Review Article

Anatomic Tunnel Placement in Anterior Cruciate Ligament Reconstruction

Aman Dhawan, MD
Robert A. Gallo, MD
Scott A. Lynch, MD

Abstract

The anatomic anterior cruciate ligament (ACL) reconstruction concept has developed in part from renewed interest in the insertional anatomy of the ACL, using surgical techniques that can reproduce this anatomy reliably and accurately during surgical reconstruction. Several technical tools are available to help identify and place the tibial and femoral grafts anatomically, including arthroscopic anatomic landmarks, a malleable ruler device, and intraoperative fluoroscopy. The changes in technique for anatomic tunnel placement in ACL reconstruction follow recent biomechanical and kinematic data that demonstrate improved time zero characteristics. A better re-creation of native ACL kinematics and biomechanics is achieved with independent femoral drilling techniques that re-create a central footprint single-bundle ACL reconstruction or double-bundle reconstruction. However, to date, limited short-term and long-term clinical outcome data have been reported that support using either of these techniques rather than a transtibial drilling technique. This lack of clear clinical advantage for femoral independent and/or double-bundle techniques may arise because of the potentially offsetting biologic incorporation challenges of these grafts when placed using these techniques or could result from modifications made in traditional endoscopic transtibial techniques that allow improved femoral and tibial footprint restoration.

From the Department of Orthopaedics and Rehabilitation, Penn State Hershey Medical Center, Penn State College of Medicine, Hershey, PA.

J Am Acad Orthop Surg 2016;24: 443-454

http://dx.doi.org/10.5435/JAAOS-D-14-00465

Reconstruction techniques for the anterior cruciate ligament (ACL) have evolved considerably over the past four decades. Technologic advances in the early 1980s made possible an arthroscopically assisted technique. The tibial tunnel was drilled using arthroscopically placed transtibial guides, much like techniques employed currently.[1] The femoral tunnel was drilled using a rear-entry guide seated against the femur using a separate femoral incision. This two-incision technique resulted in good reported outcomes.[2] To reduce morbidity and improve cosmesis, an endoscopic transtibial technique was developed in the early 1990s, along with specific instrumentation to facilitate the technique.[3] A 2006 survey of members of the American Orthopaedic Society for Sports Medicine reported that most of the surgeons who responded (90%) were using this endoscopic transtibial technique.[4]

Renewed interest in detailed ACL insertional anatomy and recent data that demonstrated suboptimal outcomes for return to play in high-level athletes in whom transtibial isometric techniques were used for ACL reconstruction have led to an interest in changing the surgical technique of ACL reconstruction once again.[5-8] Recent data from the Multicenter ACL Revision Study have demonstrated that femoral tunnels that are too high, a consequence often seen with transtibial techniques, may have been responsible at least in part for 72% of all failures of primary ACL reconstructions studied.[9] Myriad basic science time zero data have demonstrated better kinematics and better initial stability using independent femoral drilling techniques to re-create native ACL anatomy. As a result, a change in surgical technique toward anatomic methods of ACL reconstruction has occurred over the past 10 years.[10,11] In 2013, most surgeons (68%) were using femoral independent drilling techniques.[12] Recent survey data from the National Football League and the National Collegiate Athletic Association team physicians corroborated these data. Of responding surgeons, 67% preferred an independent femoral drilling technique and an anatomic reconstruction.[13]

Here, we discuss the renewed interest in and the emphasis on the insertional anatomy of the ACL and the methods required to reproduce native anatomic insertions reliably and accurately in surgical ACL reconstruction. Also discussed are the biomechanical and kinematic factors driving the shift from a transtibial isometric reconstruction to an independent femoral drilling anatomic reconstruction, the clinical data comparing transtibial and independent femoral drilling techniques, and the basic science and clinical concerns that have accompanied the changes in techniques to anatomically place the ACL tunnels.

Anterior Cruciate Ligament Insertional Anatomy

A detailed understanding of the insertional anatomy of the ACL is inherent to the discussion of anatomic tunnel placement in ACL reconstruction. The ACL has been described as being divided functionally into two bundles,[14] the anteromedial bundle (AMB) and the posterolateral bundle (PLB), which are named for their positions at the tibial insertion. The AMB of the ACL inserts more proximally and slightly anterior on the femur, whereas the PLB inserts more distal and slightly posterior.[14] The AMB occupies slightly more of the ACL femoral insertion area (52%) than does the PLB (48%).[15] On average, the ovoid ACL femoral insertion measures 8 mm × 15 mm.[15] The anterior border of the femoral insertions of the AMB and PLB is the lateral intercondylar ridge, also called the resident ridge.[16] The bifurcate ridge separates the AMB and PLB in the sagittal plane[17] (Figure 1, A).

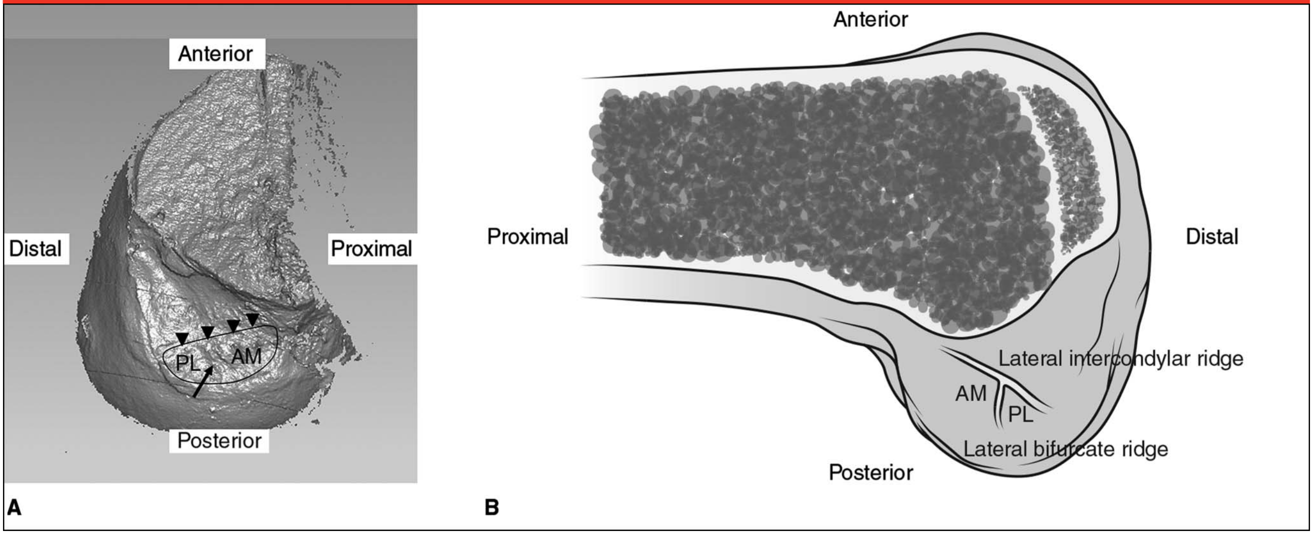
The area of the ACL tibial insertion averages 114 mm, with a coronal width of 10 mm and a sagittal length of 14 mm.[18] The tibial insertional area of the AMB is slightly larger (12%) than that of the PLB.[16] Zantop et al[18] reported that the mean insertion of the AMB is approximately 2.7 mm posterior and 5.2 mm medial to the anterior insertion of the lateral meniscus, and the PLB mean insertion is 11.2 mm posterior and 4.1 mm medial to the anterior insertion of the lateral meniscus. Other authors have found the relationship between the ACL tibial footprint and the anterior horn of the lateral meniscus to be variable, mostly because of the variability in anatomy of the lateral meniscus.[19] Ferretti et al[19] quantified these insertions in the sagittal plane using distances to the posterior edge of the intermeniscal ligament and the peak of the medial tibial spine, which they found to be less variable than the insertion of the anterior horn of the lateral meniscus. The authors found the center of the AMB to be 8.6 mm from the peak of the medial tibial spine and 4.6 mm from the posterior edge of the intermeniscal ligament. The PLB was 1.4 mm from the peak of the medial tibial spine and 13.8 mm from the posterior edge of the intermeniscal ligament.[19] The center of the ACL tibial attachment was 9.1 mm posterior to the posterior edge of the intermeniscal ligament and 5.3 mm anterior to a line projected from the peak of the medial tibial spine[19] (Figure 2). In the coronal plane, the center of the AMB was 3 mm lateral to the anteromedial rim of the articular surface of the medial tibial condyle at the medial tibial spine, and the center of the PLB was 2 mm medial to the articular surface of the lateral tibial condyle at the lateral tibial spine.[16]

Surgical Anatomy

One of the guiding principles of the anatomic ACL reconstruction concept

Dr. Dhawan or an immediate family member is a member of a speakers' bureau or has made paid presentations on behalf of and serves as a paid consultant to Zimmer Biomet and Smith & Nephew; has received research or institutional support from Smith & Nephew; and serves as a board member, owner, officer, or committee member of the American Orthopaedic Society for Sports Medicine and the Arthroscopy Association of North America. Dr. Gallo or an immediate family member has received research or institutional support from Aesculap/B. Braun and serves as a board member, owner, officer, or committee member of the American Academy of Orthopaedic Surgeons, The American Orthopaedic Association, the American Orthopaedic Society for Sports Medicine, and the Arthroscopy Association of North America. Neither Dr. Lynch nor any immediate family member has received anything of value from or has stock or stock options held in a commercial company or institution related directly or indirectly to the subject of this article.

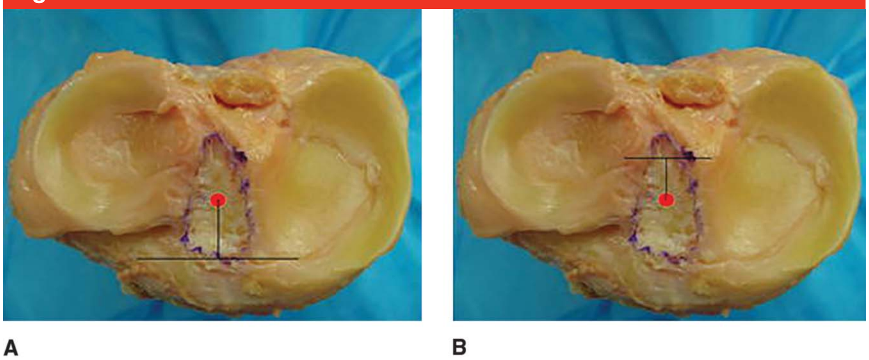
Figure 1



A, Three-dimensional laser scan with the knee in 90° of flexion showing the lateral intercondylar ridge (arrowheads) running anterior to the entirety of the anterior cruciate ligament femoral insertion. The lateral bifurcate ridge (arrow) divides the posterolateral (PL) bundle attachment from the more proximal anteromedial (AM) bundle attachment. **B,** Illustration demonstrating the lateral intercondylar ridge and the lateral bifurcate ridge. (Panel A reproduced with permission from Ferretti M, Ekdahl M, Shen W, Fu FH: Osseous landmarks of the femoral attachment of the anterior cruciate ligament: An anatomic study. *Arthroscopy* 2007:23[11]:1218-1225.)

is the re-creation of the insertion sites of the native ACL.[20] Surgically, this re-creation is accomplished by using drilling techniques that allow the placement of tunnels within the native ACL footprint. This concept can be achieved using several methods. One approach involves femoral-independent drilling methods of femoral and tibial tunnel creation, including the outside-in technique, the two-incision technique, and anteromedial portal femoral drilling. Other methods, such as single-bundle or double-bundle reconstruction and augmentation techniques, also can be used.

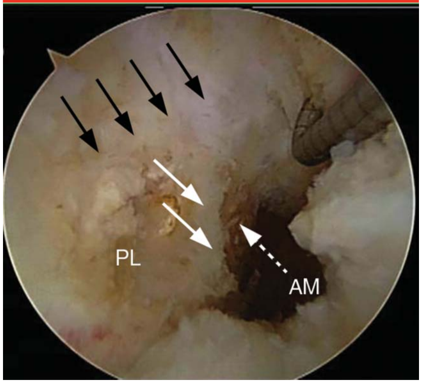
Figure 2



Photographs of cadaver specimens demonstrating the center of the anterior cruciate ligament (ACL) tibial attachment (red dot). **A,** The center of the ACL tibial attachment is 9.12 ± 1.54 mm behind the posterior edge of the intermeniscal ligament. **B,** The center of the ACL tibial attachment is 5.3 ± 1.14 mm anterior to a line projected from the peak of the medial tibial spine. (Reproduced with permission from Ferretti M, Doca D, Ingham SM, Cohen M, Fu FH: Bony and soft tissue landmarks of the ACL tibial insertion site: An anatomical study. *Knee Surg Sports Traumatol Arthrosc* 2012;20[1]:62-68.)

Various modifications of the transtibial technique have been proposed to re-create the native ACL anatomy more accurately, especially on the femur; however, because of these modifications, compromises have been made with incomplete anatomic restoration of the femoral footprint, posteriorization of the tibial footprint, the creation of a femoral anteromedial to tibial posterolateral construct, enlargement of the tibial intra-articular aperture, or the creation of a short and oblique tibial tunnel.[21-23] These alterations have the potential to create challenges in kinematics, graft fixation, and/or biologic healing.[21-23] The recent literature has suggested that the tibial tunnel location may be more important kinematically than the femoral tunnel location in ACL reconstruction.[24]

Figure 3



Arthroscopic image taken with a 30° arthroscope placed through the anteromedial portal of the lateral wall of the intercondylar notch in the right knee showing the lateral intercondylar ridge (black arrows) and the lateral bifurcate ridge (white arrows). The femoral insertions of the anteromedial (AM) bundle and posterolateral (PL) bundle also are shown. (Reproduced with permission from Ferretti M, Ekdahl M, Shen W, Fu FH: Osseous landmarks of the femoral attachment of the anterior cruciate ligament: An anatomic study. *Arthroscopy* 2007:23[11]:1218-1225.)

Figure 4

Arthroscopic image demonstrating the lateral wall of the intercondylar notch, viewed from the anteromedial portal in the right knee. The ruler is positioned on the side wall of the notch with the end at the proximal border of the articular margin deep in the notch. The shallow/distal end of the ruler measures 22 mm. A microfracture pick marks the midpoint of the side wall at 11 mm below and posterior to the intercondylar ridge. (Reproduced with permission from Bird JH, Carmont MR, Dhillon M, et al: Validation of a new technique to determine midbundle femoral tunnel position in anterior cruciate ligament reconstruction using a three-dimensional computed tomography analysis. *Arthroscopy* 2011;27[9]:1259-1267.)

Anatomic ACL reconstruction is not synonymous with double-bundle ACL reconstruction. Techniques, such as the two-incision technique, the outside-in technique, and medial portal femoral drilling, are preferred when creating an anatomic tunnel location for ACL reconstruction. Such techniques allow the creation of the femoral and tibial tunnels independently and locate them centrally within the native ACL footprints for single-bundle reconstruction or create an accurate AMB and PLB for double-bundle reconstruction. Here, we focus on central footprint single-bundle ACL reconstruction because this technique is used most commonly by surgeons currently performing anatomic ACL reconstructions.[12]

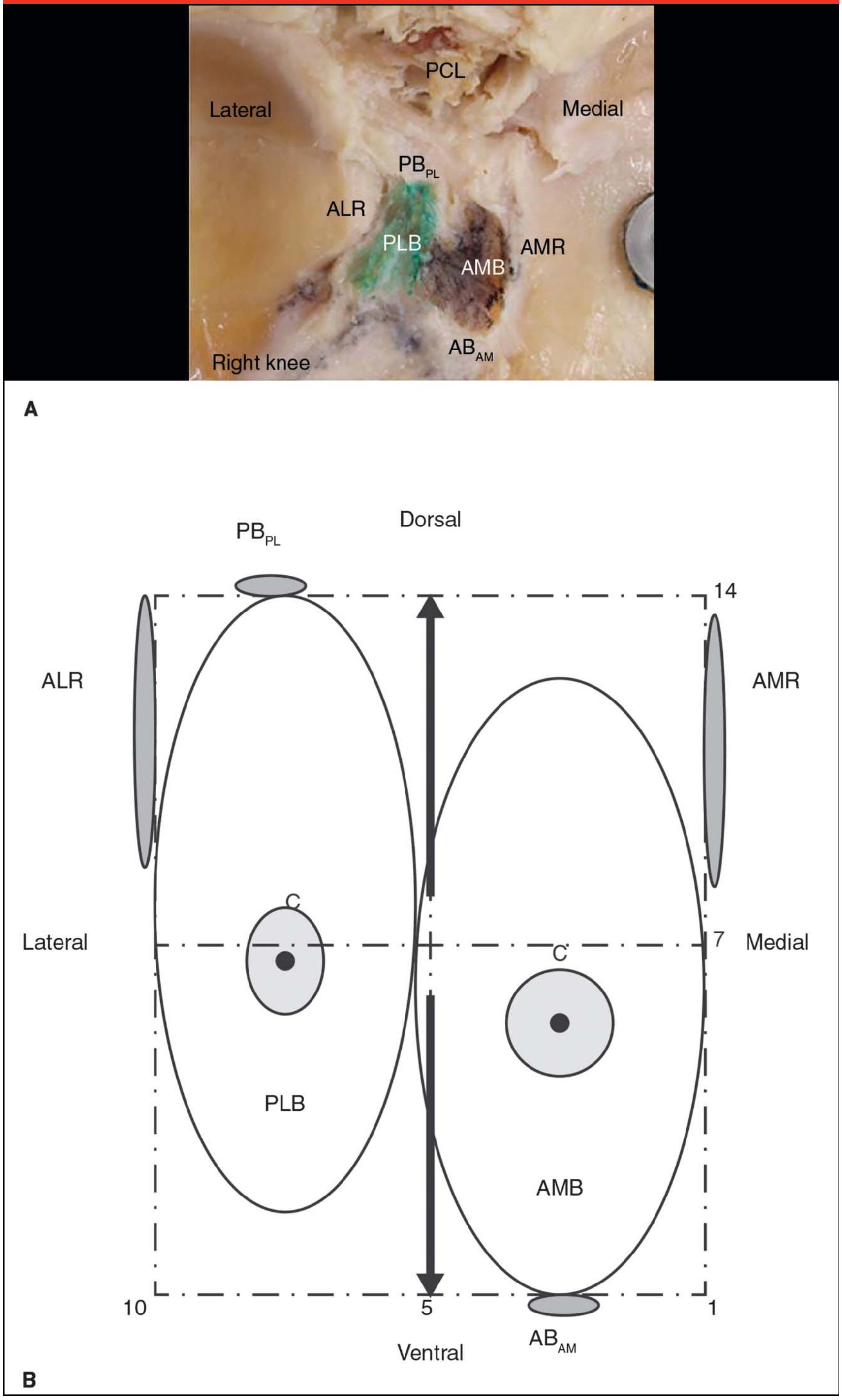
Intraoperatively, the surgeon has three key tools for identifying and placing the tibial and femoral graft apertures to re-create the native anatomy: (1) arthroscopic anatomic landmarks, including remnant ACL tissue and osseous anatomy; (2) a malleable ruler device, especially useful for the femoral tunnels; and (3) intraoperative fluoroscopy. Using arthroscopic anatomic landmarks is a reliable and reproducible method for placing the reconstruction tunnels in the native ACL footprint. On the femoral side, the lateral intercondylar ridge, which is present in 88% of chronic ACL-deficient knees, and the bifurcate ridge, which is present in 48% of chronic ACL-deficient knees, can be used when present to guide femoral tunnel placement[16,25] (Figure 1). The femoral tunnel (or tunnels in the case of double-bundle reconstruction) should be placed anatomically posterior to the lateral intercondylar ridge.[17] Several commercially available aiming devices and guides for the femur and tibia that use various reproducible anatomic landmarks as points of reference are available to assist the surgeon. We use an anatomic description instead of an arthroscopic description to reference femoral and tibial tunnel locations (Figure 1). The bifurcate ridge separates the two bundles anatomically from proximal to distal[17] (Figures 1 and 3). For single-bundle ACL reconstruction, the center of the femoral tunnel should be placed 1.7 mm proximal to the bifurcate ridge and approximately 8 mm anterior to the posterior articular margin of the lateral femoral condyle.[26] If the bifurcate ridge is not visible arthroscopically, a malleable ACL ruler can be used to determine a point that is 45% to 50% of the distance from proximal to distal along the posterior one third of the wall. This location approximates the center of the native ACL femoral footprint[27] (Figure 4).

The tibial tunnel can be located using the tibial square model and the mean distances to reliable arthroscopically visible landmarks.[28] The tibial square model, as described by Sielbold et al,[16] is the square footprint of the native ACL and is marked off reliably anteriorly by the anterior border of the remnant AMB footprint and posteriorly by the posterior border of the remnant PLB footprint and the posterior insertion of the lateral meniscus. The medial and lateral borders of the square are the articular margins of the medial and lateral tibial plateaus at the intercondylar eminences (Figure 5). For further confirmation of the native anatomy, or if the tibial ACL remnant is not visible, the center of the native ACL tibial footprint for single-bundle anatomic ACL reconstruction is located in the sagittal plane 9 mm behind the posterior edge of the intermeniscal ligament and 5 mm anterior from a projected coronal plane line from the peak of the medial tibial spine[19] (Figure 2). In the coronal plane, the center of the native ACL tibial footprint is located midway between the tibial spines.[20] We do not recommend using the anterior insertion of the lateral meniscus as a landmark for anterior/posterior or medial/lateral placement of the tibial tunnel because of the considerable variability in its relationship with the center of the ACL tibial footprint.[19]

The localization of these anatomic landmarks is predicated on the adequate visualization of the anatomy, which includes en face viewing of the lateral wall of the intercondylar notch and a bird's eye view of the tibial plateau. A high proximal anteromedial portal is recommended for viewing if a 30° arthroscope is used. Alternatively, a 70° arthroscope may be used to achieve these views through a standard anterolateral portal while identifying and preparing tunnel locations[29,30] (Figure 6).

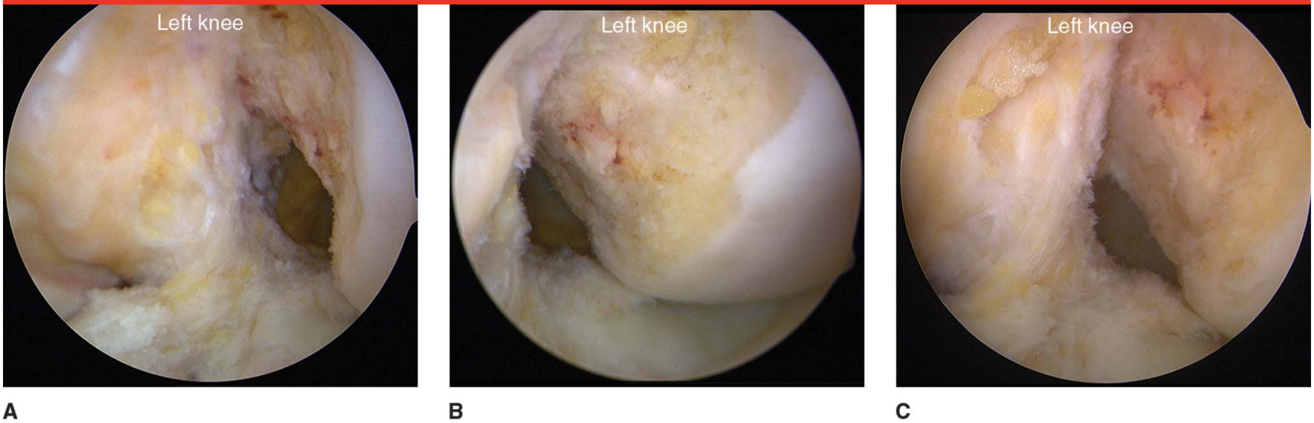
Using intraoperative fluoroscopy to localize the native ACL femoral and tibial footprints has been proven reproducible, reliable, and accurate. This method of footprint localization can be especially helpful in revision cases, in which previous anatomic landmarks, such as the lateral intercondylar ridge, may not be visible because of an earlier notchplasty and/or tunnel creation. The grid system developed by Bernard et al[31] is a technique that can be used to find the footprint on a lateral view using intraoperative fluoroscopy. For single-bundle reconstruction, the center of the femoral footprint can be referenced on a grid using the Blumensaat line; it is located 28% of the distance

Figure 5



Photograph and illustration demonstrating the approximation of the center of the native anterior cruciate ligament femoral footprint. **A,** Photograph of a human cadaver knee showing the arthroscopic tibial landmarks. **B,** Illustration showing the tibial square model, which can be used to locate the tibial tunnel. AB_{AM} = anterior border of the anteromedial bundle of the anterior cruciate ligament, ALR = anterolateral rim, AMB = anteromedial bundle footprint, AMR = anteromedial rim, PB_{PL} = posterior border of the posterolateral bundle of the anterior cruciate ligament, PCL = posterior cruciate ligament, PLB = posterolateral bundle footprint

Figure 6



Arthroscopic images showing en face views of the lateral wall of the intercondylar notch. **A,** The lateral wall of the intercondylar notch is shown using a 30° arthroscope placed through the anterolateral portal. **B,** A view of the lateral wall using a 30° arthroscope placed through the anteromedial portal. **C,** A view of the lateral wall using a 70° arthroscope placed through the anterolateral portal. (Reproduced with permission from Dhawan A, Bush-Joseph CA: Patellar tendon autograft for anterior cruciate ligament reconstruction, in Cole B, Sekiya JK: *Surgical Techniques of the Shoulder, Elbow, and Knee in Sports Medicine*, ed 2. Philadelphia, PA, Elsevier, 2008, pp 755-766.)

from proximal to distal and 34% posterior to the Blumensaat line[31] (Figure 7, A). On the tibial side, the Stäubli and Rauschning[32] technique is used for localization of the tibial tunnel. Using this method for single-bundle anatomic ACL reconstruction, the center of the tibial footprint reliably is located 43% of the distance anterior to posterior of the midsagittal tibial diameter (Figure 7, B). In the coronal plane, the tibial footprint is 51.5% (medial to lateral) or approximately midway across the knee on a fluoroscopic AP projection.[33,34]

Biomechanics and Kinematic Data

Studies demonstrate that independent femoral drilling achieves central tunnel placement within the native femoral ACL footprint more accurately and reproducibly than does transtibial drilling.[35-38] In their meta-analysis, Riboh et al[39] demonstrated that femoral tunnels drilled using a femoral-independent technique were 2.69 mm closer ($P = 0.02$) to the center of the anatomic femoral footprint than transtibially drilled femoral tunnels. The femoral tunnels drilled with a transtibial technique generally were placed anterior and proximal to the central location. Although modifications of the transtibial technique have been proposed and developed to better recreate the native ACL anatomy, compromises have been made regarding incomplete anatomic restoration of the femoral footprint, posteriorization of the tibial footprint, creation of a femoral AMB to tibial PLB construct, enlargement of the tibial intra-articular aperture, or creation of a short and very oblique tibial tunnel.[23-25] These compromises in tibial tunnel location or characteristics may adversely affect the initial reconstruction biomechanics and kinematics more than changes in femoral tunnel location and characteristics.[27]

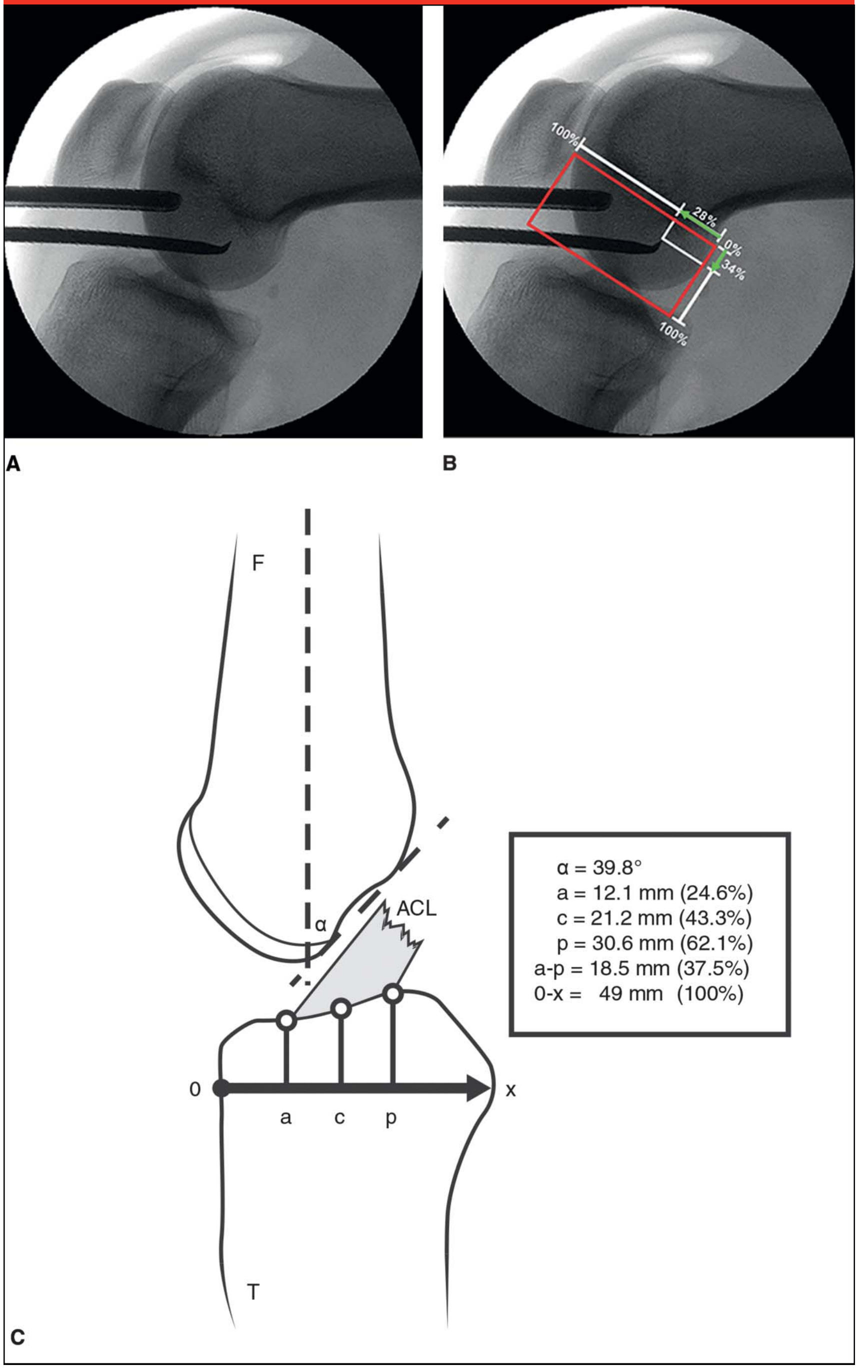
In addition to more reproducible central footprint placement, independent femoral drilling demonstrates improved obliquity compared with transtibial techniques. Increased graft obliquity is shown to result in better restoration of knee kinematics to the native ACL.[38,40-43]

Collectively, time zero cadaver data have demonstrated better restoration of native ACL kinematics using tunnels created through the centroid of the native ACL tibial and femoral footprints. Kato et al[44] compared the effect of different single-bundle femoral graft tunnels on initial reconstruction knee biomechanics. The authors found that the central placement of a single-bundle graft on the tibial and femoral footprints best approximated the normal kinematics of the native ACL compared with other anatomic constructs. In their meta-analysis, Riboh et al[39] found an additional 2.2 mm of average anterior translation on simulated Lachman testing after ACL reconstruction using a transtibial technique rather than an independent femoral drilling technique. Similarly, rotational stability has shown decreased anterior tibial subluxation after using independent femoral drilling techniques for ACL reconstruction.[39] On average, 3.36 mm more anterior tibial subluxation was seen on simulated pivot shift testing with transtibial techniques than with independent femoral drilling techniques.[39] However, these collective comparisons include a multitude of different studies, including different transtibial and independent femoral drilling techniques. Therefore, pooling and analysis of the conglomerate data are inherently problematic methodologically.

Kopf et al[45] compared the intraoperative stability of the PLB portion of the double-bundle reconstruction with the final double-bundle reconstruction. Double-bundle reconstruction demonstrated improved kinematics compared with single PLB reconstruction. Plaweski et al[46] compared a single-bundle construct that was placed with computer assistance with a standard double-bundle reconstruction. In this study, the double-bundle technique biomechanically outperformed the single-bundle construct. Bedi et al[47] evaluated the biomechanical differences between a centrally placed anatomic single-bundle ACL reconstruction and an anatomic double-bundle reconstruction. The authors found that the double-bundle reconstruction approximated the kinematics of the native knee more closely than did a single-bundle reconstruction with tibial and femoral tunnels placed centrally within their respective footprints. No difference was found in anterior translation between the reconstructions in a simulated Lachman test.

Conversely, Kato et al[44] found that a double-bundle graft offered no biomechanical or kinematic benefit compared with a central single-bundle reconstruction. Similarly, a cadaver study by Goldsmith et al[42] demonstrated no difference between single-bundle and double-bundle

Figure 7



A and **B,** Intraoperative lateral fluoroscopic images of the knee obtained with a C-arm showing the tip of a microfracture awl placed at the proposed anterior cruciate ligament femoral tunnel location for single-bundle reconstruction using the Bernard and Hertel grid (in red). For single-bundle reconstruction, the center of the femoral footprint can be referenced on a grid using the Blumensaat line; it is located 28% of the distance from proximal to distal and 34% posterior to the Blumensaat line. **C,** Illustration demonstrating that the center of the tibial footprint for single-bundle anatomic anterior cruciate ligament reconstruction is located 43.3% of the distance anterior to posterior of the midsagittal tibial diameter. ACL = anterior cruciate ligament (Panel A copyright Charles Brown, Doha, Qatar.)

reconstructions in terms of the results of a simulated Lachman and pivot shift test. In their study, the single-bundle reconstruction also was placed centrally within the footprints. Based on the available time zero biomechanical data, double-bundle ACL reconstructions restore the native knee kinematics more closely than do single-bundle ACL reconstructions, even more closely than single-bundle reconstructions placed through the anatomic central tibial and femoral footprints.

Clinical Outcomes

Direct clinical comparisons of anatomic and isometric graft tunnel placement during ACL reconstructions are limited by incomplete descriptions of the surgical techniques. Comparisons between anatomically placed and isometrically placed grafts can be inferred by whether the femoral drilling technique used was transtibial or independent. These studies lack detail regarding the placement of the femoral and tibial tunnels and their relationship to native ligamentous attachments, however. The use of other anatomic landmarks, such as the lateral intercondylar and bifurcate ridges, are not well described in the literature and are reported in only 13% (lateral intercondylar ridge) and 6% (bifurcate ridge) of studies describing double-bundle reconstructions.[48]

A recent proliferation of meta-analyses that compare single-bundle and double-bundle reconstructions has been observed.[49-52] Although conflicts and bias exist in the data, several themes have emerged. First, a substantial difference exists in various objective measures between the two groups. The testing of anterior laxity, as measured by a KT-1000 arthrometer, Lachman and pivot shift tests, and objective International Knee Documentation Committee (IKDC) scores, favors double-bundle reconstructions.[49-52] Second, no difference in subjective outcomes, including IKDC, Lysholm, and Tegner scores, has been elucidated between single-bundle and double-bundle reconstructions in the intermediate (6 months to 2 years postoperatively) or long-term (2 to 5 years postoperatively) follow-up periods.[49-52] Third, no statistically significant differences have been observed in long-term knee pain, graft failure, or other adverse events or complications.[51] Finally, based on limited data from a systematic review, increased rates of return to preinjury function have been observed in patients undergoing double-bundle reconstructions.[51]

Limited clinical comparisons have been made between transtibial and independent femoral drilling reconstruction techniques for the ACL. Original controlled clinical studies compared traditional two-incision techniques with transtibial reconstructions. Most of the studies reported no notable objective or subjective differences between the two techniques.[53-56] O'Neill[55] reported that using a two-incision technique resulted in an 8% increase in instrumented laxity of <3 mm and a 6% increase in the number of patients in whom return to normal activity was seen. The clinical relevance of these statistically significant differences are uncertain.[57] Furthermore, the four available studies were performed between 1996 and 1999, were devoid of objective information on rotational stability, and lacked power analysis.[57]

More recent comparison studies have focused on transtibial versus independent femoral drilling using an anteromedial portal technique. Among the five available clinical studies, none has demonstrated any substantial differences between the two groups in subjective outcome measures, such as subjective IKDC, Lysholm, Knee Injury and Osteoarthritis Outcome Score (KOOS), and Tegner scores.[58-62] Differences in objective outcome parameters remain equivocal, however. Two studies report substantially less laxity using KT-1000 arthrometry, Lachman testing, and pivot shift testing, as well as better objective IKDC scores in those with femoral tunnels created through the anteromedial portal.[59,60] Two other studies found no statistically significant differences in objective criteria between the two technical groups.[58,61] Only one study demonstrated substantially less rotational and sagittal instability with transtibial reconstructions.[62] Azboy et al[58] and Alentorn-Geli et al[59] found a shorter time to return to play in patients with ACL reconstructions using an independent femoral drilling technique rather than a transtibial technique. Duffee et al[5] found statistically significant higher odds (odds ratio, 2.49; $P = 0.006$) of revision after ACL reconstruction with a transtibial technique than after an anteromedial technique. The authors also found that the femoral tunnel drilling technique was not a predictor of the KOOS Quality of Life subscore ($P = 0.72$) or the KOOS Function, Sports, and Recreational Activities subscore ($P = 0.36$) at the 6-year follow-up evaluation. Conversely, Rahr-Wagner et al[62] reported an increased relative risk (2.04; 95% confidence interval, 2.40 to 3.41) of undergoing revision ACL reconstruction if the primary reconstruction was performed using an anteromedial drilling technique. They also found no difference in KOOS and Tegner scores using a transtibial technique compared with an anteromedial portal femoral drilling technique at 1 year postoperatively. Table 1 highlights

Table 1

Comparison of Anterior Cruciate Ligament Reconstructions Using Transtibial or Anteromedial Portal Drilling Techniques

	No. of Patients		Instrumented Laxity		Grade 0 Pivot Shift		Normal IKDC Score		Lysholm Score		Tegner Score	
Study	TT	AM	TT	AM	TT (%)	AM (%)	TT (%)	AM (%)	TT	AM	TT	AM
Azboy et al[58]	34	30	NA	NA	76.5	86.7	61.8	66.7	NA	NA	6.1 ± 1.0	6.7 ± 1.2
Rahr-Wagner et al[62]	3,812	1,945	11.4% > 2 mm	19.8% > 2 mm	86.4	80.5	NA	NA	NA	NA	4.9 ± 0.1	5.0 ± 0.2
Hussein et al[60]	72	78	2.0 ± 0.9 mm	1.6 ± 0.8 mm	41.7	66.7	79.2	88.5	90.9 ± 7.0	91.8 ± 4.3	NA	NA
Zhang et al[61]	34	31	2.14 ± 0.91 mm	1.96 ± 1.02 mm	NA	NA	NA	NA	94.5 ± 1.1	95.1 ± 1.0	NA	NA
Alentorn-Geli et al[59]	21	26	1.9 ± 1.8 mm	0.2 ± 1.6 mm	41.2	79.2	33.3	73.1	97.1 ± 7.2	99.3 ± 2.3	7.1 ± 1.3	7.8 ± 1.6

AM = anteromedial, IKDC = International Knee Documentation Committee, NA = not available, TT = transtibial

the results of available controlled studies comparing ACL reconstructions using transtibial portal techniques with those using anteromedial portal techniques.

The largest comparison between ACL reconstructions performed using transtibial techniques and those using anteromedial portal femoral tunnel drilling techniques with pooled data included 859 patients from 21 prospective experimental studies.[63] Reconstructions using anteromedial portal drilling demonstrated substantially less laxity on Lachman testing and improved range of motion within the first 2 years after surgery. Although these advantages persisted up to 10 years after surgery, the differences were not statistically significant beyond the first 2 years. Subjective parameters, including Lysholm scores and total IKDC scores, were not significantly different statistically between the groups at any point. After the first 3 years postoperatively, patients who had ACL reconstructions performed using a transtibial technique were significantly more likely statistically to describe their activity level as strenuous or moderate than those who had reconstructions performed using a femoral-independent technique.[63]

A recent meta-analysis by Bedi et al[40] reviewed all comparison series of ACL reconstructions that compared the transtibial drilling technique with an independent femoral drilling technique. Six studies formed the basis for comparison. Four of them used the two-incision outside-in technique, and two used anteromedial portal techniques to create the femoral tunnel. The authors demonstrated that, although failure rates, IKDC objective scores, and Tegner scores were similar between the two groups, ACL reconstructions performed using femoral-independent techniques resulted in statistically significant less instrumented anterior laxity and improved Lysholm scores.[40] However, the authors cautioned that the 0.62-point difference in Lysholm scores in the study fell well below the previously reported value of 8.9 points, which was thought to be a clinically notable difference following ACL reconstructions.[39,63]

Concerns

Potential challenges, such as increased strain through the graft and shortened femoral sockets, have arisen with the new anatomic tunnel placement reconstruction technique shift in ACL reconstruction. Specific characteristics of the anatomic ACL reconstruction, such as anatomic obliquity, although similar to the native ACL, cause more changes in strain and length with flexion and extension than do grafts placed using the endoscopic transtibial ACL reconstruction technique.[64-66] Using an animal model, Ma et al[67] demonstrated that anisometric grafts with high tension through range of motion that was analogous to the anatomic reconstructions had inferior early healing and incorporation into the osseous tunnel compared with isometric grafts. Bedi et al[40] demonstrated a short femoral tunnel length of <25 mm in 42% of their drilled tunnels. Increasing knee flexion with anteromedial portal drilling contributed to an increased risk of a short tunnel and posterior wall blowout. Similarly, Chang et al[38] found that anteromedial portal drilling resulted in a more oblique tunnel than did transtibial drilling but also resulted in short femoral tunnels in 26% of patients studied compared with 2% of those undergoing transtibial drilling. Silver et al[68] demonstrated that using a curved guide and flexible reamer system may obviate some of these technical challenges. The increase in graft strain and changes in length, combined with shorter tunnels and a potentially smaller contact area for biologic graft integration, may have clinical implications for early graft incorporation in the setting of contemporary early aggressive rehabilitation protocols.

Using the Danish Registry of Knee Ligament Reconstruction, which included 9,239 primary ACL reconstructions over a 4-year period, Rahr-Wagner et al[62] found a substantially higher risk of revision when using an anteromedial femoral drilling technique (5.16%) compared with a transtibial technique (3.20%). After adjusting for confounders, including age, gender, chondral injury, choice of graft, and meniscal surgery, the authors found an overall relative risk of revision of 2.04 in the anteromedial femoral drilling group compared with the transtibial group. The risk was slightly higher than double the risk of revision when anteromedial portal drilling was used. The authors attributed this increased risk to multiple potential factors, including decreased tunnel length, an increased chance of proximal femoral wall compromise, potential challenges with fixation techniques and biologic healing because of increased strain, and the learning curve that accompanies the introduction of a new technique.[62]

Summary

Reconstruction techniques for the ACL have evolved considerably over the past four decades. An era of renewed interest and emphasis on the insertional anatomy of the ACL has arrived, using methods and techniques that can reproduce this anatomy reliably and accurately during surgical reconstruction. The identification and placement of the tibial and femoral graft apertures to re-create the native anatomy is fundamental to the concept of anatomic ACL reconstruction. Abundant time zero biomechanical and kinematic data demonstrate the improved time zero characteristics of independent femoral drilling and double-bundle reconstructions. Limited short-term or long-term clinical outcome data have been available to support using either of these two techniques rather than a transtibial drilling technique. The lack of a clear clinical advantage for either technique may derive from potentially offsetting biologic incorporation challenges of femoral-independent and/or double-bundle techniques and/or from modifications made in traditional endoscopic transtibial techniques that allow improved femoral and tibial footprint restoration.[69] In addition, complex changes that occur in the knee and in the patient during the initial ACL injury, including changes to the chondral microanatomy and biology, likely are not reconciled by any currently available technique of ACL reconstruction.[70]

The anatomy of the native ACL is highly complex. Despite attempts to better restore the native dimensions, collagen orientation, and insertion sites of the ACL, no currently available surgical technique can replicate the nuances of complex fiber orientation and rotation, cross-sectional dimensions, and anatomic changes that occur within this ligament during knee flexion and extension.[14] An unbiased adequately powered direct comparison of modern transtibial techniques with independent femoral drilling techniques using anatomic and/or radiographic landmarks would be of great value in determining whether any single technique produces improved clinical results.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, references 39, 49-52, 54-56, 60, 61, and 63 are level I studies. References 6, 8, 48, 57, and 62 are level II studies. References 5, 53, 58, and 59 are level III studies. References 2, 7, 9, and 27 are level IV studies. References 1, 3, 4, 12, 13, 20-22, and 29 are level V expert opinion.

References printed in **bold type** are those published within the past 5 years.

1. **Chambat P, Guier C, Sonnery-Cottet B, Fayard JM, Thaunat M: The evolution of ACL reconstruction over the last fifty years. *Int Orthop* 2013;37(2):181-186.**

2. Bach BR Jr, Tradonsky S, Bojchuk J, Levy ME, Bush-Joseph CA, Khan NH: Arthroscopically assisted anterior cruciate ligament reconstruction using patellar tendon autograft: Five- to nine-year follow-up evaluation. *Am J Sports Med* 1998;26 (1):20-29.

3. McCulloch PC, Lattermann C, Boland AL, Bach BR Jr: An illustrated history of anterior cruciate ligament surgery. *J Knee Surg* 2007;20(2):95-104.

4. Duquin TR, Wind WM, Fineberg MS, Smolinski RJ, Buyea CM: Current trends in anterior cruciate ligament reconstruction. *J Knee Surg* 2009;22(1):7-12.

5. **Duffee A, Magnussen RA, Pedroza AD, Flanigan DC, Kaeding CC; MOON Group: Transtibial ACL femoral tunnel preparation increases odds of repeat ipsilateral knee surgery. *J Bone Joint Surg Am* 2013;95(22):2035-2042.**

6. **McCullough KA, Phelps KD, Spindler KP, et al; MOON Group: Return to high school- and college-level football after anterior cruciate ligament reconstruction: A Multicenter Orthopaedic Outcomes**

Network (MOON) cohort study. *Am J Sports Med* 2012;40(11):2523-2529.

7. Shah VM, Andrews JR, Fleisig GS, McMichael CS, Lemak LJ: Return to play after anterior cruciate ligament reconstruction in National Football League athletes. *Am J Sports Med* 2010;38(11): 2233-2239.

8. Carey JL, Huffman GR, Parekh SG, Sennett BJ: Outcomes of anterior cruciate ligament injuries to running backs and wide receivers in the National Football League. *Am J Sports Med* 2006;34(12):1911-1917.

9. **Morgan JA, Dahm D, Levy B, Stuart MJ; MARS Study Group: Femoral tunnel malposition in ACL revision reconstruction. *J Knee Surg* 2012;25(5): 361-368.**

10. Musahl V, Plakseychuk A, VanScyoc A, et al: Varying femoral tunnels between the anatomical footprint and isometric positions: Effect on kinematics of the anterior cruciate ligament-reconstructed knee. *Am J Sports Med* 2005;33(5): 712-718.

11. Bedi A, Maak T, Musahl V, et al: Effect of tunnel position and graft size in single-bundle anterior cruciate ligament reconstruction: An evaluation of time-zero knee stability. *Arthroscopy* 2011;27(11): 1543-1551.

12. **Chechik O, Amar E, Khashan M, Lador R, Eyal G, Gold A: An international survey on anterior cruciate ligament reconstruction practices. *Int Orthop* 2013;37(2):201-206.**

13. **Erickson BJ, Harris JD, Fillingham YA, et al: Anterior cruciate ligament reconstruction practice patterns by NFL and NCAA football team physicians. *Arthroscopy* 2014;30(6):731-738.**

14. Girgis FG, Marshall JL, Monajem A: The cruciate ligaments of the knee joint: Anatomical, functional and experimental analysis. *Clin Orthop Relat Res* 1975;106: 216-231.

15. Siebold R, Ellert T, Metz S, Metz J: Femoral insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: Morphometry and arthroscopic orientation models for double-bundle bone tunnel placement. A cadaver study. *Arthroscopy* 2008;24(5): 585-592.

16. Siebold R, Ellert T, Metz S, Metz J: Tibial insertions of the anteromedial and posterolateral bundles of the anterior cruciate ligament: Morphometry, arthroscopic landmarks, and orientation model for bone tunnel placement. *Arthroscopy* 2008;24(2):154-161.

17. Ferretti M, Ekdahl M, Shen W, Fu FH: Osseous landmarks of the femoral attachment of the anterior cruciate ligament: An anatomic study. *Arthroscopy* 2007;23(11):1218-1225.

18. Zantop T, Wellmann M, Fu FH, Petersen W: Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: Anatomic and radiographic findings. *Am J Sports Med* 2008;36(1): 65-72.

19. **Ferretti M, Doca D, Ingham SM, Cohen M, Fu FH: Bony and soft tissue landmarks of the ACL tibial insertion site: An anatomical study. *Knee Surg Sports Traumatol Arthrosc* 2012;20(1):62-68.**

20. van Eck CF, Lesniak BP, Schreiber VM, Fu FH: Anatomic single- and double-bundle anterior cruciate ligament reconstruction flowchart. *Arthroscopy* 2010;26(2):258-268.

21. Piasecki DP, Bach BR Jr, Espinoza Orias AA, Verma NN: Anterior cruciate ligament reconstruction: Can anatomic femoral placement be achieved with a transtibial technique? *Am J Sports Med* 2011;39(6):1306-1315.

22. Heming JF, Rand J, Steiner ME: Anatomical limitations of transtibial drilling in anterior cruciate ligament reconstruction. *Am J Sports Med* 2007;35 (10):1708-1715.

23. Herbort M, Lenschow S, Fu FH, Petersen W, Zantop T: ACL mismatch reconstructions: Influence of different tunnel placement strategies in single-bundle ACL reconstructions on the knee kinematics. *Knee Surg Sports Traumatol Arthrosc* 2010;18(11):1551-1558.

24. Bedi A, Maak T, Musahl V, et al: Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: Is the tibial tunnel position most important? *Am J Sports Med* 2011;39 (2):366-373.

25. van Eck CF, Morse KR, Lesniak BP, et al: Does the lateral intercondylar ridge disappear in ACL deficient patients? *Knee Surg Sports Traumatol Arthrosc* 2010;18 (9):1184-1188.

26. Ziegler CG, Pietrini SD, Westerhaus BD, et al: Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *Am J Sports Med* 2011;39 (4):743-752.

27. Bird JH, Carmont MR, Dhillon M, et al: Validation of a new technique to determine midbundle femoral tunnel position in anterior cruciate ligament reconstruction using 3-dimensional computed tomography analysis. *Arthroscopy* 2011;27(9): 1259-1267.

28. Siebold R: The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2011;19(5):699-706.

29. **Rasmussen JF, Lavery KP, Dhawan A: Anatomic anterior cruciate ligament reconstruction with a flexible reamer system and 70° arthroscope. *Arthrosc Tech* 2013;2(4):e319-e322.**

30. **Dhawan A, Bush-Joseph CA: *Patellar tendon autograft for anterior cruciate ligament reconstruction, in* Cole BJ, Sekita JK (eds): Surgical Techniques of the Shoulder, Elbow, and Knee in Sports Medicine. Philadelphia, PA, Elsevier Saunders. 2013.**

31. Bernard M, Hertel P, Hornung H, Cierpinski T: Femoral insertion of the ACL: Radiographic quadrant method. *Am J Knee Surg* 1997;10(1):14-21.

32. Stäubli HU, Rauschning W: Tibial attachment area of the anterior cruciate ligament in the extended knee position: Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo. *Knee Surg Sports Traumatol Arthrosc* 1994;2(3):138-146.

33. Tsukada H, Ishibashi Y, Tsuda E, Fukuda A, Toh S: Anatomical analysis of the anterior cruciate ligament femoral and tibial footprints. *J Orthop Sci* 2008;13(2): 122-129.

34. Forsythe B, Kopf S, Wong AK, et al: The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am* 2010;92(6): 1418-1426.

35. **Gadikota HR, Sim JA, Hosseini A, Gill TJ, Li G: The relationship between femoral tunnels created by the transtibial, anteromedial portal, and outside-in techniques and the anterior cruciate ligament footprint. *Am J Sports Med* 2012; 40(4):882-888.**

36. Kaseta MK, DeFrate LE, Charnock BL, Sullivan RT, Garrett WE Jr: Reconstruction technique affects femoral tunnel placement in ACL reconstruction. *Clin Orthop Relat Res* 2008;466(6):1467-1474.

37. **Tompkins M, Milewski MD, Brockmeier SF, Gaskin CM, Hart JM, Miller MD: Anatomic femoral tunnel drilling in anterior cruciate ligament reconstruction: Use of an accessory medial portal versus traditional transtibial drilling. *Am J Sports Med* 2012;40(6):1313-1321.**

38. Chang CB, Choi JY, Koh IJ, Lee KJ, Lee KH, Kim TK: Comparisons of femoral tunnel position and length in anterior cruciate ligament reconstruction: Modified transtibial versus anteromedial portal techniques. *Arthroscopy* 2011;27(10): 1389-1394.

39. **Riboh JC, Hasselblad V, Godin JA, Mather RC III: Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: A systematic review, meta-analysis, and meta-regression. *Am J Sports Med* 2013;41(11): 2693-2702.**

40. Bedi A, Raphael B, Maderazo A, Pavlov H, Williams RJ III: Transtibial versus anteromedial portal drilling for anterior cruciate ligament reconstruction: A cadaveric study of femoral tunnel length and obliquity. *Arthroscopy* 2010;26(3): 342-350.

41. Bowers AL, Bedi A, Lipman JD, et al: Comparison of anterior cruciate ligament tunnel position and graft obliquity with transtibial and anteromedial portal femoral tunnel reaming techniques using high-resolution magnetic resonance imaging. *Arthroscopy* 2011;27(11):1511-1522.

42. **Goldsmith MT, Jansson KS, Smith SD, Engebretsen L, LaPrade RF, Wijdicks CA: Biomechanical comparison of anatomic single- and double-bundle anterior cruciate ligament reconstructions: An in vitro study. *Am J Sports Med* 2013;41 (7):1595-1604.**

43. Dalldorf PG, Alexander J, Lintner DM: One- and two-incision anterior cruciate ligament reconstruction: A biomechanical comparison including the effect of simulated closed-chain exercise. *Arthroscopy* 1998;14(2):176-181.

44. Kato Y, Ingham SJ, Kramer S, Smolinski P, Saito A, Fu FH: Effect of tunnel position for anatomic single-bundle ACL reconstruction on knee biomechanics in a porcine model. *Knee Surg Sports Traumatol Arthrosc* 2010;18(1):2-10.

45. **Kopf S, Musahl V, Bignozzi S, Irrgang JJ, Zaffagnini S, Fu FH: In vivo kinematic evaluation of anatomic double-bundle anterior cruciate ligament reconstruction. *Am J Sports Med* 2014;42 (9):2172-2177.**

46. Plaweski S, Grimaldi M, Courvoisier A, Wimsey S: Intraoperative comparisons of knee kinematics of double-bundle versus single-bundle anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2011;19(8): 1277-1286.

47. Bedi A, Musahl V, O'Loughlin P, et al: A comparison of the effect of central anatomical single-bundle anterior cruciate ligament reconstruction and double-bundle anterior cruciate ligament reconstruction on pivot-shift kinematics. *Am J Sports Med* 2010;38(9):1788-1794.

48. **Desai N, Alentorn-Geli E, van Eck CF, Musahl V, Fu FH, Karlsson J, Samuelsson K: A systematic review of single- versus double-bundle ACL reconstruction using the anatomic anterior cruciate ligament reconstruction scoring checklist. *Knee Surg Sports Traumatol Arthrosc.* 2016;24(3):862-872.**

49. **van Eck CF, Kopf S, Irrgang JJ, et al: Single-bundle versus double-bundle reconstruction for anterior cruciate ligament rupture: A meta-analysis. Does anatomy matter? *Arthroscopy* 2012;28(3): 405-424.**

50. **Xu M, Gao S, Zeng C, et al: Outcomes of anterior cruciate ligament reconstruction using single-bundle versus double-bundle technique: Meta-analysis of 19 randomized controlled trials. *Arthroscopy* 2013;29(2): 357-365.**

51. **Tiamklang T, Sumanont S, Foocharoen T, Laopaiboon M: Double-bundle versus single-bundle reconstruction for anterior cruciate ligament rupture in adults. *Cochrane Database Syst Rev* 2012;11: CD008413.**

52. **Li YL, Ning GZ, Wu Q, et al: Single-bundle or double-bundle for anterior cruciate ligament reconstruction: A meta-analysis. *Knee* 2014;21(1):28-37.**

53. Brandsson S, Faxén E, Eriksson BI, Swärd L, Lundin O, Karlsson J: Reconstruction of the anterior cruciate ligament: Comparison of outside-in and all-inside techniques. *Br J Sports Med* 1999;33 (1):42-45.

54. Gerich TG, Lattermann C, Fremerey RW, Zeichen J, Lobenhoffer HP: One- versus two-incision technique for anterior cruciate ligament reconstruction with patellar tendon graft: Results on early rehabilitation and stability. *Knee Surg Sports Traumatol Arthrosc* 1997;5(4):213-216.

55. O'Neill DB: Arthroscopically assisted reconstruction of the anterior cruciate ligament: A prospective randomized analysis of three techniques. *J Bone Joint Surg Am* 1996;78(6):803-813.

56. Reat JF, Lintner DM: One-versus two-incision ACL reconstruction: A prospective, randomized study. *Am J Knee Surg* 1997; 10(4):198-208.

57. George MS, Huston LJ, Spindler KP: Endoscopic versus rear-entry ACL reconstruction: A systematic review. *Clin Orthop Relat Res* 2007;455(455):158-161.

58. **Azboy I, Demirtaş A, Gem M, Kıran S, Alemdar C, Bulut M: A comparison of the anteromedial and transtibial drilling technique in ACL reconstruction after a short-term follow-up. *Arch Orthop Trauma Surg* 2014;134(7):963-969.**

59. Alentorn-Geli E, Samitier G, Alvarez P, Steinbacher G, Cugat R: Anteromedial portal versus transtibial drilling techniques in ACL reconstruction: A blinded cross-sectional study at two- to five-year follow-up. *Int Orthop* 2010;34(5):747-754.

60. **Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH: Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. *Am J Sports Med* 2012;40 (3):512-520.**

61. **Zhang Q, Zhang S, Li R, Liu Y, Cao X: Comparison of two methods of femoral tunnel preparation in single-bundle anterior cruciate ligament reconstruction: A prospective randomized study. *Acta Cir Bras* 2012;27(8):572-576.**

62. **Rahr-Wagner L, Thillemann TM, Pedersen AB, Lind MC: Increased risk of revision after anteromedial compared with transtibial drilling of the femoral tunnel during primary anterior cruciate ligament reconstruction: Results from the Danish Knee Ligament Reconstruction Register. *Arthroscopy* 2013;29(1): 98-105.**

63. Alentorn-Geli E, Lajara F, Samitier G, Cugat R: The transtibial versus the anteromedial portal technique in the arthroscopic bone-patellar tendon-bone anterior cruciate ligament reconstruction. *Knee Surg Sports Traumatol Arthrosc* 2010;18(8):1013-1037.

64. Brophy RH, Pearle AD: Single-bundle anterior cruciate ligament reconstruction: A comparison of conventional, central, and horizontal single-bundle virtual graft positions. *Am J Sports Med* 2009;37(7): 1317-1323.

65. Brophy RH, Voos JE, Shannon FJ, et al: Changes in the length of virtual anterior cruciate ligament fibers during stability testing: A comparison of conventional single-bundle reconstruction and native anterior cruciate ligament. *Am J Sports Med* 2008;36(11):2196-2203.

66. Xu Y, Liu J, Kramer S, et al: Comparison of in situ forces and knee kinematics in anteromedial and high anteromedial bundle augmentation for partially ruptured anterior cruciate ligament. *Am J Sports Med* 2011;39(2):272-278.

67. **Ma R, Schaer M, Chen T, et al: The effect of dynamic changes in ACL graft force on soft tissue ACL graft-tunnel incorporation. *Orthop J Sports Med* 2014;2(2 suppl): 232596114S00087.**

68. Silver AG, Kaar SG, Grisell MK, Reagan JM, Farrow LD: Comparison between rigid and flexible systems for drilling the femoral tunnel through an anteromedial portal in anterior cruciate ligament reconstruction. *Arthroscopy* 2010;26(6):790-795.

69. Rue JP, Busam ML, Bach BR Jr: Hybrid single bundle anterior cruciate ligament reconstruction technique using a transtibial drilled femoral tunnel. *Tech Knee Surg* 2008;7(2):107-114.

70. Johnson DL, Urban WP Jr, Caborn DN, Vanarthos WJ, Carlson CS: Articular cartilage changes seen with magnetic resonance imaging-detected bone bruises associated with acute anterior cruciate ligament rupture. *Am J Sports Med* 1998; 26(3):409-414.