SPRING 2017

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# Individualized Anatomic Anterior Cruciate Ligament Reconstruction

**FREDDIE H. FU, MD, DSC (HON), DPS (HON)**
*Chair and David Silver Professor, Department of Orthopaedic Surgery*

**ELMAR HERBST, MD**
*Research Fellow, Department of Orthopaedic Surgery*

**MARCIO ALBERS, MD**
*Research Fellow, Department of Orthopaedic Surgery*

*Anterior cruciate ligament (ACL) injury is one of the most frequent sports injuries, with an incidence of 35 per 100,000 people per year, and with an approximately two to eight-times higher risk in female than in male athletes. It is estimated that between 75,000 and 100,000 ACL reconstruction procedures are performed annually in the United States alone.*[1]

ACL injury, without appropriate treatment, results in increased joint laxity, instability of the knee, reduced physical activity, and decreased sports participation. A recent systematic review supported the proposition that ACL injury predisposes knees to osteoarthritis. The ACL does not heal on its own, and as a result, reconstruction of the ACL is the standard surgical treatment. This is particularly important in physically active patients, allowing them to return to daily activities, including sports, and reducing their risk of developing degenerative knee changes at 10 years post injury.

## Historical Perspective on the Anatomy of the ACL

The earliest known descriptions of the human ACL were made around 3000 BCE and written on an Egyptian papyrus scroll. During the Roman era, Claudius Galen of Pergamon (199–129 BCE) described the ligaments of the knee, naming them the “ligamenta genu cruciate.”[2] In 1543, Andreas Vesalius completed the first known formal anatomic study of the human ACL in his book *De Humani Corporis Fabrica Libri Septum*.

For about 400 years, the ACL was thought of as a single, homogenous structure. The two bundles of the ACL were described for the first time in 1938 by Palmer et al.[3] Despite other subsequent descriptions of the two-bundle anatomy by Abbott et al. (1944) and Girgis et al. (1975), the discovery did not become well known for many decades.[3,4] Each author described an anteromedial bundle and a posterolateral bundle based on their relative tibial insertion sites; the same nomenclature used today (See Figure 1 on Page 2). Since then, the two-bundle composition of the ACL has been widely accepted.[5]

## Historical Perspective on ACL Reconstruction

The first ACL repair is attributed to the English surgeon Arthur William Mayo Robson, in 1895. Two decades later, Ernest William Hey Groves reported the first ACL reconstruction using an iliotibial band graft.[6] In 1934, the Italian surgeon Riccardo Galeazzi described a technique for ACL reconstruction using the semitendinosus tendon, and in 1935, Willis Campbell, from the United States, described the first use of a patellar tendon graft and fixation through tunnels in the femur and tibia.

In the 1970s, nonanatomic ACL reconstruction techniques, such as the extra-articular MacIntosh procedure, came into favor even though primary ACL repair was commonly performed. Then, in the 1980s, intraarticular ACL reconstruction developed. John Insall is often given credit for the early intraarticular reconstructions using a band of fascia lata.[7] MacIntosh described another reconstruction technique in which a central strip of the patellar tendon was taken, leaving it attached distally. A free patellar tendon graft came shortly thereafter with Clancy, establishing the first step of the current standard of practice: using a free tendon graft through tunnels in the tibia and femur along the course of the native ACL.[8]

Since the development of the arthroscopically assisted reconstruction that was initially performed by Dandy in 1980, arthroscopic techniques for ACL reconstruction have become increasingly popular.[9] There were two distinct schools of thought with regard to this. Some surgeons preferred the outside-in method, where the graft is routed into the joint through a femoral tunnel. Other surgeons preferred the inside-out technique, where the graft is routed from inside the joint into a femoral tunnel.[10,11] This transtibial single-bundle (SB) technique, in which the femoral tunnel is drilled inside-out through the tibial tunnel, was the most common ACL reconstruction technique.

Though the two-bundle anatomy of the ACL was described in the mid-1900s, reconstruction techniques initially restored only one bundle. It was not until 1982 that an open method of double-bundle (DB) ACL reconstruction was described and published by Mott, and not until 1994 when Rosenberg described the arthroscopic method later popularized in Japan by Yasuda and Muneta.[12-14] In 2003, Marcacci et al. described a DB technique with gracilis and semitendinosus graft that they claimed guaranteed a more anatomic ACL reconstruction.[15] This technique is designed to reproduce the kinematic effect of both AM and PL bundles of the ACL. Modifications of this technique have been described by a number of authors, and research into this area continues.

Nowadays, extensive research in Pittsburgh is illuminating the benefits of the Individualized Anatomic ACL Reconstruction Concept. This concept is defined as the functional restoration of the ACL to its native dimensions, collagen orientation, and insertion sites according to individual anatomy.[16] This concept additionally examines whether the patient should receive an operation or rehabilitation, and in the case of surgery, which is the best-suited graft choice, graft size, surgical technique (single-bundle, double-bundle, one-bundle augmentation, remnant preservation, or even ligament repair), and postoperative care to match the patient's individual anatomy and needs.

## ACL Reconstruction Indications

Several studies indicate that ACL reconstruction decreases pathologic knee laxity, reduces episodes of instability, and decreases the incidence of subsequent injuries, including meniscal tears and degenerative changes.[17-19] These findings defined ACL reconstruction surgery as the standard treatment for ACL injuries.

The ideal patient for ACL reconstruction is a young patient (< 40 years) with an active lifestyle and an acute ACL injury.

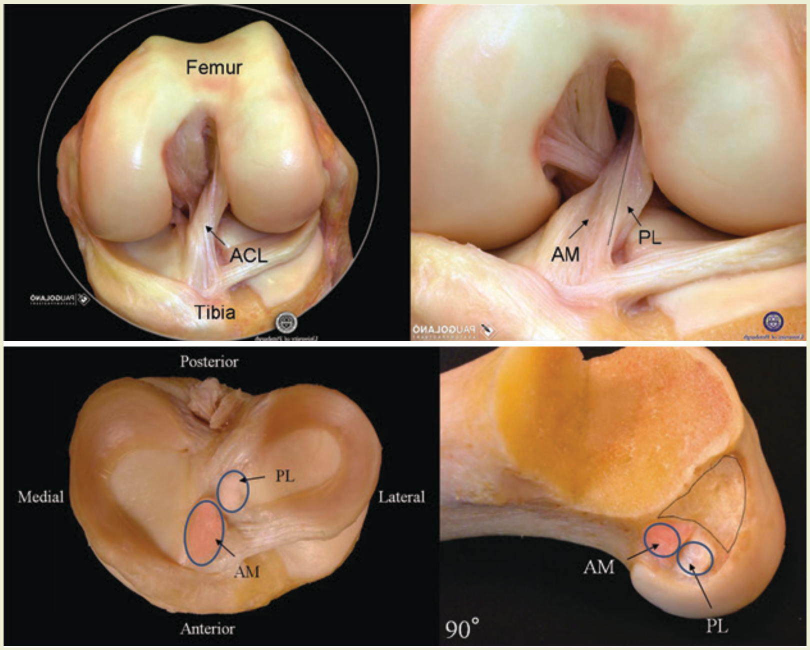


**Figure 1.** Double-bundle anatomy of the anterior cruciate ligament (ACL). AM = anteromedial; PL = posterolateral.

**Table 1.** Graft Choice for ACL Reconstruction

| Graft | Advantages | Disadvantages |
|---|---|---|
| **Bone-patellar tendon-bone** | — Bone-to-bone healing in both tunnels<br>— Comparable stiffness to native ACL | — Not suitable for DB reconstruction<br>— Risk of anterior kneeling pain<br>— Invasive, large incision<br>— Risk of patellar fracture<br>— Fixed length<br>— Weaker than native ACL |
| **Hamstring** | — Ease of harvest<br>— Cosmesis<br>— Minimal donor-site morbidity<br>— Comparable strength to native ACL | — Soft-tissue healing<br>— Graft size can be unpredictable<br>— Not suitable for certain athletes who rely heavily on their hamstring muscles<br>— Less stiffness than native ACL |
| **Quadriceps tendon** | — Large graft<br>— Can be used for SB or DB reconstruction<br>— Option of a one-sided bone block | — Invasive, large incision<br>— Risk of patellar fracture |
| **Allograft** | — No donor-site morbidity<br>— Available in various types and sizes<br>— Shortens operative time | — Theoretical risk of disease transmission<br>— Longer healing time<br>— Increased risk of rerupture, especially in younger patients and irradiated grafts |

Knee instability is the main indication for surgical treatment, and it should be evaluated subjectively (history, symptoms) and objectively (physical exam and instrumented side-to-side differences). One should also consider the patient's sports practice, including type of sport and frequency of practice.

## ACL Reconstruction Contraindications

ACL reconstruction is contraindicated in patients who present with partial tears and/or minimal instability, and no joint laxity on examination. It is also contraindicated in elderly, low-demand patients with minimal instability, patients with significant malalignment (such as a high posterior tibial slope) in the setting of chronic ACL-deficient knee, and patients with comorbidities that make surgical intervention unsafe (e.g., active infection). Relative contraindications include patients with open physes (Tanner stage ≤ 3), radiographic evidence of degenerative joint disease, a sedentary or inactive lifestyle, and an unwillingness or inability to comply with the required postoperative rehabilitation protocol.

## Nonoperative Treatment

Considering contraindications to surgical treatment and a patient's preferences, there are some patients for whom nonoperative treatment is indicated. Some studies have shown that nonoperative treatment does provide satisfactory results in a subset of patients.[20,21]

In a Norwegian study, the treatment between nonoperative and ACL reconstruction was chosen by the patients. At a 1- or 2-year follow-up examination, no differences were detected between the two groups with regard to the ability to resume preinjury activity level, muscle strength, or functional performance.[22]

Another Norwegian study reported that there were few differences between the clinical courses following nonsurgical and surgical treatment of ACL injury, highlighting the potential for good outcomes with nonoperative care following ACL injury.[23] Roughly a third of the entire study population experienced good function and low reinjury rates with nonoperative treatment. However, these good outcomes were likely due to the careful screening, personalized rehabilitation program, and close follow-up monitoring for at least 2 years afforded to the study participants. Additionally, one third of the patients in the nonsurgical group crossed over to the surgical group, presumably because of reinjury, unacceptable function, or limitations imposed by the treatment protocol. This critical limitation significantly hinders the clinical applicability of the results.

Similarly, a Swedish randomized controlled trial reported that an ACL reconstruction could be avoided in 61% of the patients, without compromising the results evaluated at 2 years after injury, by initially providing a structured rehabilitation followed by an optional delayed ACL reconstruction instead of directly performing an early reconstruction.[19] Nevertheless, the frequency of meniscal resections was greater in the delayed-surgery than in the early-surgery group (70% versus 48%, respectively). These data might demonstrate that menisci may be saved by an early surgical reconstruction.[24]

Different methods have been described in trying to define the individualized requirements of treatment after the ACL injury. Hurd et al. classified highly active patients (International Knee Documentation Committee – IKDC – level I or II) with good dynamic knee stability early after ACL rupture, using simple hop tests and validated knee outcome surveys (KOS–ADLS: Knee Outcome Survey–Activities of Daily Living Scale).[25] These so-called "potential copers," who represented 42% of the initial population of ACL-injured patients in this study, had good potential to be conservatively treated with physical therapy over a 2 to 5-week protocol.[26] However, after the rehabilitation program, 59% of the "potential copers" required ACL reconstruction. The other ACL-deficient patients who didn't require surgery could return to preinjury sports activities and were very satisfied with this choice at the latest follow-up (range: 1–10 years). Nevertheless, another study showed that ACL-deficient patients with residual instability can present by giving way during sports activities six times more frequently than ACL reconstruction patients (18% and 3% respectively).[27]

The most recent systematic review reported that there is limited evidence to support nonsurgical management, even in less active patients with less laxity.[27] In fact, 25% of the low-risk patients with ACL-deficient knees ultimately require surgery, including ACL reconstruction or meniscal surgery.[28]

## Operative Treatment

### Timing for Surgery

Once the decision to proceed with the operative treatment of an ACL rupture is made, timing of the procedure becomes an important variable to consider. Preoperative range of motion (ROM), swelling, and quadriceps strength have been investigated as factors that can affect the ultimate success of ACL reconstruction.[29] Preoperative limited ROM and swelling have been related to the development of arthrofibrosis after surgery.[29] Preoperative quadriceps strength deficits of > 20% have been shown to significantly affect the 2-year functional outcomes of ACL reconstruction with bone-patellar tendon-bone autograft.[30]

Surgical intervention is recommended to be delayed until any postinjury knee effusion has resolved, full knee ROM has been regained, quadriceps control is achieved, and personal and professional issues permit that the patient is physically and psychologically prepared for surgery and a full postoperative physical therapy program.

Although some studies haven't reported significant differences in objective and subjective clinical outcomes between early (< 2 weeks) versus late ACL reconstruction (> 4 to 12 weeks), most recent recommendations, based on moderate quality evidence, supports surgery timing at 3 weeks to 5 months after injury.[18,31] Surgery at earlier than 3 weeks can increase the rate of reoperation from 0% to 8%, while surgery after 5 months can increase the incidence of meniscus tears from 37% to 62%, and subsequent meniscectomy from 8% to 44%.[32] Also, surgery within this period is associated with improved objective knee stability, as measured by the Lachman and pivot shift test, higher activity level, and better knee function when compared with reconstruction after 5 months.[18] However, more recently, one study showed that in highly active or competitive athletes, acute ACL reconstruction within 48 hours had decreased extension deficit.[33]

### Partial Tears, Augmentation, and Remnant Preservation

Diagnostic arthroscopy is performed first to assess for concomitant injuries and to confirm the ACL rupture pattern. If a partial one-bundle rupture is evident, augmentation surgery should be considered.[34] Partial ACL ruptures have been reported to occur in approximately 5% to 35% of patients.[33] Performing a one-bundle augmentation surgery carries the theoretical advantages of maintaining proprioceptive fibers, biomechanical strength, and biological healing potential. Careful dissection and preservation of the native insertion sites can facilitate determination of the appropriate tunnel location.

### Anatomic ACL Reconstruction Concept

Presently, the majority of surgeons who perform ACL reconstructions do so using a SB technique. Regardless, it is important to understand the two-bundle anatomy of the ACL so that surgeons can follow the anatomic ACL reconstruction concept, regardless of their choice to perform SB or DB reconstruction.

The concept of anatomic ACL reconstruction is based on four fundamental principles: 1) restore the two functional bundles of the ACL; 2) restore the native insertion sites of the ACL by placing the tunnels in the true anatomic positions; 3) correctly tension each bundle; 4) individualize surgery for each patient, so that tunnel diameter and graft size are dictated by native insertion sites (See Table 2 on Page 5).

The approach to ACL reconstruction surgery is governed by this principle, and the restoration of normal anatomy is necessary to restore normal function of the knee. This concept applies to SB and DB reconstruction by following the well-defined soft-tissue and osseous landmarks to restore the ACL native insertion site. For example, if SB reconstruction is indicated, the graft should be positioned anatomically on both the tibia and femur ("center to center," "PL to PL," and "AM to AM"), so that the graft will acquire the functional properties of the native two-bundle ligament.

### Single-bundle Versus Double-bundle ACL Reconstruction

The decision to perform SB or DB reconstruction is based on several criteria. The variation in size of the tibial insertion site

**Table 2.** Tips for Successful ACL Reconstruction

| | |
|---|---|
| **Surgery** | — ACL reconstruction should be performed following the anatomic and individualized concept, which is focused on the restoration of the ACL to its native dimensions, collagen orientation, and insertion sites, with the aim to provide the patient with the best potential for a successful outcome. This concept can be applied to SB and DB ACL reconstruction.<br>— Proper patient selection is essential to decide between SB and DB reconstruction.<br>— The key to obtaining a reproducible anatomic ACL reconstruction is to have a satisfactory visualization of the notch, soft-tissue remnants, and bony landmarks of native anatomy for an adequate tunnel placement.<br>— Correct portal placement is critical in ACL reconstruction. Care and needle localization should be used to create the anteromedial and accessory medial portals as they are in close proximity to the medial meniscus and medial femoral condyle.<br>— Avoid using the "clock face" method to create the femoral ACL tunnels. Native ACL insertion sites and bony landmarks should be used for an accurate tunnel(s) placement.<br>— Graft fixation has many critical points, including the specific technique of the fixation device, and the adequate knee flexion and tension of the graft. |
| **Rehabilitation** | — A proper rehabilitation protocol must be followed that focuses on functional tests, rather than time points, to advance through phases. |

is one element to consider. A tibial insertion site < 14 mm, measured arthroscopically, makes it difficult to perform a DB reconstruction without obtaining nonanatomic tunnels or damaging the meniscal roots. Other variables that support an SB reconstruction technique are concomitant arthritic changes (≥ grade 3), multiligament injury, severe bone bruising, open physes, and a narrow and/or shallow intercondylar notch (< 14 mm each).[33,35]

Open physes and severe bone bruising are conditions that probably benefit from less iatrogenic damage by less tunnel drilling, and severe arthritic changes may worsen more rapidly by constraining the knee with two bundles. A small notch does not easily accommodate a DB reconstruction because of the technical challenge for placing both femoral tunnels anatomically and the risk of motion deficits or early failure due to potential graft impingement.

A recent study analyzed the area of the tibial footprint of the ACL in 126 patients who had their native insertion sites measured by three subsequent slices of both their MRI in sagittal and coronal planes, as well as intraoperatively.[36] The results confirmed the previous findings that there is variation of the native ACL footprints regarding its size, but this can be reliably predicted by the measurements based on the preoperative MRIs. Also, the shape of the tibial insertion site was previously shown to be predominantly oval, although, once again, variation is the rule and multiple shapes were subjectively observed.[37]

The objective evaluation of the ACL anatomy, with special attention to nuances that cannot be fully appreciated during gross dissection, were further delineated using 3D laser scanning with a robotic testing system to analyze the dynamic changes of the shape and size of the ACL during different flexion angles and loadings.[38] A total of eight cadaveric specimens were studied with confirmation that the ACL shape is complex; has an isthmus located at approximately the mid-portion between the tibial and femoral insertion sites; and that compared to the projected area of the tibial insertion site to different planes, the isthmus measures from 35% to 50% of the tibial insertion site, and the femoral insertion site measures 69% of the tibial insertion site. Thus, the graft is sized to cover 50% to 70% of the estimated native tibial insertion area.

Biomechanical studies have shown that DB reconstruction restores knee kinematics better than transtibial SB reconstruction, leading to less rotational laxity, increased tibiofemoral contact area, and lower contact pressures.[39] Also, several prospective level I or II clinical studies have reported superior clinical results of anatomic SB reconstruction compared with DB reconstruction. Conversely, other studies have shown no difference between SB and DB reconstruction in terms of improvement in laxity or function. However, for several of the above-mentioned studies, it remains unclear whether both the SB and DB reconstructions performed in these studies were anatomic or not.

On the basis of the evolution of clinical studies comparing both techniques, multiple authors have conducted systematic reviews and meta-analyses comparing SB and DB reconstruction.[40] Recently, nine available overlapping meta-analyses about this topic were evaluated in an attempt to reconcile conclusions from both techniques.[41] The current highest level of evidence suggests that DB reconstruction provides improved postoperative knee laxity compared with SB reconstruction. This was evaluated using KT-arthrometer, Lachman, and anterior drawer tests for AP translation, and the pivot-shift test for rotational laxity. Nevertheless, this difference between SB and DB clinical results should be interpreted cautiously. For example, the significant difference in the KT-arthrometer may have questionable clinical significance because its magnitude ranged from 0.56 mm to 0.74 mm. Also, the differences for the clinical tests (Lachman, anterior drawer, and pivot-shift) were heterogeneous between studies. This can be explained by the subjectivity in grading, inter-examiner variability, and dependence on patient cooperation for these tests. The other clinical outcomes and risk of graft failure were not found to be significantly different between SB and DB in this systematic review.[40]

The most recent clinical practice guidelines confirmed the similarity between the clinical outcomes of SB and DB techniques. Considering high-quality studies with consistent findings, these guidelines strongly recommend that in patients undergoing ACL reconstruction the surgeon should use either the SB or DB technique, because the measured outcomes are similar.[18]

### Graft Choice

Typical graft options for ACL reconstruction include hamstring tendon autograft, bone-patellar tendon-bone autograft, quadriceps tendon autograft, and allograft. For the purposes of preoperative planning, studies have evaluated the use of MRI in predicting hamstring graft size and have found that cross-sectional area measurements on MRI correlate positively with intraoperative graft size. However, measurements of graft diameter on the MRI do not correlate with intraoperative graft size.[42] For patellar and quadriceps tendons preoperative measurements, the sagittal thickness measured on MRI can provide the surgeon an idea of the potential graft size.[43]

### Hamstrings Versus Bone-Patellar Tendon-Bone Grafts

Most recent systematic review and meta-analysis, based on high-quality studies, have reported that there is no significant difference between hamstrings and bone-patellar tendon-bone autografts when considering stability testing, patient satisfaction, IKDC score, and graft failure.[18,32] However, more postoperative kneeling pain was present in the patellar tendon group (48% to 65% versus 30% to 35% at ≥ 2 years follow-up).[44] Consequently, sports activities and patient lifestyle should influence graft choice for ACL reconstruction. For example, in a patient with daily activities that include kneeling (sports or religious), the use of a bone-patellar tendon-bone autograft may be contraindicated because of the higher prevalence of anterior knee pain. On the other hand, athletes such as skiers and soccer players, who require the medial knee stabilizers for sport-specific tasks, make hamstring autografts less ideal.

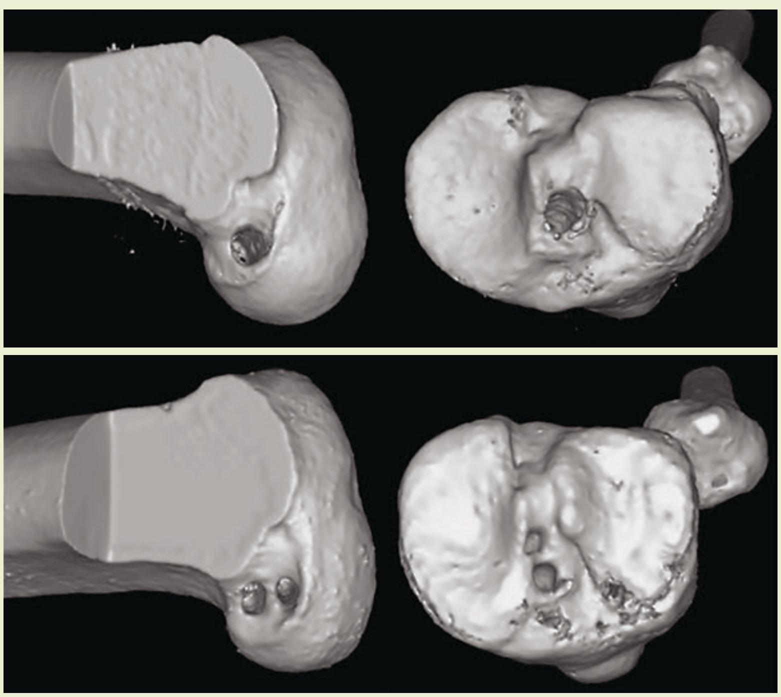

**Figure 2.** Postoperative computed tomography scan of a single-bundle ACL reconstruction (top), and double-bundle ACL reconstruction (bottom)

### Autograft Versus Allograft

In patients having primary reconstruction, allograft may be considered when there are concerns of donor-site morbidity or cosmesis. Some studies report that appropriately processed allograft has similar clinical outcomes as autograft. However, these results may not be generalizable to all patients (e.g., young and active patients) or all allografts (e.g., irradiated allografts).

For example, several studies have reported a higher failure rate of allograft in younger patients, and the most recent clinical practice guidelines recommend against allografts for young and highly active patients.[45]

Comparing autograft and allograft data, studies have reported 6% failure rate with autograft, 9% failure rate with non-irradiated allograft, and 34% failure rate with irradiated allograft (2.5 Mrad).[46] The difference between autograft and non-irradiated allograft was not statistically significant, in contrast with the difference between failures in the autograft group and the irradiated allograft group.[47]

### ACL Remnant Preservation

The ACL reconstruction preserving the remnant can potentially improve the graft maturation process, or "ligamentization," since the functional remaining fibers biomechanically protect the graft, contribute to proprioception and vascularization, and may prevent the synovial fluid leakage to the tunnel, which can prevent future tunnel enlargement.[48]

### Tunnel Placement for ACL Reconstruction

Proper tunnel placement is critical to restore the native ACL insertion site (See Figure 2 on Page 6). Nonanatomic tunnel placement can result in abnormal knee kinematics, limited range of motion, nonphysiologic graft tension, and ultimately graft failure.[49]

Soft tissue remnants, along with bony landmarks, are essential in determining the anatomic tunnel positions during ACL reconstruction surgery. A deficient interobserver agreement between surgeons can be present if these structures are not considered for anatomic tunnel placement.[50]

The ACL tibial insertion site has a fanned-out shape, with an insertion length of 17 mm average in the sagittal plane (range 12 mm to 22 mm) and 11 mm width average in the coronal plane.[51] The insertion site is aligned with the anterior horn of the lateral meniscus, and has a close relationship with the medial and lateral tibial spine (See Figure 1 on Page 2).[50]

The ACL femoral insertion site is oval-shaped and normally smaller than the tibial insertion site.[50] The AM bundle originates from the proximal portion of the lateral notch wall, while the PL bundle lies more distally, near the posterior articular cartilage surface of the lateral femoral condyle (See Figure 1 on Page 2).[52] The lateral intercondylar ridge, or so-called "resident's ridge," denotes the anterior border of the femoral insertion site.[53] The lateral bifurcate ridge runs perpendicular to the lateral intercondylar ridge, between the femoral insertion sites of the AM and PL bundles.[54]

For SB reconstruction, a single femoral and tibial tunnel is positioned midway between the center of the AM and PL insertion sites (See Figure 2 on Page 6). It is important to consider tibial drill-guide angle because it can affect tibial tunnel aperture size and orientation, as well as tibial tunnel length.[55]

For DB reconstruction (See Figure 2 on Page 6), the femoral PL tunnel is created first, through the accessory AM portal, followed by the tibial AM and PL tunnels. A tibial guide is set to 45° for PL bundle and 55° for AM bundle, and the tunnel entrance should be 2 cm apart on the tibial extra-articular cortex. Then, the femoral AM tunnel is drilled. Depending on individual anatomy and surgical preference, it can be drilled using a transtibial or medial portal (MP) technique.

For femoral tunnel drilling in SB and DB techniques, traditionally rigid guide-wires and reamers are used to place and drill the tunnels. However, this instrumentation often requires knee hyperflexion in order to avoid iatrogenic damage to nearby structures and to increase femoral tunnel length. Flexible reamers do not require knee hyperflexion and can decrease the susceptibility for posterior cortical violation by altering the drill exit point and increasing the tunnel length.[56]

### Transtibial Versus Tibial Independent Approach for Femoral Tunnel Drilling

Various techniques for ACL femoral tunnel drilling exist, including four primary techniques: arthroscopic transtibial (TT) technique; anteromedial portal (AMP) technique; outside-in (OI) technique; and outside-in retrograde drilling (RD) technique.

Discrepancy between tunnel position and the native ACL insertion site is common when the femoral tunnel is drilled using the TT technique. The popularity of "tibial independent" femoral tunnel techniques (AMP, OI, RD) has increased because these techniques are designed for more accurate and anatomic ACL femoral tunnel placement. Each of these techniques has its own risks and benefits. A recent systematic review summarized the advantages and disadvantages of each of them.

Even though the AMP technique has many advantages related to the anatomic ACL reconstruction, some studies have shown a higher graft failure with this technique. The Danish Knee Ligament Reconstruction Register reported a revision rate of 5.2% for the AMP technique versus 3.2% for the TT technique.[57] One explanation for this is that in the TT technique, since the graft is not anatomically positioned, it is submitted to less stress and thus presents with less graft failure. Other possible explanations for the increased risk of rerupture by independent drilling techniques are shorter femoral tunnels, generating less integration between the graft-bone, and cases of blow-out of the rear wall of the lateral condyle, compromising integration of the graft.[58]

The most recent systematic review and clinical practice guidelines state that moderate evidence supports the use of either tibial independent or TT technique, because measured outcomes are similar.[59] Only long-term prospective studies and randomized controlled trials will be able to demonstrate that the independent femoral drilling techniques will be able to prevent joint degeneration and osteoarthritis.

Finally, the choice of the femoral tunnel technique should be based on a combination of variables, including surgeon experience, available equipment, cost, efficiency, patient age, patient activity level, graft choice, and cosmesis.

## Postoperative Evaluation

Postoperatively, AP and lateral radiographs can be used to evaluate tunnel angle and implant position. Illingworth et al. described a femoral tunnel angle measurement based on the long axis of the femur on an AP radiograph whereby an angle of < 32.7° is likely to be non-anatomic.[60]

Postoperative MRI measurements of the insertion site, inclination angle, and length of the ACL can also be compared with those made preoperatively. A three-dimensional computed tomography (3D-CT) scan is presently considered the gold standard for postoperative evaluation of tunnel placement (See Figure 2 on Page 6). Moreover, a 3D-CT scan can be particularly useful in planning for knees in which revision surgery may eventually be required.[61]

## Postoperative Care and Rehabilitation

Immediately after surgery, the knee is immobilized with a brace. The patient is discharged with adequate pain medication and a cooling device the same day.

During the first week(s), focus should be placed on reducing pain and swelling, and restoring full ROM and quadriceps muscle strength. The day after surgery, patients begin to perform ankle pumps, straight leg raises, quadriceps sets, gastrocnemius stretch, and heel slides. At the end of the first week, continuous passive motion is initiated with progression to full extension.

Depending on the progress made, crutches and brace are typically weaned after 6 weeks. Once quadriceps muscle strength returns, straight line walking can be initiated at 6 weeks, with progression to jogging in a straight line and a stationary bike around 3 months.

Pivoting and cutting exercises are not initiated until at least 6 months, and return to sport is generally no sooner than 9 months postoperatively. A functional ACL brace for sports is recommended until the patient is 2 years from the reconstruction. However, there is insufficient evidence to support its routine use.[62]

Patient progression through the rehabilitation phases is dependent on the patient's readiness according to the periodic evaluation of the physical therapist and surgeon. Clinical findings and rehabilitation tests should be evaluated in this process. Some authors consider evaluation on MRI to assess graft healing.[63]

To standardize the management of ACL reconstruction rehabilitation, an evidence-based rehabilitation guideline was developed by the Multicenter Orthopaedic Outcomes Network (MOON). This guideline is focused on progression phases, which are based on achieving functional criteria rather than the time elapsed since surgery.[64]

Most recent systematic review and meta-analysis, based on moderate-quality evidence, show no difference in clinical outcomes between accelerated and nonaccelerated rehabilitation protocols.[65] The benefit of early accelerated rehabilitation is that patients may be able to return to full, unrestricted activity sooner. However, the impact on long-term outcomes (e.g., progression of osteoarthritis) of the timing and intensity of rehabilitation programs is currently unknown.

## Return to Sports After ACL Reconstruction

Return to sports (RTS) is a primary goal of ACL reconstruction, but the timing of RTS after ACL reconstruction is multifactorial, considering preoperative, intraoperative, and postoperative factors (See Table 3 on Page 9).

Preoperative factors that can affect return to play are age, preoperative rehabilitation, full knee extension, and neuromuscular control.[66] The most important intraoperative factor is graft choice. The advantages of bone-patellar tendon-bone autograft, considering RTS, include good graft strength/stiffness and stable interference screw fixation, allowing for bone-to-bone healing within the ACL tunnels. Whereas incorporation of the graft does not equate to maturation, earlier graft incorporation may allow for more aggressive rehabilitation protocols and a more rapid RTS.

Considering postoperative factors, several authors have reported that RTS is more dependent on the rehabilitation than on the technique or the graft choice used intraoperatively.[67] This is directly related to the rehabilitation protocol, functional assessment according to specific sports, and psychological factors of the patient.

In a systematic review and meta-analysis, 69 studies with a total of 7,556 patients at a mean follow-up of 40 months after ACL reconstruction were evaluated.[68] On average, 81% of people returned to sport, 65% returned to their preinjury

**Table 3.** Return to Activity Depending on the Graft

| Activity | Running | Low-Level Agility | Jumping | Cutting, Pivoting, and Hopping | Return to Sport |
|---|---|---|---|---|---|
| Autograft BPTP | 4 months | 5 months | 7 months | 8 months | 9 months |
| Autograft Hamstring/Quad | 6 months | 7 months | 8 months | 9 months | 10 months |
| Allograft BPTB | 6 months | 8 months | 9 months | 10 months | 12 months |
| Soft Tissue Allograft | 8 months | 9 months | 10 months | 11 months | > 12 months |

level of sport, and 55% returned to competitive level sport after surgery. Factors that favored returning to the preinjury level sport were younger age, male gender (OR = 1.4), playing elite sport (OR = 2.5), symmetrical hopping performance, and having a positive psychological response. In fact, one of the leading reasons given for not returning to sporting activity is fear of reinjury.

The same review compared ACL reconstruction grafts, showing that hamstring autograft favored returning to competitive level sport (OR = 2.4), whereas bone-patellar tendon-bone autograft favored returning to the preinjury level sport (OR = 1.2).

According to the last systematic review, there is no high-level evidence that can support a specific time for RTS.[18] Although an expeditious return to sport can be an achievable and realistic goal, the factors that most influence safe, timely, and successful return to play remain unknown. Further research is warranted to validate reliable, consensus guidelines with objective criteria to facilitate the return to play process.

## Complications

ACL reconstruction, as with any surgical intervention, can have associated morbidity. Some studies reported 23% to 28% of re-intervention after ACL reconstruction during a median follow-up of 32 months, or a mean follow-up of 89 months, respectively. The most frequent morbidities were meniscal injury (6.9%) and ROM deficits (6.3%). Infection was reported in 0.6% of the cases. Other common minor complications after the surgery can be related to morbidity secondary to graft harvest or fixation devices, and cyclops lesion.[69,70]

The most frequent intraoperative complications are technical errors, which have been described in 9.6% of the cases during graft harvesting, tunnel placement, or graft fixation. These complications might not have an effect on the final outcome if the surgeon has the expertise required to solve these incidents during the surgery.[71]

The most serious complications after ACL reconstruction are neurologic or vascular injuries, arthrofibrosis, and infections.[72] The incidence of the most severe complications, not readily published, is probably underestimated because of publication bias.

One of the most important and serious postoperative complications is graft rupture. The incidence of graft rupture increases with time after surgery: 3%, 6%, 9%, and 12% at 2-, 5-, 8-, and 13-year follow-up, respectively.[73,74] A contralateral ACL rupture has been reported to occur in 3% to 24% of the surgically treated patients, depending on the length of the follow-up.[72,73] It is not known if this incidence is higher than in a normal, active population or in subjects who were conservatively treated after an ACL injury. But, as mentioned by Salmon et al., the high percentage (34%) of patients in their series suffering a subsequent ACL injury, graft rupture, or contralateral ACL rupture might be greater than that seen in the normal population.[75] They suggested that specific motor-retraining programs, as described by Myklebust et al., should be added to the rehabilitation of ACL-reconstructed patients to reduce this risk.[76] Finally, the increase of ACL revision reconstruction publications gives evidence that ACL reconstruction is not a 100% guaranteed successful treatment.

All these unforeseen events could explain why a return to the same level of sport activities, which is the primary goal of ACL reconstruction, has generally been reported as 65% of the patients on average.[77] Also, the reported results for IKDC have been judged A or B with the IKDC form in only 70% of the patients, and the Tegner activity level dropped from 8 to 6 at a median of 32 months follow-up (21 to 117 months) after ACL reconstruction.[68] This suggests that there remains considerable room for improvement in ACL reconstruction surgery.

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Kaufmann Medical Building
3471 Fifth Ave., Suite 1010
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