled in the location of the tibial and femoral footprints. (D) The anteromedial (AM) and posterolateral (PL) bundle grafts are passed. Online video available at www.jospt.org.

### Anatomic Single-Bundle Reconstruction

In cases when the insertion site is smaller than 14 mm and the width of the intercondylar notch is narrower than 12 mm, double-bundle reconstruction can be a challenge. When the intercondylar notch is small, drilling the femoral tunnel is obscured by the medial wall of the notch. Additionally, a notch width narrower than 12 mm increases the risk of damaging the medial condyle, especially when drilling the AM tunnel.[80] In our opinion, a small notch is an anatomical variation, but there are studies showing that a narrow notch is a risk factor for noncontact ACL injuries.[34,36] As such, we do not refer to a narrow notch as notch stenosis, which implies that the narrow notch is pathologic. Therefore, we recommend that the notch should be measured in all patients undergoing ACL reconstruction to determine whether double-bundle or single-bundle ACL reconstruction should be performed. Rather than performing a notchplasty to create the additional room necessary for double-bundle reconstruction, we believe that single-bundle ACL reconstruction should be performed when there is a narrow notch.

Further indications for single-bundle reconstruction are described in the literature. These include open physes, severe arthritic changes (grade III or greater), multiligamentous injuries, and severe bone bruises, particularly of the lateral femoral condyle (partial indication). In patients with severe arthritic changes, a double-bundle ACL reconstruction could overconstrain the knee and lead to increased pain and degeneration. A bone bruise of the lateral femoral condyle could potentially affect graft incorporation.[61,69]

For anatomic single-bundle reconstruction, we apply the same principles that are used for anatomic double-bundle reconstruction. The femoral and tibial tunnels are placed in the center of the femoral and tibial ACL insertion sites. The size of the drilled tunnel is based on measurements of the width and length of the footprint. For example, if the insertion site is 12 mm long and 9 mm wide, a drill bit of 9 mm should be used to ensure that the tunnel remains within the borders of the footprint and to avoid damaging adjacent structures, especially on the tibial side. In these cases, we accept that single-bundle ACL reconstruction does not completely restore the size of the native ACL footprint. In our example, the tunnel may be smaller than the insertion site area, although it must be pointed out that perpendicular drilling is not possible; consequently, drilling will result in an oval-shaped tunnel aperture that may actually restore the length of the footprint.

### Failure After ACL Reconstruction

Graft failure is an ongoing topic of discussion in the literature, as well as at meetings and conferences. Rates of functional graft failure are reported to be between 0% and 27.3%.[65] The main cause of graft failure is related to malposition of the tunnel, for example, placing the tibial tunnel too anteriorly or placing the graft too vertically.[17,42] Poor biological incorporation of the graft,[54] recurrent trauma, or early return to sport[27] may also lead to graft failure. Most studies that reported graft failure after ACL reconstruction included patients who underwent nonanatomic ACL reconstruction. However, after anatomic ACL reconstruction, a higher graft failure rate may be expected because, as demonstrated by Kato et al,[45] the forces in an anatomically placed graft will be greater (comparable to the native ACL) than those in a nonanatomically placed graft (less force than the native ACL due to the nonanatomic position of the graft). Therefore, rehabilitation and return to sport after anatomic ACL reconstruction may need to be progressed slower than after a traditional, nonanatomic ACL reconstruction.

## REHABILITATION

Except for a slower return to functional activities, rehabilitation after anatomic ACL reconstruction follows rehabilitation guidelines similar to those of traditional, nonanatomic single-bundle ACL reconstruction. Initially, we were concerned that anatomic double-bundle ACL reconstruction might interfere with the restoration of range of motion; however, our clinical experience indicates that this has not been the case. In fact, we have observed an earlier and better return of the full range of knee extension and flexion after anatomic ACL reconstruction. Another concern is that, based on biomechanical studies, graft forces are greater when the graft is anatomically positioned.[45] For this reason, functional activities that place a high load on the graft, such as jumping, cutting, pivoting, and return to sport, are more gradually initiated and progressed after anatomic ACL reconstruction.

Below is a description of the rehabilitation program followed at our institution. The rehabilitation programs after anatomic single-bundle and double-bundle ACL reconstruction are the same. Immediately after surgery, the focus is to minimize pain and swelling, restore full passive extension symmetrical to the noninvolved knee, achieve 90° to 100° of knee flexion, restore the ability to perform a straight leg raise (SLR) without a quadriceps lag, and progress to full weight bearing so the individual can walk without assistive devices or a gait deviation. The day after surgery, patients begin to perform ankle pumps, quadriceps sets, SLRs, gastrocnemius and hamstring stretches, and heel slides. The patient is encouraged to make frequent use of cold to control postoperative pain and swelling. The patient ambulates with axillary crutches, using weight bearing as tolerated, with the knee brace locked in full extension. Unless the patient had a concomitant meniscus repair, the brace can be unlocked for ambulation at the end of the first week after surgery. If the patient had a concomitant meniscus repair, use of the brace locked in full extension is continued for 4 to 6 weeks to minimize shear stresses on the healing meniscus during ambulation.[72]

During the first 4 to 6 weeks after surgery, the rehabilitation program is gradually progressed. Active and active-assisted range-of-motion exercises are used to restore range of motion as tolerated. If the patient had a concomitant meniscus repair, knee flexion is limited to 90° for 4 weeks after surgery. Patellar mobilization is used to maintain or increase patellar mobility, especially superior glide. Emphasis is placed on being able to perform a full, sustained isometric contraction of the quadriceps that results in superior migration of the patella and the ability to perform a SLR with the knee at the end range of full extension. High-intensity electrical stimulation that is sufficient to produce a full, sustained contraction of the quadriceps is used to improve quadriceps strength. Several randomized clinical trials have demonstrated the benefits of high-intensity electrical stimulation to improve quadriceps strength,[21,71] gait,[71] and patient-reported outcomes[21,46] following ACL reconstruction. As range of motion improves, quadriceps strengthening can be progressed to include limited-arc (from 90° to 60°) non–weight-bearing (open-chain) knee extension exercises and low-level weight-bearing (closed-chain) exercises, with weight equally distributed on both extremities (eg, minisquats, wall slides). Standing weight shifts progressing to unilateral balance exercises can be used to improve the ability to tolerate full weight bearing and to begin to improve balance and postural control. Gait training is performed as necessary to ensure that the individual uses a normal heel-toe gait and does not walk with a flexed knee during the midstance of gait. Progressive resisted exercises are also initiated for the hamstrings and hip muscles; however, to allow for healing of the harvest site, we delay resisted hamstring exercises for 4 to 6 weeks following harvest of the hamstring. If available, pool exercises can be used to improve range of motion, strength, and gait.

If the patient fails to progress with range of motion and/or has difficulty initiating a quadriceps contraction for more than 1 to 2 weeks after surgery, the postoperative rehabilitation program may need to be altered and the surgeon should be alerted. Joint mobilization and cyclic or static stretching of the joint may be needed to restore extension or flexion of the knee. If extension and flexion are both limited, we believe that emphasis should first be placed on restoring extension. If stretching contributes to increased pain and inflammation, it may be necessary to temporarily limit or discontinue stretching exercises until irritability of the joint

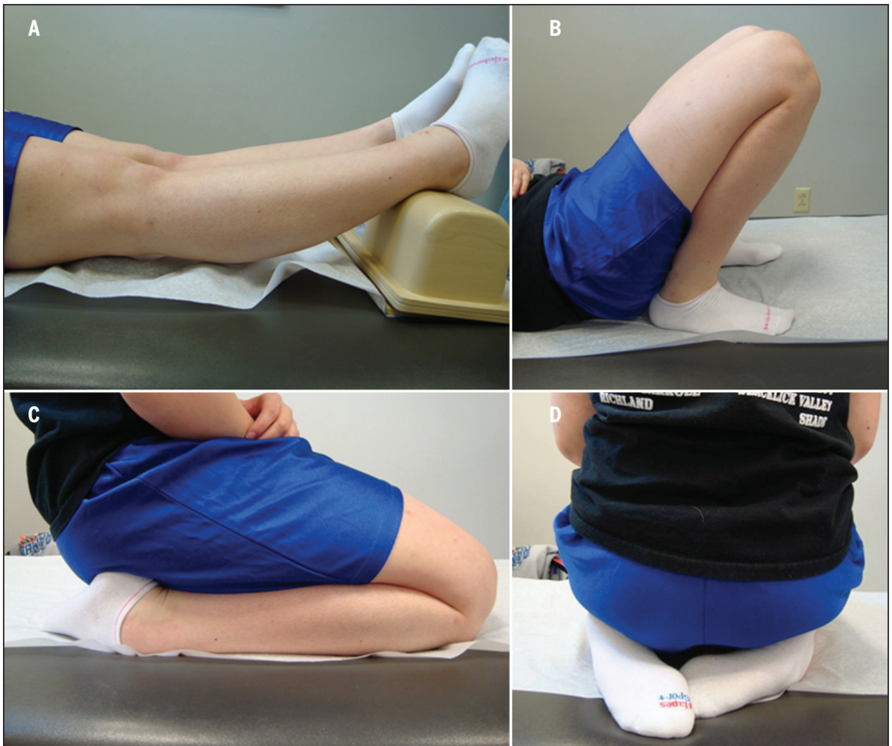


**FIGURE 7.** Patient 3 months after anatomic anterior cruciate ligament reconstruction of the right knee. Full range of motion in extension (A), flexion (B), and kneeling (C and D) is achieved when compared to the uninjured side.

is reduced. Biofeedback may be considered if the patient has difficulty recruiting the quadriceps muscle. Active-assisted, terminal, non–weight-bearing knee extension in the range of 20° of flexion to full end-range extension can be used to re-educate and strengthen the quadriceps if a quadriceps lag is present.

When the patient has no pain or swelling, full passive knee extension (90° to 100° of knee flexion), and can perform a SLR without a lag and walk without assistive devices or gait deviations, use of assistive devices can be discontinued and the intensity of the rehabilitation program can be increased. At this time, the brace can also be discontinued. This typically occurs 3 to 4 weeks after surgery. At this time, range-of-motion and stretching exercises can be used to restore full motion (**FIGURE 7**). We strive for full passive knee extension symmetrical to the noninvolved knee and knee flexion to within 5° of the noninvolved knee.

Resistance for non–weight-bearing and weight-bearing exercises for the quadriceps, hamstrings, and hip and trunk musculature is increased, as tolerated, about 4 weeks after surgery. Non–weight-bearing and weight-bearing quadriceps exercises both produce similar strain levels in the graft; however, as the resistance for non–weight-bearing quadriceps exercises is increased, the amount of ACL strain increases in comparison to weight-bearing exercises.[22] It is unknown whether graft strain during non–weight-bearing and weight-bearing quadriceps exercises improves healing or negatively affects it.[10] There is evidence that weight-bearing quadriceps exercises yield better patient-reported outcomes, less patellofemoral pain, and less laxity than non–weight-bearing exercises.[13,68] On the other hand, it appears that non–weight-bearing quadriceps exercises increase quadriceps femoris muscle strength without affecting knee stability in patients with an ACL-deficient knee.[50,66] While the advantages and disadvantages of non–weight-bearing and weight-bearing quadriceps exercises have been debated, a review of the available evidence suggests that both forms of exercise are beneficial when appropriate precautions are taken to protect the healing graft and avoid excessive stress on the patellofemoral joint.[11,20,56] As such, when performing non–weight-bearing quadriceps exercises, we limit the arc of motion from 90° to 60° of knee flexion for the first 3 months after surgery to minimize strain on the healing graft. Additionally, the range of motion for non–weight-bearing and weight-bearing quadriceps exercises may need to be adjusted depending on patellofemoral symptoms.

In addition to strengthening the quadriceps and hamstrings, emphasis is placed on strengthening the hip and core trunk muscles, particularly the hip abductors and external rotators, to reduce valgus collapse of the knee,[62] which has been associated with noncontact ACL injuries.[31,32]

Within the first 3 months after surgery, low-impact aerobic training exercises, including pedaling a stationary bicycle ergometer or walking on an elliptical trainer or treadmill, can be initiated. Balance and perturbation exercises can be used to enhance development of neuromuscular control.

Three to 4 months after surgery, the patient can be progressed to running at a slow pace on a treadmill or over ground for 5 to 10 minutes every other day, provided the patient has quadriceps strength that is 75% to 80% of the noninvolved limb, as determined by isokinetic testing or a single-repetition maximum quadriceps strength test.[37] The running program is gradually increased as long as the patient does not develop pain, swelling, or gait asymmetries. During this time, the patient can also be progressed to low-level submaximal (less than 50% effort) agility drills, including side-to-side shuffling, forward and backward running, and jumping and landing on both limbs simultaneously from distances less than 50% of the individual's height. The brace is no longer needed during exercise.

As the time from surgery increases,

the progression of the patient to higher-level functional activities becomes more variable and difficult to predict. This is due to variations in the surgical procedure, surgeon preferences, and individual factors. Therefore, the initiation of higher-level functional activities, such as running, jumping and landing, cutting and pivoting, and return to sport, may deviate from the time periods listed in the postoperative rehabilitation guidelines. Because of variations between patients, we progress the functional training and return-to-sport phases based on the patient's ability to perform the activities without deviations or symptoms (pain, swelling, sense of instability).

During the functional training and return-to-sport phases of rehabilitation after ACL reconstruction, emphasis is placed on strengthening through the full range of motion, improving neuromuscular control, and ensuring a gradual increase in function that culminates in return to sport.

Once the patient is able to tolerate running 2.4 to 3.2 km without pain or swelling, the patient can be progressed to a higher order of agility and plyometric drills. Typically, these activities begin approximately 6 months after surgery. Initial agility drills can include side-to-side shuffling, forward and backward running, and ladder drills. More challenging agility drills include carioca and cone drills that involve changing directions at various angles. Initially, these activities should be performed at 50% effort, progressing to 75% and eventually 100% effort, as tolerated.

During this time, the patient can also be progressed to plyometric jumping and landing drills. Initially, these activities should focus on landing and appropriate attenuation of force through the lower extremity. Such activities include double-limb jumping, single-limb jumping, and dropping and landing from a plyometric box. As the patient becomes proficient with correct jumping and landing mechanics, plyometric exercises can be made more challenging by increasing the height or distance of the jump, increasing the duration of the drills, incorporating changes in direction, and combining multiple tasks.

Once the patient is able to tolerate full-effort running, jumping, and agility drills, return to sport can be considered and a functional brace can be readjusted for at least 6 months. The time frame for return to sport following anatomic ACL reconstruction is variable, but generally occurs 9 to 12 months after surgery and is dependent on concomitant surgical procedures, individual patient tolerance for the activities, surgeon preferences, and the physical demands of the sport. Initially, training for return to sport should begin with unopposed components of the individual's athletic activity. As the patient becomes proficient and can perform these activities safely, the speed and complexity of the activities can be increased. Training with opposition from other players should be gradually introduced. To return to full participation in sports, the patient should be progressed from partial return to practice to full return to practice, followed by return to competition.

## DISCUSSION

In recent years, traditional approaches and methods to reconstruct the ACL have been critically evaluated, and it has been shown that the femoral and tibial tunnels are often placed in a nonanatomic position.[30] Nonanatomic placement of tunnels is most likely due to the surgeon's efforts to avoid roof impingement and abrasion of the graft, which occurs when the tibial tunnel is placed too anteriorly. As a result, the surgeon may place the tibial tunnels more posteriorly. Use of a transtibial method to create the femoral tunnel also contributes to nonanatomic placement of the graft.[48] For example, to place the femoral tunnel close to the native location of the femoral ACL insertion site, it is often necessary to position the tibial tunnel within the tibial insertion site for the PL bundle. Despite this posterior placement of the tibial tunnel, use of a transtibial method to drill the femoral tunnel still results in a femoral tunnel that is too high in the intercondylar notch (the high-AM position of the femoral tunnel). To avoid this, we recommend using a 3-portal technique that allows for use of the medial portal to create the AM femoral tunnel independent of the tibial tunnel, allowing one to achieve a more anatomic reconstruction.

Misplaced grafts are one of the most important causes of graft failure.[25,73] Furthermore, a misplaced graft can result in worse clinical outcomes, with limited range of motion and nonphysiological knee kinematics,[75,92] especially when roof impingement occurs. If the graft is misplaced, revision ACL reconstruction to place the graft more anatomically may need to be considered. A misplaced graft may also adversely affect biological healing of the graft within the tunnel and compromise healing of the bone-tendon interface.[61] It is our opinion that a delay or failure to regain full range of motion during rehabilitation is often an indicator of nonanatomic placement of the graft.

The concerns related to nonanatomic graft placement have prompted us to use more anatomic and individualized ACL reconstruction. Single-bundle and double-bundle ACL reconstruction can be performed in an anatomic manner.[69] Data from recent studies that have compared the clinical outcomes after single-bundle and double-bundle ACL reconstruction must be carefully interpreted. For example, one study compared single-bundle ACL reconstruction, which was performed using a transtibial method to create the femoral tunnel, to anatomic double-bundle reconstruction.[2] When comparing the clinical outcomes of single-bundle and double-bundle ACL reconstruction, both procedures should have been performed anatomically. Difficulty in conducting a randomized clinical trial to compare single-bundle ACL reconstruction to double-bundle ACL reconstruction may arise if the individual's anatomy precludes double-bundle

ACL reconstruction. This can occur if the insertion sites are too small or the intercondylar notch is too narrow to permit double-bundle ACL reconstruction. For this reason, a prospective randomized controlled trial that compares single-bundle ACL reconstruction to double-bundle ACL reconstruction may need to exclude patients who have insertion sites that are too small or a notch that is too narrow. Furthermore, a study that compares single-bundle ACL reconstruction to double-bundle ACL reconstruction should exclude individuals with associated injuries, such as meniscal tears, chondral injuries, or multiple ligament injuries, to achieve homogeneous groups.

The limitations of currently available clinical outcome measures must be considered when comparing single-bundle to double-bundle ACL reconstruction. It is hypothesized that the addition of the PL bundle during anatomic double-bundle ACL reconstruction will result in improved rotational stability of the knee. As such, a measure of rotational laxity of the knee is an important outcome to include in a trial comparing single-bundle to double-bundle ACL reconstruction. Clinical studies comparing single-bundle and double-bundle ACL reconstruction have relied on clinical measures of laxity such as the KT1000 Knee Ligament Arthrometer and pivot shift test. These clinical measures may not be sensitive enough to detect differences in laxity between single-bundle and double-bundle ACL reconstruction. Reliance on the pivot shift test as an end point for a study comparing single-bundle to double-bundle ACL reconstruction is a concern, particularly when the test is performed on a patient who is awake. Alternate methods to quantify rotation are needed. High-technology methods to precisely measure knee kinematics, such as dynamic stereoradiography, have shown promising results in 6 degrees of freedom[75,76] but are not feasible at most centers. A simple, clinically applicable tool, similar to the KT1000 Knee Ligament Arthrometer, that could be used to reliably quantify rotational laxity of the knee needs to be developed.

To date, evaluating the clinical outcomes of anatomic double-bundle ACL reconstruction has focused on the ability of the procedure to restore normal anteroposterior and rotational laxity of the knee. In the future, researchers should also consider the effects of anatomic double-bundle ACL reconstruction on the sense of instability and the ability to participate in strenuous sports. Long-term follow-up studies are needed to determine the effects of double-bundle ACL reconstruction on preventing or reducing the risk of knee osteoarthritis and its associated pain and disability. In the interim, high-field magnetic resonance imaging could be used to detect early evidence of cartilage changes.

In comparison to nonanatomic grafts, an anatomically placed graft will experience greater in situ forces.[45] Although increased loading of the graft may protect other structures in the knee from progressive degeneration, the higher load on the graft must be considered during postoperative recovery and rehabilitation while the graft is still healing and maturing. Because of the higher graft loads after anatomic ACL reconstruction, we recommend that rehabilitation be progressed more carefully. As a result, we do not recommend return to sport until 9 to 12 months after surgery, which is slower than the more commonly used accelerated rehabilitation approach described by Shelbourne and Nitz,[68] which advocates return-to-sport activities 3 to 6 months after surgery.

## CONCLUSION

In our opinion, anatomic ACL reconstruction can more closely restore the anatomy of the ACL, which we believe results in more normal kinematics of the knee. Ultimately, we believe that anatomic ACL reconstruction may promote better long-term knee health. Anatomic tunnel placement and restoration of the ACL insertion site can be accomplished by performing either single-bundle or double-bundle ACL reconstruction. The choice of technique should be based on individual measurements of the ACL insertion site and femoral intercondylar notch size. To decrease the failure rate, it is necessary to carefully plan and carry out the postoperative rehabilitation program. The patient needs to be aware that, although anatomic ACL reconstruction provides better kinematics of the knee and ultimately may lead to improved long-term health of the knee, the graft needs time to remodel and heal, and one should therefore resist the temptation of a more aggressive rehabilitation program. ◉

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