Anatomic anterior cruciate ligament reconstruction: a changing paradigm

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CHAPTER 10

ANATOMIC SINGLE- AND DOUBLE-BUNDLE ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION FLOWCHART

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Abstract

Anatomy is the foundation of orthopedic surgery and the advancing knowledge of the anterior cruciate ligament (ACL) anatomy has led to the development of improved modern reconstruction techniques that approach the anatomy of the native ACL. Current literature on the anatomy of the ACL and its reconstruction techniques, as well as our surgical experience, were used to develop a flowchart intended to aid the surgeon in performing anatomic ACL reconstruction. A guideline was written to supplement this flowchart with more detailed information on anatomic ACL reconstruction and its pitfalls, and with relevant literature and helpful figures. Although there is still much to be learned about anatomic ACL reconstruction methods, we believe that this flowchart is a helpful instrument for surgeons. We will continue to update the flowchart as more information becomes available about the anatomy of the ACL and about how to better reproduce it.

Introduction

Anatomy is the basis of orthopedic surgery and the advancing knowledge of the anatomy of the anterior cruciate ligament (ACL) has led to the development of modern reconstruction techniques that can replicate the anatomy of the native ACL.

The ACL consists of two functional bundles, the anteromedial (AM) and posterolateral (PL) bundle, which work together to provide both anteroposterior and rotational stability of the knee. This two-bundle anatomy is present during fetal development and persists throughout life (Figure 1).

Figure 1: Cadaveric specimen of the right knee showing the two-bundle anatomy of the ACL.
Traditional ACL reconstruction techniques – reconstructing the ACL using a single bundle – have been shown to result in normal IKDC scores in only 61-67% of patients. Biomechanical studies have shown that these single-bundle reconstructions effectively restore anterior-posterior stability, but that they fail to restore rotational stability. Double-bundle reconstruction however, has been demonstrated to restore more accurately rotational stability.

Various recent level I and II studies have shown that double-bundle reconstruction results in superior short-term clinical outcomes for rotational, and in most studies also for anterior-posterior stability, as compared to single-bundle reconstruction. However, some studies showed no advantage of double-bundle reconstruction.

The goal of ACL reconstruction should be to closely reproduce the native anatomy, which we believe will result in superior clinical outcomes. However, anatomic ACL reconstruction is a complex and detailed surgical procedure that has many pitfalls. Therefore, a flowchart has been developed that can help orthopedic surgeons in performing anatomic ACL reconstruction.

Methods

The current literature on the anatomy of the ACL and our surgical experience were used to develop a flowchart that takes a surgeon through all the steps of an anatomic anterior cruciate ligament reconstruction procedure. A guideline was written to accompany this flowchart containing more detailed information and literature to support each step. Figures were added to the guideline where necessary to assist in explaining the steps. The flowchart was designed to be a dynamic document that can easily be modified when more information about ACL anatomy becomes available. It is applicable to the anatomic ACL reconstruction concept of both single- and double-bundle reconstruction.

Results

The result is the “Anatomic Single- and Double-Bundle Anterior Cruciate Ligament Reconstruction Flowchart” (Appendix 1). All the steps of the flowchart will be extensively discussed below supplemented with figures and references to relevant literature.

Pre-operative assessment

The first step of the flowchart is taking a detailed history to assess the injury mechanism and a physical examination to assess knee stability. Physical examination includes the Lachman, Anterior Drawer and Pivot Shift testing, as well as KT-1000 arthrometer testing. A complete physical exam should be done to rule out multi-ligamentous injuries and other associated pathologies. Another key
component of the physical exam is the neurovascular assessment. The injury mechanism and the degree of instability can provide information about the rupture pattern. For example, if a patient has a 2+ Pivot Shift, but only a 1B Lachman, an isolated PL bundle tear is more likely\textsuperscript{13}. When this is suspected special attention can be paid to the Magnetic Resonance Imaging (MRI) scan to confirm this diagnosis\textsuperscript{13} (\textbf{Figure 2}). A radiograph should always be obtained to evaluate the bony morphology and presence of bony pathology, i.e. fractures.

It is strongly advised to repeat the physical examination under anesthesia. Due to guarding of the patient as a consequence of pain, the result of the physical examination under anesthesia could significantly differ from the examination in the office. Comparison to the uninjured side provides the surgeon with an estimate of the patient’s normal stability.

\textbf{Figure 2:} Sagittal MRI scan of the ACL. \textbf{A.} Intact ACL with AM and PL bundle visible. \textbf{B.} Isolated PL bundle tear, AM bundle is intact.

\textbf{Rupture pattern}

The first objective during arthroscopy is to confirm and examine the rupture pattern of the ACL. By visualizing and probing the remnants of the native ACL, a possible single-bundle rupture can be detected (\textbf{Figure 3}). When assessing the rupture pattern, if there is doubt about the functionality of the whole ACL or one of the bundles, the provocative tests can be performed while probing the ligament or bundle. The soft-tissue remnants of the ACL should be preserved on tibia and femur to guide the identification of the native insertion sites of the AM and PL bundle.
Figure 3: Arthroscopic lateral portal view of the ACL of the right knee. A. Intact ACL with AM and PL bundle visible. B. Isolated PL bundle tear, AM bundle is intact.

Accessory medial portal obviates need for notchplasty

The use of an accessory medial portal aids the visualization of the femoral insertion site 15 (Figure 4). The accessory anteromedial portal is located superior to the medial joint line approximately 2 centimeters medial to the medial border of the patellar tendon. This additional portal is used for instrumentation. This allows the standard medial portal to be used for viewing the entire lateral wall of the intercondylar notch, including the femoral insertion sites of the AM and PL bundles.

Figure 4: Arthroscopic view of the femoral intercondylar notch of the right knee. The probe is indicating the superior border of the femoral ACL insertion site. A. Lateral portal view. B. Medial portal view.
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The flowchart contains a note to advise against the surgeon performing a notchplasty. The disadvantage of the notchplasty lies in the removal of the remnants and all osseous landmarks of the femoral ACL insertion. It cannot be emphasized enough that the remnants of the ACL and bony ridges are critical anatomic landmarks in identifying the true ACL insertions. Removal of them by notchplasty can therefore compromise correct anatomic tunnel placement. Moreover, it can lead to abnormal graft forces and tightening of the graft during flexion due to elevated pretension and relocation of the internal edge of the femoral tunnel. This can ultimately lead to graft failure 16. Also, possible re-growth and overgrowth of the notch after notchplasty have been linked to graft failure 17. The use of an accessory medial portal makes a notchplasty unnecessary. Notchplasty to avoid graft impingement is also unnecessary in anatomic ACL reconstruction, since the native ACL does not impinge. Therefore, if the ACL is reconstructed in an anatomic fashion, impingement should not occur.

ACL footprint and landmarks

The first decision box in the flowchart asks the surgeon if the insertion sites are visible (Figure 5). In chronic cases, this is more likely not to be the case than in acute cases, especially for the femoral side. If the femoral remnants are not present, the location of the insertion site can be determined by the bony landmarks: the lateral intercondylar ridge and the lateral bifurcate ridge 18,19. The lateral intercondylar ridge, also known as the ‘residents ridge’, was first described by William Clancy Jr. and is located on the medial wall of the lateral femoral condyle. It runs from anterior to posterior with the knee in 90° flexion (operating position). The lateral bifurcate ridge runs perpendicular to the lateral intercondylar ridge and is located between the AM and PL bundle insertion site 18,19 (Figure 6). It is suspected, however, that the lateral intercondylar ridge exists because of osseous remodeling in response to force from the ligament fibers, in accordance with Wolff’s law 20.

Figure 5: ACL insertion sites of the AM and PL bundle. A. Arthroscopic lateral portal view of the tibial ACL insertion site. B. and C. Arthroscopic medial portal view of the femoral ACL insertion site. In B the probe indicates the PL insertion site. In C the probe indicates the AM insertion site.
If this hypothesis is true, the ridge may gradually disappear when there is no ACL, for example after chronic ACL rupture. Indeed, it has been reported by surgeons that in chronic ACL cases the remnants as well as the ridge are less visible or not visible at all.

Figure 6: Arthroscopic medial portal view of the bony landmarks for identifying the femoral ACL insertion site: the lateral intercondylar ridge forms the superior border of the ACL insertion site and the lateral bifurcate ridge separates the AM and PL bundle insertion site.

The left side of the flowchart focuses on when the insertion sites can be visualized. The location of the native femoral and tibial footprint should be marked and their location used to determine the tunnel positions. Measuring the insertion site will inform the surgeon of the size of the patient’s native ACL. This measurement can be used to make the decision for either double- or single-bundle reconstruction and should determine the size of the tunnels. When a patient has an insertion site smaller than 14 mm in diameter, double-bundle reconstruction can present a challenge. Other indications for single-bundle reconstruction are open physes, severe bone bruising, a narrow notch, severe arthritic changes (grade 3 or more) or multiple ligamentous injuries (Figure 7, Table 1). A narrow notch can make it difficult to place the guide pins, especially the AM guide pin, in the native femoral insertion site. With such a narrow notch, it is difficult to drill the femoral tunnels without damaging the medial femoral condyle with the drill. A current study at our institution aims to determine the minimal notch width for double-bundle reconstruction. There are no definite results yet. However, it seems that, when a notch is smaller than 12 mm, double-bundle reconstruction often cannot be performed.
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**Figure 7:** Arthroscopic pictures of the right knee showing the indications for single-bundle reconstruction. **A.** Lateral portal view of the tibial insertion site measuring only 14 mm in length. **B.** Medial portal view of the notch width measuring only 10 mm. **C.** In this patient with a narrow notch, when placing the tip of the drill on the femoral AM insertion site to drill the femoral AM tunnel, the drill would damage the articular cartilage of the medial femoral condyle.

**Table 1. Indications for single-bundle reconstruction**

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1</td>
<td>ACL insertion site &lt; 14 mm</td>
</tr>
<tr>
<td>2</td>
<td>Notch width &lt; 12 mm</td>
</tr>
<tr>
<td>3</td>
<td>Open physes</td>
</tr>
<tr>
<td>4</td>
<td>Severe bone bruising</td>
</tr>
<tr>
<td>5</td>
<td>Severe arthritic changes (&gt; grade 3)</td>
</tr>
<tr>
<td>6</td>
<td>Multiple ligamentous injuries</td>
</tr>
</tbody>
</table>

**Single-bundle reconstruction**

The next decision box on the left side of the flowchart asks the surgeon if there are indications to consider single-bundle reconstruction. If so, he has to proceed with the box on the left side. For anatomic single-bundle reconstruction, the femoral and tibial tunnels are placed in the center of the measured femoral and tibial ACL insertion site. The femoral and tibial tunnel location should be matched. The size of the tunnel is determined by the size of the ACL footprint. If the insertion site length is 12 mm, but the width is only 9 mm, it is advised to respect the width and choose 9 mm for the tunnel diameter. This example illustrates that single-bundle reconstruction can cover less of the native ACL footprint than double-bundle reconstruction, and that double-bundle reconstruction may therefore be better at replicating the native ACL anatomy (**Figure 8**).
Figure 8: 3D laser scan image of the femoral insertion site of the right knee in 90° of flexion. The whole medial wall of the lateral femoral condyle is outlined. The orange area represents the PL insertion site and the blue area the AM insertion site. A. Double-bundle reconstruction with a 6 mm PL and 8 mm AM tunnel results in better coverage of the insertion site than a single-bundle reconstruction with a 10 mm tunnel (B) even though it results in exactly the same area. The reason for this is the shape of the ACL insertion site, which is better covered by two smaller parallel tunnels than one bigger tunnel.

Determining tunnel size

If there are no contra-indications for double-bundle reconstruction, the femoral and tibial tunnels should be placed in the center of the femoral and tibial AM and PL bundle insertion sites. Just as in single-bundle reconstruction, the size of the tunnels is determined by the size of the ACL footprint. When the PL footprint is smaller than the AM, this should be respected and a 2 mm bony bridge should always be present between the two bundles. For example, when the insertion site length is 16 mm, the AM bundle width is 8 mm and the PL bundle width is 6 mm, with a bony bridge of 2 mm, the tunnels can be 6 mm for the PL and 8 mm for the AM. The graft size should be equal to the tunnel diameter. When an allograft is used, this is relatively easy, whereas with an autograft the graft diameter limits the possible tunnel size.

What if the insertion sites cannot be visualized?

The right side of the flowchart focuses on the situation when the insertion
sites cannot be visualized. For the tibial insertion site, knowledge of the tibial
plateau anatomy can aid the surgeon. For example, the close relationship of the
tibial ACL footprint with the tibial spine, anterior horn of the lateral meniscus and
the PCL\textsuperscript{25} (Figure 9). For the femoral insertion site, the bony landmarks, i.e. lateral
intercondylar ridge and lateral bifurcate ridge, can be used to determine the
location of the femoral ACL footprint\textsuperscript{18,19}. It is recommended to measure the
insertion site, even when not completely sure of the full extent of it, to help in
deciding to do a single-bundle or a double-bundle reconstruction and in
determining the tunnel size.

\textbf{Figure 9:} Caudal view of the tibial plateau of a right cadaveric specimen. The
ACL insertion site is marked and its relationship with the medial tibial spine and
anterior horn of the lateral meniscus is shown.

Regardless of whether the insertion sites can be visualized or not, the
indications for considering single-bundle reconstruction are the same. The next
decision box on the right side concerns the choice for single- or double-bundle
reconstruction. When single-bundle reconstruction is indicated, the tibial tunnel
should be placed in the tibial footprint, according to the surrounding anatomic
structures. The femoral tunnel should be placed below the lateral intercondylar
ridge. If this bony landmark cannot be identified, the surgeon has to visualize the
whole medial wall of the lateral femoral condyle and place the tunnel in the lower
30-35\% of the notch wall. This applies to the operating position with the knee in
90\degree of flexion (Figure 10). It is important to match the location of the femoral and
tibial tunnels\textsuperscript{24}. When performing double-bundle reconstruction, the tibial tunnels
should be placed in the tibial ACL footprint with the AM tunnel anteromedial and
the PL tunnel posterolateral. The femoral tunnels should be placed below the
lateral intercondylar ridge, with the PL tunnel anterior and the AM tunnel posterior
to the lateral bifurcate ridge. Again, if these bony landmarks cannot be visualized,
visualize the whole medial wall of the lateral intercondylar notch and place the
tunnels in the lower 30-35% of the medial wall of the notch, with the PL tunnel anterior to the AM tunnel.

**Figure 10:** Arthroscopic medial portal view of the whole lateral wall of the femoral intercondylar notch of the right knee. The knee is in 90° of flexion. This figure shows that the femoral ACL insertion site is located in the lower 30-35% of the notch wall.

**Figure 11:** A cadaveric knee is shown with the medial femoral condyle removed to visualize the femoral ACL insertion site. This figure shows how the o’clock position changes when the knee moves from extension (A.) into flexion (B.). From: Application of the Anatomic Double-Bundle Reconstruction Concept to Revision and Augmentation Anterior Cruciate Ligament Surgeries. J Bone Joint Surg Am 2008 90: 2023. Reprinted with permission from The Journal of Bone and Joint Surgery, Inc.
O’clock reference
The flowchart contains a note that advises against the use of the o’clock reference to determine the femoral tunnel position(s). Although the “clock face” reference has been widely accepted in the literature to describe femoral tunnel positioning during ACL reconstruction, it has generated more confusion than clarification in helping surgeons to locate the ACL footprint. It is based on radiographs of the knee in extension, but ACL surgery is typically performed at or near 90° of knee flexion. Therefore, the orientation of the o’clock face is no longer correct as the femoral AM and PL insertion sites move from vertical to horizontal alignment as the knee moves from extension to 90° of flexion. Furthermore, the femoral intercondylar notch is a three-dimensional structure and the o’clock position refers to a two-dimensional structure and disregards the depth of the notch (Figure 11). Perhaps most importantly, the o’clock reference provides a disservice to anatomic reconstruction methods as it provides a generic formula that cannot be applied universally and does not correlate with any specific anatomic landmarks. Therefore, it should play no role in anatomic ACL reconstruction.

Imaging
It is advisable to use intra-operative fluoroscopy or navigation to confirm the positions of the drill guide before drilling the tunnels. The tunnel positions should also be documented arthroscopically with several informative pictures that show the tunnel positions relative to neighboring anatomic structures. Post-operatively, the tunnel positions can be documented by anterior-posterior and lateral X-rays of the knee, allowing for measurement of the tunnel angles. MRI and Computer Tomography (CT) scanning can also be used, preferably with three-dimensional reconstruction (Figure 12), to evaluate the tunnel positions, graft conditions and impingement.

Figure 12: 3D reconstructed CT scan of the right knee showing the ACL tunnel positions after anatomic double-bundle ACL reconstruction. A. Femoral AM and PL tunnel. B. Tibial AM and PL tunnel.
Discussion

Non-anatomic tibial and femoral tunnel placement represents one of the most important causes of ACL graft failure \(^{29}\). If the tibial tunnels are placed too anteriorly, this may lead to roof impingement, which is associated with loss of extension and abrasion of the graft \(^{30}\). To prevent this, some surgeons move the tibial tunnel more posteriorly. However, this approach creates tunnel mismatch \(^{31}\). A tibial tunnel positioned at the PL insertion site is often combined with an AM or a high AM femoral tunnel. Tunnel mismatch is common if the femoral AM tunnel is drilled in a transtibial fashion. It results in tunnel placement outside of the native insertion site, which may cause abnormal knee kinematics \(^{32}\). Various studies have demonstrated that non-anatomic tunnel placement creates limited range of motion, higher than physiologic graft tension, and ultimately graft failure \(^{33,34}\). Biological healing of the graft-bone interface may also be affected \(^{22}\).

Furthermore, it is the suboptimal outcomes of traditional transtibial single-bundle ACL reconstruction that have been the motivation for exploring the possibilities of double-bundle reconstruction. Indeed recent studies have already shown the benefits of adding a PL bundle \(^{4,8,11,35}\), but we also prefer double-bundle reconstruction because the normal anatomy of the ACL should be restored (Figure 13). However, by the same anatomic reconstruction principle, single-bundle reconstruction can also be performed in anatomic fashion \(^{33}\) when indications for this are present. Most of the published clinical studies comparing single-bundle to double-bundle reconstruction do not present a fair comparison, since in may cases one or both surgical procedures were not performed anatomically \(^{5,8,11}\). For example, a transtibial single-bundle and an anatomic double-bundle were compared \(^{5}\). In addition, associated injuries such as cartilage defects and meniscus tears should be considered as exclusion criteria. The research should focus on isolated ACL injuries. Randomizing patients for a trial comparing anatomic single-bundle to anatomic double-bundle reconstruction is difficult because the patient's individual anatomy should determine the type of procedure. Furthermore, the lack of readily available, reliable, and valid clinical outcome measures makes it difficult to compare different anterior cruciate ligament reconstruction techniques. Various authors use different outcome measures, and in the office setting it is difficult to quantify differences in rotational stability in absolute terms \(^{36}\).

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The use of more accurate and standardized outcome measures will demonstrate the benefits of anatomic anterior cruciate ligament reconstruction with regard to the restoration of the normal structure and function of the knee. For example, currently important outcome measures, such as range of motion, are underreported\textsuperscript{37}, even though it gives important clues to the accuracy of tunnel placement and the presence of impingement.

The flowchart presented in this thesis incorporates the fundamental principles that should be taken into account when performing anatomic ACL reconstruction: respecting the anatomy, replicating the native ACL insertion site to restore normal knee kinematics and individualizing ACL surgery for each patient (Table 2).

| Table 2. Pearls and tips for anatomic anterior cruciate ligament reconstruction |
|---------------------------------|---------------------------------------------------------------|
| Pearls                          | Accompanying tips                                           |
| Respect the individual          | Visualize the soft tissue remnants of the ACL, and follow the |
| anatomy of the patient          | remnants to determine the native femoral and tibial ACL      |
|                                 | insertion sites.                                            |
|                                 | Use an accessory medial portal so that the anteromedial      |
|                                 | portal can be used to optimally view the femoral ACL         |
|                                 | insertion site.                                             |
|                                 | Visualize other surrounding anatomic structures that display  |
|                                 | a close relationship with the ACL: the femoral intercondylar|
|                                 | notch, femoral bony ridges, PCL, menisci and tibial spine.   |
| Replicate the native ACL        | Measure the insertion site size as well as the notch size.   |
| insertion site                  | Use the insertion site location and size to determine the    |
|                                 | tunnel positions and sizes.                                 |

Figure 13: Anatomic ACL reconstruction restores the native ACL anatomy. A. Arthroscopic medial portal view of the native ACL of the right knee. B. Arthroscopic medial portal view of an ACL graft of the right knee three years after anatomic double-bundle ACL reconstruction.
Individualize the surgery for each patient

Consider switching from double-bundle to single-bundle reconstruction if indications for this are present. Document the tunnel positions with arthroscopic images, intraoperative fluoroscopy or navigation and post-operative X-ray, MRI or CT.

**Conclusions**

Anatomic ACL reconstruction intends to replicate normal anatomy, restore normal kinematics and advance long-term knee health. This type of anatomic ACL reconstruction is a complex and detailed surgical procedure that has many pitfalls. Therefore, a flowchart has been developed that can help orthopedic surgeons in performing anatomic ACL reconstruction. It serves as a guideline that gives a systematic approach to each case: first, the normal anatomy and injury pattern are identified, then ACL reconstruction is tailored to closely replicate the native anatomy of the patient. The flowchart is applicable to both single- and double-bundle reconstruction and even to revision and augmentation surgery and is accompanied by informative tables, pictures, video’s and valuable literature.

Although there is still much to be learned about anatomic ACL reconstruction methods, we believe that our flowchart is already a helpful instrument for surgeons. We will continue to update and modify the flowchart as more information about the anatomy of the ACL and about how to more closely replicate it becomes available.

**References**


**Appendix 1:** Anatomic Single- and Double-Bundle ACL Reconstruction Flowchart. The objective of anatomic single- or double-bundle reconstruction is to restore 80-90% of the native ACL anatomy in a matched fashion. This flowchart was created by Carola F. van Eck, MD, Bryson P. Lesniak, MD and Freddie H. Fu, MD, University of Pittsburgh.
Anatomic Single- and Double-Bundle ACL Reconstruction Flowchart

1. **Patients with ACL injury**
   - **Pre-op**
     - History to assess injury mechanism, physical examination to assess knee integrity
   - **Radiograph to evaluate bone morphology and pathology; high-quality MRI to evaluate ACL rupture pattern**
   - **Surgery**
     - Repeat physical examination (under anesthesia)
   - **Visualize and probe femoral (2) and tibial remnants of native ACL, and determine rupture pattern. Note anterior联合ridges offer superior view of femoral remnants (3)**
   - **Individualize the surgery for each patient. Follow remnants of native ACL to identify isometric femoral insertion site. Are insertion sites visible?**

2. **Mark isometric insertion site and measure it to determine tunnel size.**
   - **Mark isometric insertion site using biplanar anesthesia. Anatomically, relationship of biplanar, anterior horn lateral transverse and PCL with ACL (4) and measure to determine tunnel size.**
   - **If the isometric condylar ridge is visible (5), use it to mark femoral insertion site and measure isometric insertion site to determine tunnel size.**

3. **Is femoral insertion site smaller than 14 mm in length or does patient have a narrow notch? (8)**
   - **Yes**
     - **Mark isometric insertion site smaller than 14 mm in length or does patient have a narrow notch? (9)**
     - **Yes**
       - **Consider anatomic double-bundle reconstruction.**
       - **Consider using intra-operative fluoroscopy or navigation to confirm drill guide positions.**
       - **Document tunnel positions arthroscopically.**
     - **No**
       - **Consider anatomic single-bundle reconstruction.**
       - **Place femoral and tibial tunnels in a matched fashion (9).**
   - **No**
     - **Consider anatomic double-bundle reconstruction.**
     - **Place isometric tunnels in center of ACL insertion site and femoral tunnel below remnants ridge, if no remnants ridge is visible in lower 30-35% of lateral notch wall (knee 90° flexion) and in a matched fashion (9).**
     - **Place isometric tunnels in center of isometric insertion site with AM tunnel anterolateral and PL tunnel posterolateral, and place femoral tunnels below remnants ridge with the AM tunnel posterior and the PL tunnel anterior to the lateral biplanar ridge, or if remnants not visible, place femoral tunnels in use of 30-35% of lateral notch wall (knee 90° flexion).**

4. **References:**