Gross, Arthroscopic, and Radiographic Anatomies of the Anterior Cruciate Ligament

Foundations for Anterior Cruciate Ligament Surgery

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KEYWORDS

• Anterior cruciate ligament • Anatomy • Double bundle • Arthroscopy • Embryology

KEY POINTS

- The understanding of the double bundle anatomy of the anterior cruciate ligament (ACL) is the key to performing an individualized anatomic ACL reconstruction.
- The arthroscopic view during ACL reconstruction grants a 10 times magnification that allows excellent anatomic landmarks identification.
- Respecting the variation of ACL anatomy makes every case technically unique and ensures that optimum treatment is tailored to all patients.

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is one of the most common orthopedic procedures, with more than 130,000 ACLRs performed annually in the United States alone.[1] The objective of ACLR is to reestablish knee function and prevent future meniscal and chondral damage, which can lead to secondary degenerative changes in the knee joint.[2–4] Approaches to ACLR surgery are governed by the principle of restoring native anatomy, which in turn may better replicate normal knee function.

Anatomic ACLR is based on the following 4 fundamental principles: (1) restore the anteromedial (AM) and posterolateral (PL) bundles, the 2 functional anterior cruciate ligament (ACL) bundles; (2) restore native ACL insertion sites by aligning the tunnels in proper anatomic positions; (3) correctly tension each bundle; and (4) adapt ACLR to each patient, thus ensuring that tunnel diameter and graft size are dictated by the characteristics of their native insertion sites.[5] The concept of anatomic ACLR

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Clin Sports Med 36 (2017) 9–23
http://dx.doi.org/10.1016/j.csm.2016.08.002 sportsmed.theclinics.com
0278-5919/17/

has received considerable attention because the biomechanical and clinical results of this approach have been correlated with better outcomes than nonanatomic ACLR.[6–13] Because of the importance of understanding the detailed anatomy of the ACL in order to perform anatomic ACLR, this article aims to clarify the microscopic and macroscopic anatomy of this ligament.

HISTORY OF ANTERIOR CRUCIATE LIGAMENT ANATOMY

The earliest known description of the human ACL was recorded around 3000 BC on an Egyptian papyrus scroll. During the Roman era, Claudius Galen (199–129 BC) described the knee ligaments, terming the ACL the "ligamenta genu cruciate."[14] In 1543, Andreas Vesalius completed the first known formal anatomic study of the human ACL in his book *De Humani Corporis Fabrica Libris Septum*.

For about 400 years, the ACL was thought of a single homogenous structure. Two bundles of the ACL were described for the first time in 1836 by Weber and Weber.[15] Despite other subsequent descriptions of the two-bundle anatomy by Palmer,[16] Abbott and colleagues,[17] and Girgis and colleagues,[18] the discovery did not become well known for many decades. These first reports characterized the ACL bundles based on their relative tibial insertion sites, with the resulting AM and PL bundle nomenclature still in use today. Although it is now widely accepted that the ACL is composed of 2 bundles,[19] there is a considerable amount of variation regarding the relative sizes of the AM and PL bundles depending on the type of study (ie, fetal, arthroscopic, or cadaveric).

More recently, Norwood and Cross[20] and Amis and Dawkins[21] described a third ACL bundle termed the intermediate bundle. Because the anatomic and biomechanical properties of the intermediate bundle are most similar to the AM bundle, the intermediate bundle is commonly considered part of the AM bundle.

EMBRYONIC ANTERIOR CRUCIATE LIGAMENT ANATOMY

The ACL begins to appear in the fetus as early as week 8 of the gestation period.[22–26] The ACL likely originates in the embryo as a ventral condensation of the fetal blastoma that then migrates posteriorly with the development of the intercondylar space.[27] Similarly, knee menisci may originate from the same process as the ACL, which would give further support to the idea that these structures function interdependently with one another. Another proposed method for fetal ACL formation is a confluence between ligamentous collagen fibers and periosteum fibers.[28] Following initial ligament formation, no major organizational or compositional changes occur throughout the remainder of fetal development.[22]

The AM and PL bundles of the ACL begin to become apparent by week 16 of gestation.[22,24–26,29] The fetal ACL is similar to the adult ligament, but differs in that the bundles are more parallel in orientation and the femoral origins are broader in size.[30] Histologically, the fetal ACL demonstrates a higher amount of cellularity and vascularity.[29] The 2 bundles in the fetal ACL are separated by a membranous septum, similar to the adult ligament[29] (**Fig. 1**).

MICROSCOPIC ANATOMY AND HISTOLOGY OF THE ANTERIOR CRUCIATE LIGAMENT

The ACL is an intra-articular, extrasynovial structure enveloped by 2 synovial layers.[14,19,31,32] This ligament is composed of numerous dense connective tissue fascicles predominantly composed of type I collagen and, secondarily, of type III collagen.[14,33,34] As stated earlier, a septum of connective tissue–containing vascular-derived stem cells separates the AM and PL bundles.[35] This membrane contains

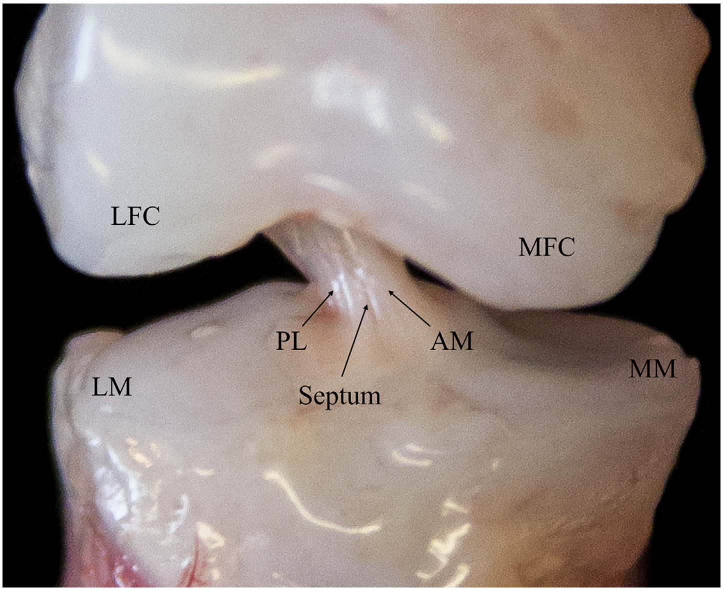

Fig. 1. Sixteen weeks of gestational age fetus knee showing the ACL bundle anatomy. LFC, lateral femoral condyle; LM, lateral meniscus; MFC, medial femoral condyle; MM, medial meniscus.

periligamentous vessels that transversely penetrate the ligament and anastomose with a longitudinal network of endoligamentous vessels that vascularize the ACL[36] (**Fig. 2**).

The ACL insertion site is divided into a 4-layered structure with mixed histology, where chondrocyte-like cells are integrated with typical-appearing tenocytes.[14,19,32,33] These layers include ligamentous, fibrocartilaginous, and mineralized fibrocartilage, in addition to a subchondral bone plate.[37] The gradual transition of the layers acts to dissipate force transmitted through the ACL, thereby preventing excessive stress to act at the insertion sites.[14,31,33,37]

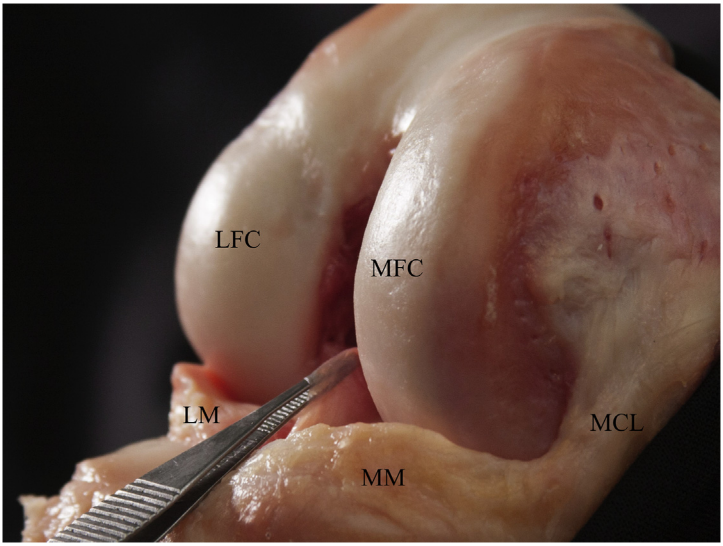

Fig. 2. ACL synovial membrane. MCL, medial collateral ligament.

MACROSCOPIC ANATOMY OF THE ANTERIOR CRUCIATE LIGAMENT

The ACL originates on the medial surface of the lateral femoral condyle and runs an oblique course within the knee joint, going from a lateral and posterior to a medial and anterior position before inserting into a broad area of the central tibial plateau (**Fig. 3**). The average total intra-articular length of the ligament is approximately 32 mm (range 22–41 mm), a length that may vary depending on the position of the knee.[14,21,37] ACL length is shortest at 90° of flexion and can increase by 18.8 $\pm$ 10.1% during unloaded extension.[38] Application of an anterior or combined rotational load can increase ACL length during extension by almost 5%.[38]

Cross-sectional areas of the ligament vary over the length of the ACL, with a midsubstance cross-section measuring approximately 44 mm^2, whereas the origin and insertion sites of the ACL can be more than 3 times this area.[18,39] Considering that the geometry of soft tissue structures, such as the ACL, is largely dictated by loading and orientation, the precise cross-sectional area of the midsubstance is debatable.[39–44] Quantitative in situ analysis of ACL measurements by Fujimaki and colleagues[38] found the ACL cross-section at the isthmus to be the smallest in extension (39.9 $\pm$ 13.7 mm^2), although this increased with flexion of the knee (43.9 $\pm$ 12.1 mm^2 at 90°).

As the ligament inserts along both the femoral condyle and the tibial plateau, the ends of the ligament fan out in a manner that reproduces an hour-glass shape. Notably, this anatomic phenomenon causes the isthmus to be less than half the area of the insertion sites,[38] a fact that must be recognized during reconstruction because ligamentous cross-sectional area may directly play a role in the absorption of kinematic forces in the knee joint.[14,38,39]

Anatomy of Anterior Cruciate Ligament Bundles

The ACL comprises the AM and PL bundles, so termed based on the relative insertion sites on the tibia (**Fig. 4**). Both bundles can be observed arthroscopically, particularly with the knee held in 90° to 120° of flexion. Anatomic studies have characterized the

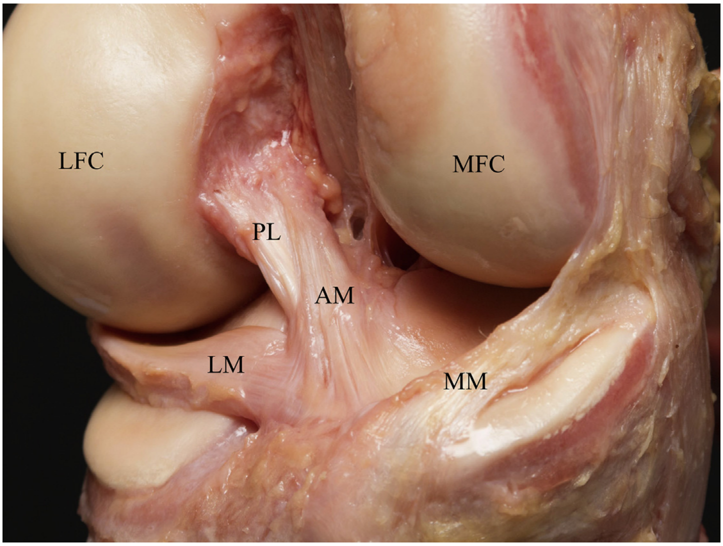

Fig. 3. ACL macroscopic anatomy.

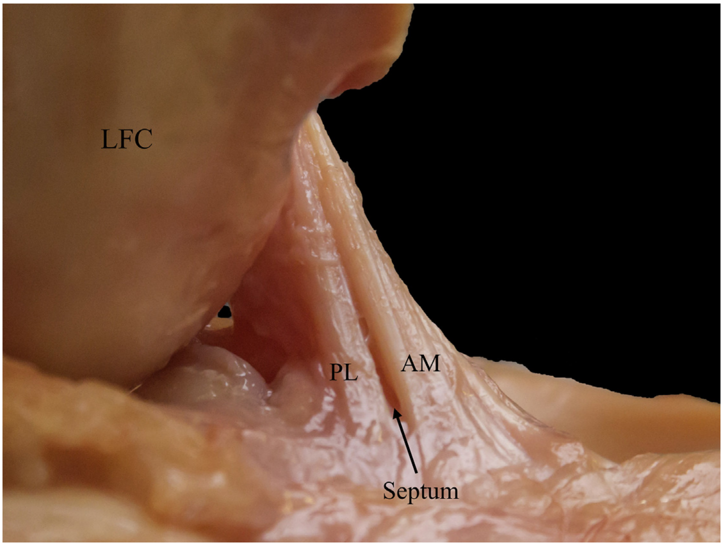

Fig. 4. ACL AM and PL bundles separated by the septum.

individual properties of the AM and PL bundles. In particular, the AM bundle is approximately 38 mm in length,[18,37] whereas the PL bundle is approximately 17.8 mm in length.[45] Despite these differences, the AM and PL bundles have similar cross-sectional diameters.[18,37,39,45,46]

Anatomy of Anterior Cruciate Ligament Insertions

The femoral origin of the ACL is an ovoid area averaging 18 mm in length and 11 mm in width.[47] Within this area, the AM bundle is located on the proximal portion of the medial wall of the lateral femoral condyle, whereas the PL bundle occupies a more distal position near the anterior articular cartilage surface of the lateral femoral condyle (**Fig. 5**). Two bony ridges define the femoral attachment site: the lateral intercondylar ridge and the lateral bifurcate ridge. The lateral intercondylar ridge, also called the resident's ridge, is an important landmark to recognize during ACLR as the native ACL always inserts inferior to this ridge.[48,49] The equally important lateral bifurcate ridge runs perpendicular to the lateral intercondylar ridge and separates the AM and PL bundles.[48]

Harner and colleagues[39] studied the origin and insertion of the AM and PL bundles using a laser micrometer system and concluded that each bundle occupies approximately 50% of the total femoral origin, with cross-sectional footprints measuring 47 ± 13 mm^2 and 49 ± 13 mm^2 for the AM and PL bundles, respectively. Mochizuki and colleagues[50] contradicted these results, observing that the AM bundle origin was 1.5 times larger than the origin of the PL bundle, although a less sensitive methodology was used to make these measurements.

On the tibia, the AM and PL bundle insertions are localized over a broad area between the medial and lateral tibial spines. Within this area, the AM bundle insertion occupies an anterior and medial position, whereas the PL bundle insertion is located more posteriorly and laterally (**Fig. 6**). The ACL tibial insertion has an average anteroposterior length of 11 mm (range 9–13 mm) and an average medial-lateral width of 17 mm (range 14–20 mm). The overall size of the tibial insertion is approximately 120% of the femoral origin. However, as is the case with the femoral origin, the

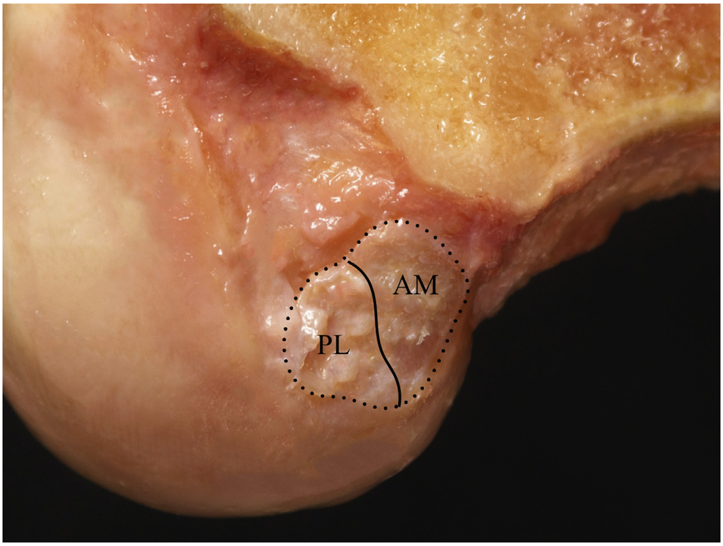

Fig. 5. Femoral insertion site.

2 bundles share approximately equal tibial insertion site areas, where the AM bundle occupies 56 $\pm$ 21 mm^2, and the PL bundle occupies 53 $\pm$ 21 mm^2.[39] However, not only does size vary among individuals but also the footprint shape differs as well, which may alter the average cross-sectional area calculated over the tibia.[18,32,33,47,51–53]

Both bundles have a close anatomic relation with the lateral meniscus. Posteriorly, fibers of the PL bundle are in close proximity to the posterior root of the lateral meniscus. In some individuals, the bundle may attach to the meniscus itself (**Fig. 7**).

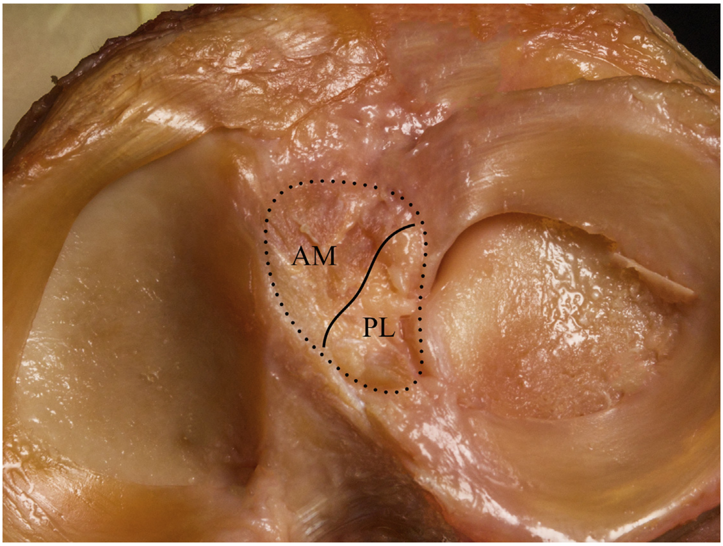

Fig. 6. Tibial insertion site.

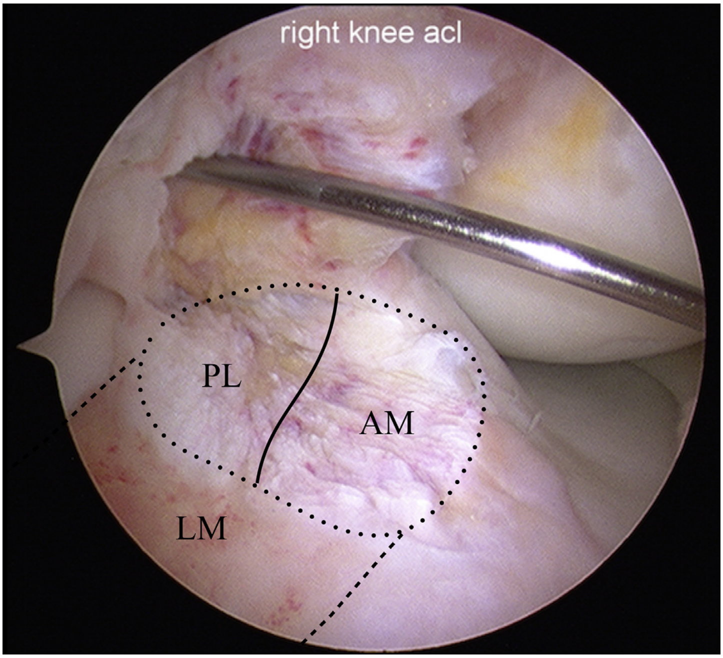

Fig. 7. Arthoscopic view of the anterior horn of the lateral meniscus relation with the ACL tibial insertion site.

Similarly, the AM bundle may have attachments to the anterior horn of the lateral meniscus. Quantitative analysis of the ACL insertion site shows that ACL intrusion onto the anterolateral meniscal root can reach 63.2% of the root attachment.[54]

Many different anatomic landmarks can be used to arthroscopically identify the tibial insertion site. The most commonly described landmarks are the anterior horn of the lateral meniscus and anterior edge of the posterior cruciate ligament. However, these are soft tissue structures that may have a varying anatomic relation with the ACL.[55] Other landmarks to take into account are the medial and lateral tibial eminences.[12,50,56] The ACL center is positioned 5.7 $\pm$ 1.1 mm anterior to a projected line from the apex of the medial tibial eminence.[55] Therefore, the tibial insertion site of the ACL may be reliably identified based on the location of the medial tibial eminence.[55]

The shape of the tibial insertion site is a topic of debate. Indeed, a recent study showed that the shape of the tibial insertion site varies when inspected after transection arthroscopically. More specifically, in 51% of cases, the shape is elliptical; in 33%, it is triangular, and in 16%, it is C-shaped.[57]

Anterior Cruciate Ligament Neurovascular Anatomy

Proximally, the ACL receives its blood supply from the middle genicular artery, which feeds a synovial plexus around the ligament.[33] Distally, the medial and lateral inferior genicular arteries supply the plexus, although to a lesser degree.[31,33,58] Furthermore, watershed areas exist around the insertion sites and along the anterior aspect of the distal third of the ligament, as supported by immunohistochemical analysis.[33,58]

Approximately 1% of the area of the ACL consists of neural tissue supplied by branches of the tibial nerve.[31] This neural tissue serves many functions within the

ACL. For example, perivascular neural elements surround the vascular plexus and assist in vasomotor control, whereas other nerve fibers transmit slow pain impulses.[59] Surrounding the synovium are slow- and rapid-adapting mechanoreceptors. The slow-adapting mechanoreceptors relay information about motion, position, and joint rotation, and the rapid-adapting mechanoreceptors detect tension changes within the ligament.[60,61] After ACL rupture, residual mechanoreceptors within the torn stumps may still function in proprioception.[62,63] However, the extent of residual function if this stump is preserved requires further research to determine its significance.

Anterior Cruciate Ligament Functional Anatomy

The AM and PL bundles change their alignment in respect to each other as the knee moves from extension to flexion. The femoral insertion sites are vertically oriented when the knee is fully extended, and, consequently, the 2 ACL bundles are oriented in parallel. As the knee moves to 90° of flexion, the AM bundle insertion site on the femur rotates posteriorly and inferiorly, in contrast to the femoral insertion of the PL bundle, which rotates anteriorly and superiorly. These modifications orient the femoral footprints more horizontally, causing the 2 bundles to twist around each other and become crossed. When the knee is flexed, the femoral insertion of the PL bundle is anterior to the AM bundle. This crossing pattern and the different lengths of each bundle have implications for the tensioning pattern of the overall ligament and each individual bundle.

In a study by Gabriel and colleagues,[64] forces were measured in each bundle while exerting an anterior tibial load of 134 N over several flexion angles. Force was also measured under a combined rotatory load over 10 Nm of valgus and 5 Nm of internal tibial torque. These assessments showed that the PL bundle is tightest in extension (in situ force of 67 $\pm$ 30 N) and becomes relaxed as the knee is flexed. When flexed and not stretched, the PL bundle shortens by 1.5 to 7.1 mm.[65,66] The PL bundle also tightens during internal and external rotation by $\approx$2.7 mm.[67] Conversely, the AM bundle is more relaxed in extension and reaches maximum tension as the knee approaches 60° of flexion (in situ force of 90 $\pm$ 17 N).[21,64] Compared with extension, at 90° of flexion, the AM bundle stretches by about 3.3 mm.[65,66,68,69]

Knee Bony Anatomy Related to the Anterior Cruciate Ligament

Just as ACL size varies among individuals, so does the bony anatomy, although the relationship of ACL size and intercondylar width may not hold a direct relationship. As such, patients can have a relatively large ACL within a very small intercondylar space. A small notch-width index, or the ratio of the notch width to epicondylar width, is linked to an increased likelihood of ACL rupture.[70,71]

Anterior Cruciate Ligament Radiographic Anatomy

To evaluate ACL anatomy, MRI is the most reliable imaging technique. MRIs can visualize the 2 bundles in the sagittal plane and in parallel orientation with the knee extended, in addition to showing the PL bundle in the coronal plane. The double-bundle structure can be more easily appreciated with higher resolution images, such as those obtained at a magnet strength of 1.5 T (**Fig. 8**).

Traditionally, ACL tunnel locations in preparation for reconstruction have been determined from plain radiographs, with several methods existing for the intraoperative radiographic evaluation of the tunnels.[72–77] Nevertheless, this technique provides a 2-dimensional projection of 3-dimensional bone geometry. Therefore, this method is not fully reliable because femoral rotation can influence the measured size of the

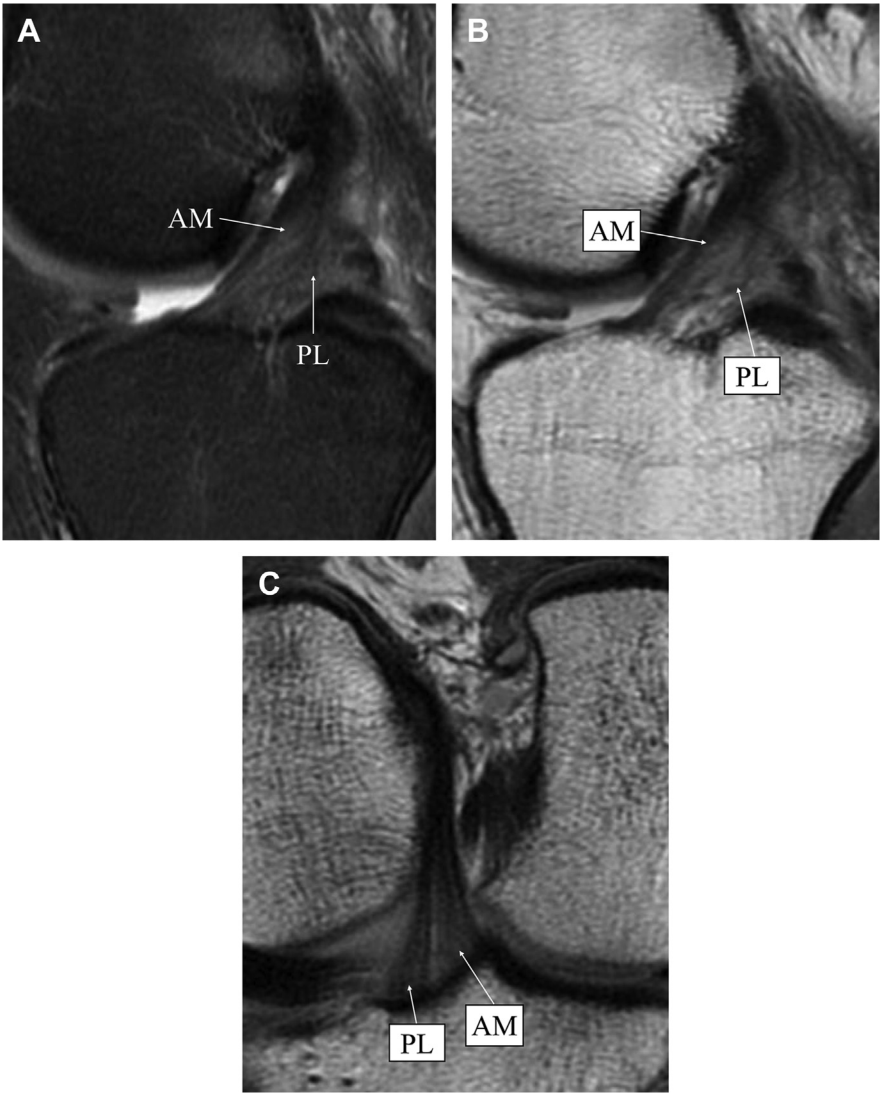

Fig. 8. ACL MRI showing both bundles. (*A*) T2 Sagittal. (*B*) T1 Sagittal. (*C*) T1 double oblique.

condyles, leading to inaccurate results.[78,79] Consequently, bony and soft tissue anatomic landmarks should be used to determine tunnel positions during ACLR.

Currently, 3-dimensional computed tomography (CT) reconstruction is the standard for postoperative tunnel position evaluation. There are 2 main methods to measure the femoral tunnel positions (ie, sagittal cut) and one method for measuring tibial tunnel positions (ie, axial cut). On the femoral side, the quadrant method references the Blumensaat line, which is understood as the most anterior (ie, superior) aspect of the notch (**Fig. 9**). The anatomic coordinate axes method is based on a report by Watanabe and colleagues,[80] who described tunnel position relative to the border between the medial wall and articular surface of the lateral condyle.

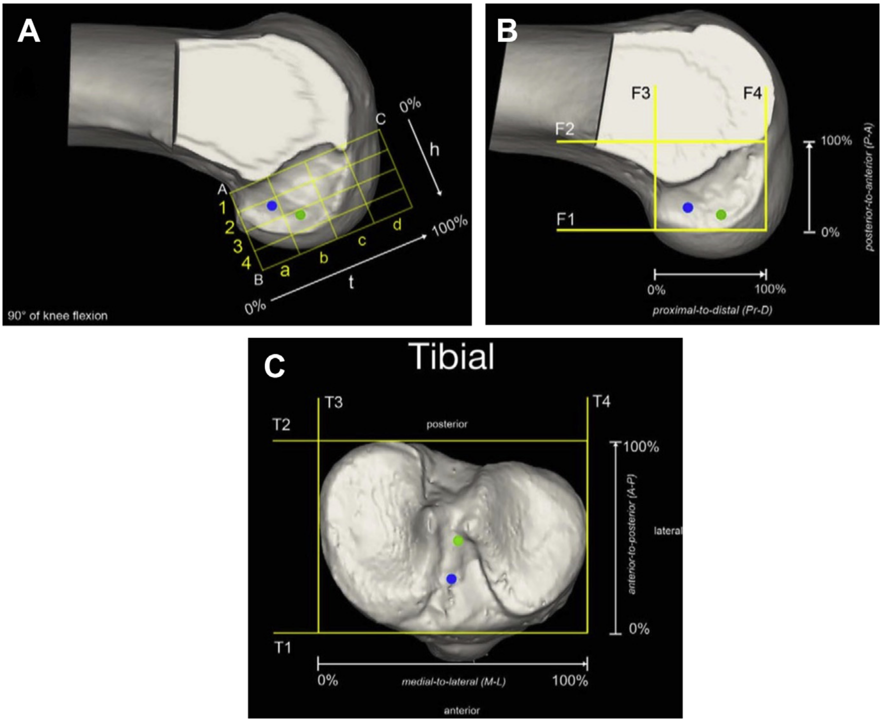

Fig. 9. Three-dimensional CT evaluation of the femoral and tibial tunnel location. Anatomic AM tunnel position: (*blue*); anatomic PL tunnel position: (*green*). (*A*) Quadrant method (for femoral side): the locations of the femoral tunnels are established within a 4 × 4 grid, which is oriented along the most anterior edge of the notch roof, parallel (t) and perpendicular (h) to the Blumensaat line. (*B*, *C*) Anatomic coordinate axes method (for the femoral and tibial sides): the locations of the tunnels are determined in the axial and sagittal planes, aligned with the respective bone anatomic axes. Lines: F1—posterior border of the medial wall of the lateral condyle; F2—most anterior point of the notch; F3—proximal border of the notch; F4—distal point of the notch roof; T1—anterior border of the tibial plateau; T2—most posterior border of the tibial plateau; T3—medial border of the tibial plateau; T4—lateral border of the tibial plateau. Axes: Femoral side—posterior-to-anterior (P-A) = F1 to F2; proximal-to-distal (Pr-D) = F3 to F4. Tibial side: anterior-to-posterior (AP) = T1 to T2; medial-to-lateral (ML) = T3 to T4. (*Adapted from* 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;92:1418–26; and Kopf S, Forsythe B, Wong AK, et al. Nonanatomic tunnel position in traditional transtibial single-bundle anterior cruciate ligament reconstruction evaluated by three-dimensional computed tomography. J Bone Joint Surg Am 2010;92:1427–31.)

SUMMARY

Detailed knowledge of ACL anatomy is essential for achieving anatomic surgical reconstruction, which is based on the native anatomy of this ligamentous structure. The anatomy of the ACL is complex because this ligament does not have a cylindrical, but rather hourglass shape, with different dimensions in regards to femoral insertion, tibial insertion, and the isthmus. Furthermore, the dimensions and shape of the midsubstance depend on the degree of knee flexion.

Soft and bony anatomic references of the knee are critical for proper positioning of the femoral and tibial tunnels during ACLR. Among the radiological tools available for assessing the ACL, preoperative MRI and postoperative CT are reliable tests for evaluating the anatomy and tunnel positioning of this ligament, respectively.

The goal of understanding ACL anatomy during ACLR is to restore the patient's knee kinematics, thereby improving function, conferring stability to the knee, and decreasing long-term degenerative changes. Although the current body of knowledge regarding the ACL is extensive, it remains incomplete. Further research will provide a better understanding of rotational stability and knee kinematics in those with an intact and reconstructed ACL.

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