Anatomy of the anterior cruciate ligament and the common autograft specimens for anterior cruciate ligament reconstruction

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Abstract: A thorough understanding of the anatomical properties of the native anterior cruciate ligament (ACL), as well as the native specimens that are most commonly considered as viable autograft choices for anterior cruciate ligament reconstruction (ACLR), is warranted for continuing to pursue the best-possible graft choice for patients undergoing ACLR. While a wide variety of graft choices remain available to the operating surgeon, choosing the correct graft choice remains a consideration and discussion with patients on the pros and cons of each option. This article combines a review of the current literature on the quantitative and qualitative anatomy of the native ACL and common autograft specimens with the expert consensus of the senior author on the surgically-pertinent anatomy of these structures. The purpose of this article is to review the anatomy pertaining to the native ACL, along with the distal anatomy of the hamstring tendons, patellar tendon and quadriceps tendon (QT). Multiple tendinous and ligamentous structures exist around the knee that serve as viable candidates for use as autologous grafts for ACLR, and the anatomy of these distal extents of these structures are discussed thoroughly, including bony attachments, quantitative and relational anatomy, cross sectional area, and histological features of these structures.

Keywords: Anatomy; anterior cruciate ligament (ACL); ACL reconstruction; grafts

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Introduction

The ligamentous structures of the knee work in concert with the surrounding musculature that traverses the tibiofemoral articulation to counter translational and rotational forces on the knee. Among these, the chief stabilizer of the knee against anterior tibial gliding on the femur is the anterior cruciate ligament (ACL) (1). Tears or avulsions of the ACL are very common injuries, affecting thousands of individuals across the United States every year (2,3). Loss of ACL integrity results in significant functional,

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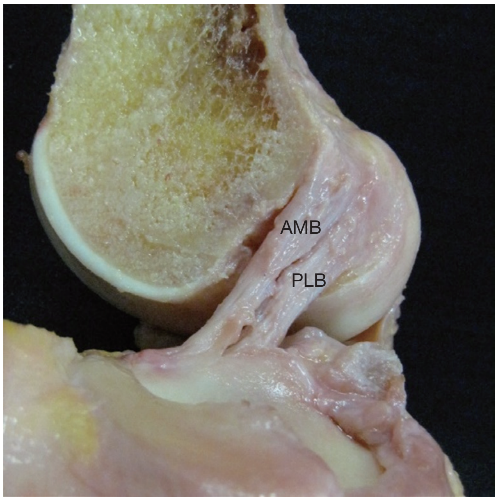

Figure 1 A photo depicting the course of the two bundles of the anterior cruciate ligament. AMB, anteromedial bundle; PLB, posterolateral bundle.

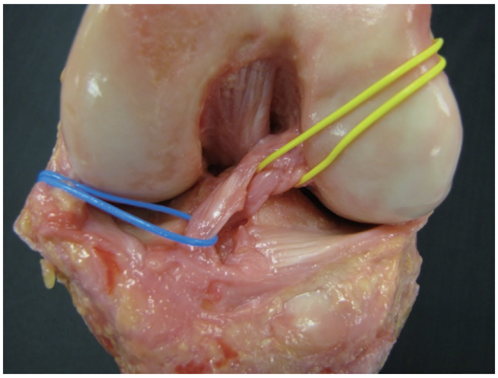

Figure 2 A photo depicting the two bundles of the ACL with a blue vessiloop wrapped around anteromedial bundle and a yellow vessiloop around the posterolateral bundle. ACL, anterior cruciate ligament.

osteochondral, and meniscal morbidity, and therefore, treatment is often pursued, especially in active patient populations (4,5). The standard of care for ACL injury continues to be surgical reconstruction (anterior cruciate ligament reconstruction, ACLR) (6). While ACLR has been shown to robustly restore function and provide patients with high rates of good to excellent surgical outcomes, it is well-documented that rates of graft failure are higher in younger and more active populations (7).

A thorough understanding of the anatomical properties of the native ACL, as well as the native specimens that are most commonly considered as viable autograft choices for ACLR, is warranted for continuing to pursue the best-possible graft choice for patients undergoing ACLR. While a wide variety of graft choices remain available to the operating surgeon, choosing the correct graft choice remains a consideration and discussion with patients on the pros and cons of each option. The purpose of this article is to review the anatomy pertaining to the native ACL, along with the distal anatomy of the hamstring tendons, patellar tendon, and quadriceps tendon (QT).

Anatomy of the native ACL

Qualitative anatomy

From the distal femur to the tibial plateau, the ACL takes an inferomedial course as it passes anterior to the posterior cruciate ligament (PCL) through the center of the tibiofemoral articulation (*Figure 1*). At either bony attachment, the collagen fibers of the ACL can be distinguished histologically into "superficial" and "deep" fibers based on their insertion, the former inserting into the periosteum and the latter inserting directly into the bone (1). The fibers of the proximal insertion of the ACL can be further subclassified as falling into either the "direct" or "indirect" attachment type based on the microstructure of their constituent collagen fibers (8). Although there once existed some debate about the sub-organization of the native ACL into one or more bundles, thanks to a number of histological and biomechanical studies, there now exists wide consensus for the assertion that the ACL is composed of two distinct macro-bundles, named based on their attachments to the tibia: the posterolateral (PL) and anteromedial (AM) bundles (*Figures 2,3*) (4,6,9,10). With the knee in full extension, the PL bundle inserts posteriorly to the AM bundle near the bifurcate ridge; however, the degree of overlap of the proximal insertions of the two bundles is currently subject to some debate (11).

The tibial insertion of the ACL is intimately associated with the anterolateral meniscal root, which inserts deep to the native ACL (10-12). Studies by LaPrade *et al.* reported the insertional overlap between the ACL and the anterolateral meniscal root (12,13). There is a higher degree of insertional overlap in the sagittal plane compared to the coronal plane (*Figure 4*) (14). The insertional footprint of the tibial attachment of the ACL has been noted to take on several different morphologies in the general population: most commonly, it takes on an elliptical (51%) shape,

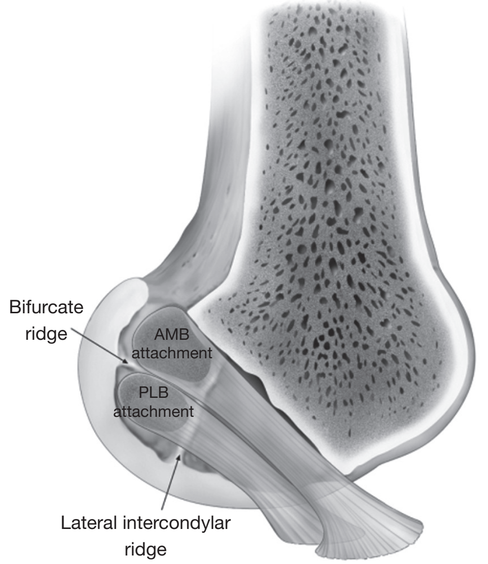

Figure 3 An illustration depicting the femoral origin of the individual bundles of the anterior cruciate ligament. AMB, anteromedial bundle; PLB, posterolateral bundle.

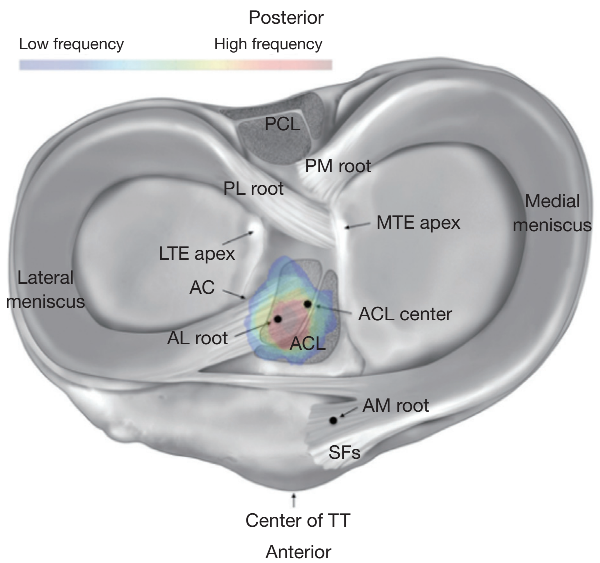

Figure 4 An illustration showing the insertional overlap of the bundles of the ACL with the anterior root of the lateral meniscus. Referring to the menisci and their roots. PCL, posterior cruciate ligament; PL, posterolateral; PM, posteromedial; LTE, lateral tibial eminence; MTE, medial tibial eminence; AC, articular cartilage; AL, anterolateral; ACL, anterior cruciate ligament; AM, anteromedial; SFs, shiny white fibers; TT, tibial tubercle.

followed next in frequency by triangular (33%) shape, and most infrequently, it has been found to take on a C-shape (16%) (11).

The microstructure of the ACL has been thoroughly analyzed through the use of electron microscopy. According to a review by Marieswaran *et al.*, such studies have revealed a hierarchical, fascicular arrangement of collagen into fibrils and fascicles, similar to other ligaments around the body (1). These bundles have been reported to be "crimped" at specific points along their length in a consistent, repetitive fashion which has been previously described as sinusoidal in nature (1). The constituent collagen bundles are further organized into two histologically distinct fiber types which are distinguished based on the uniformity of their diameter (11). Those with a uniform diameter (43.7% of ACL tissue) of approximately 45 mm specialize in countering sheer forces (11). Those with a nonuniform diameter (50.3% of ACL tissue) measure 25 to 85 mm in diameter and specialize in countering tensile forces (11). The remaining tissue largely consists of elastic tissue and associated fibroblasts (11).

Neurovascular supply to the native ACL

The vascular supply to the ACL is carried forth mainly by the middle genicular artery (MGA) (6,9,10). The MGA originates from the popliteal artery at around the proximal femoral condyles, just distal to the origin of the superior genicular artery, and just proximal to the sural artery (6).

It is widely understood that the native ACL possesses some degree of nervous innervation, which has been thought to lend the native ligament proprioceptive function (6,9,10). Innervation of the ACL is supplied mainly by the tibial nerve, which carries afferent fibers from the mechanoreceptors situated along the ligament (9). These mechanoreceptors come in the form of Ruffini receptors for sensing tensile forces along the ligament, as well as Vater-Pacini receptors which are concentrated in the proximal and distal components of the ligament and respond to sudden movements (6). Also located near the proximal and distal ends of the ACL are Golgi-like receptors for sensing tension closer to the attachment sites of the ligament (6). These nervous receptors are thought to work in concert to provide some inherent proprioceptive capability to the native ACL (6,10).

Table 1 Anatomical characteristics of ACLR graft candidates. Measurements are based on reported averages

Native tissue	Length	Width	CSA
Patellar tendon (4)	43–53 mm	25–30 mm	33–61 mm^2
Hamstring tendon (18)	240–280 mm	8–11 mm	52–64 mm^2
Quadriceps tendon (19)	68–98 mm	25–30 mm	71–91 mm^2

ACLR, anterior cruciate ligament reconstruction; CSA, cross-sectional area.

Along with these nerve receptors, free-nerve endings supplying the ACL and surrounding structures are thought to function dually as nociceptors and for modulating local effectors of vasoactivity and tissue remodeling, and may even have a role graft incorporation after fixation (6). These nociceptors are relatively few in number, which is thought to explain the commonly-observed lag time between acute ACL rupture and associated pain, as the pain is thought to be more often due to the development of a subsequent hemarthrosis (9).

Quantitative anatomy

Altogether, the proximal component of the ACL inserting into the internal aspect of the lateral femoral condyle occupies 66% of the superior-most portion of the internal aspect of the condyle (6). The center of the overall femoral attachment of the ACL can be triangulated by its proximity to four readily identifiable arthroscopic landmarks; the lateral intercondylar ridge (6.1 mm posterior to the center of the femoral attachment of the ACL), the bifurcate ridge (1.7 mm proximal to the center of the femoral attachment of the ACL), the posterior cartilage margin (8.5 mm anterior to the center of the femoral attachment of the ACL) and the distal cartilage margin (14.7 mm proximal to the center of the femoral attachment of the ACL) (15). Debate exists about the cross-sectional shape of the native ACL. It has been described by some as being triangular in cross section with an average length of roughly 25 to 35 mm and thickness of 3.9 mm (1,4,6,10,11). While multiple studies have attributed simple geometric shapes to the cross-section of the ACL, the actual cross-sectional shape and dimensions of the ACL should be thought of instead as a dynamic shape that changes with position of the knee joint (6,16,17).

The diameters of the collagen bundles that comprise the native ACL range from 50 to 300 micrometers (1). The previously discussed sinusoidal crimping pattern of these bundles has been quantitatively described, with collagen fibrils consistently displaying a crimp at 67 nm intervals and collagen fascicles displaying a crimp at 45 micrometer intervals along the length of the ACL (1). The cross-sectional area (CSA) of the ligament ranges from 4 to 10 mm in width. Its CSA is highest at its ends (nearest to its proximal and distal bony insertions) and tapers from either direction towards its midpoint. It displays its lowest CSA at what is defined as its isthmus (11). This usually occurs at a point within the midsubstance of the ACL, on average at 53.8% of its length from its proximal tibial attachment (11,16).

As the AM and PL bundles course distally, they coalesce into what has been described as a "flat ribbon" before inserting into the proximal tibia at a center-to-center distance of 5.0 mm from the anterolateral meniscal root insertion (11,12). Studies by LaPrade *et al.* found the insertional overlap between the ACL and the anterolateral meniscal root to be 41% of the ACL insertion area and 63% of the anterolateral meniscal root insertion area on average (12,13). Similar to the femoral attachments, the overall center of the tibial footprint can be triangulated by its proximity to readily identifiable arthroscopic landmarks; ACL ridge (10.5 mm posterior to the center of the tibial attachment of the ACL), the lateral retroeminence ridge (13 mm anterior posterior to the center of the tibial attachment of the ACL), and the anterior horn of the lateral meniscus (7.5 medial posterior to the center of the tibial attachment of the ACL) (12). *Table 1* outlines the anatomical characteristics of ACLR graft candidates.

Anatomy of the ACLR graft candidates

The native hamstring tendons

The conjoined tendons of the sartorius, gracilis and semitendinosus muscles form the pes anserinus ("goose foot") (18,20-22). The distal sartorius muscle and tendon are incased in the crural fascia (21,23). The sartorius originates from the anterior-superior iliac spine and crosses the thigh anteriorly. Traveling inferomedially, it inserts on the proximal tibia (21,23). The deeper gracilis and semitendinosus tendons are located between crural fascia and the superficial medial collateral ligament (MCL) (21,23). The former muscle arises from the ischiopubic ramus in the pelvis and travels inferiorly within the medial compartment of the thigh on its way to the knee, where it inserts just posterior to the insertion of the sartorius tendon (21,23). The latter muscle arises from the ischial tuberosity and runs inferiorly muscle into the knee, where it inserts posteriorly to the insertion of the gracilis tendon (21,23).

The sartorius tendon adheres to the crural fascia, while the gracilis and semitendinosus tendons are situated deep in the layer deep to the fascia. The tibial insertion of the pes anserinus is located proximal and anterior to the tibial insertion of the MCL. This conjoined tendon attaches 42±7 mm distal to the medial tibial plateau, distal and medial to the tibial tuberosity (24,25).

The tendons of the pes anserinus insert at the lateral edge of the pes anserinus bursa in a linear orientation: the sartorius (8.0 mm average width) inserts proximally, followed by gracilis (8.4 mm) and semitendinosus (11.3 mm) tendons (18). The most anatomically inconsistent tendon is the semitendinosus tendon, as it may possess up to three attachments and soft-tissue extensions, including a steady branch joining it to the gastrocnemius fascia (24-29). A synovial bursa is located between the pes anserinus and the distal sMCL. It is not uniformly round, nor does it communicate with knee joint as it pursues the track of sartorius muscle and tendon. The bursa extends proximally to the joint line (28). There is an additional bursa composed of the semimembranosus and MCL bursae, which does not communicate with the previously mentioned bursa. The semimembranosus bursa is located posterior and superior to the pes anserinus bursa, the MCL Bursa is between the deep and superficial fibers of MCL (30-32).

The native QT

The fiber organization of the QT is composed of the fibers of four muscle bellies: rectus femoris, vastus lateralis, vastus medialis (superficially), and vastus intermedius (deep) (33-37). The rectus femoris forms the superficial-most layer of the trilaminar QT and attaches to the superior patellar pole. The intermediate layer is formed by the vastus lateralis and the vastus medialis; in the descent of this layer, the vastus lateralis sends out a fibrous expansion which is fused with the lateral patellar retinaculum, both of which directly insert together into the tibia. The distal extent of the vastus medialis sends inferomedially-directed fibers into the common tendon and medial patellar aspect. Similar to the vastus lateralis, the vastus medialis has a distal fibrous expansion fused with the medial patellar retinaculum. The fibers of the vastus intermedius and rectus femoris attach orthogonally into the superior patellar apex, while the fibers of the vastus lateralis and medialis attach diagonally. Andrikoula *et al.* reported that the width of the QT at mid-length and at the superior patellar pole is 22.7 mm (SD 4.16) and 41.1 mm (SD 6.99), respectively (36). The common tendon inserts in the patella. The medial and lateral components of the QT course inferiorly and attach into the proximal tibia on either side of tuberosity and blend into the capsule, forming the medial and the lateral retinaculae. The medial patella-femoral ligament (MPFL) is formed by a band of retinacular tissue joining the medial femoral epicondyle with the proximal two-thirds of the medial patellar border. The lateral component of the QT is made up of the transverse epicondylopatellar band, the transverse retinaculum and the patellotibial band, which courses superolaterally, from the iliopatellar band to the patella, and between the patella and tibia inferiorly.

The QT is considered a suitable graft choice for an ACLR. It has an average length between 6 and 8 cm reported from the superior pole of patella and myotendinous junction, an average width from 2.5 to 3 cm, and a regular thickness (7.1–7.4 mm) (33,38). Several studies have demonstrated that thickness of the QT is diminished in the proximal and lateral portions of the tendon, with most of its density residing in its central and medial portions (19,39,40). On average, the thickness of the QT is almost double that of what has been reported for bone-patellar tendon-bone (BPTB) grafts (41). The QT has also been noted to have 30% more fibroblasts and 20% more collagen per square-millimeter compared to BTPB grafts (41,42).

Four arteries supply the QT, namely, the geniculate artery, lateral circumflex artery, and medial and lateral superior geniculate arteries. While the superficial edge of QT is completely vascularized from the myotendinous junction to the patella, the inferior aspect has an avascular area 10 mm near the patella, measuring about 450 mm^2 (35,43). Biomechanically, the ultimate load to failure of a 10-mm wide QT graft is significantly greater than that of a BPTB graft of comparable wedge, and also significantly higher than that of the native ACL (19,44-46).

The native patellar tendon

The PT continues distally from the inferior patellar apex to the tibial tuberosity, over the course of which it is then commonly referred to as the patellar tendon. It is strong and flat, about 48.6±5.2 mm in length, and derived primarily from the center fibers of the rectus femoris (47-49). Its attachment to the patella is crescent shaped, and medial and lateral fascicles attached to the patella more proximal than the central fascicles (48). The anterior fascicles are longer than the corresponding posterior fascicles, because their attachment is more proximal to the patella and more distal to the tibia than that of the corresponding posterior fascicles. The inferior patellar apex is never found along the midline of the PT, but instead, it usually resides medial to it (50-56).

The insertion of the patellar tendon into the tibial tuberosity is oblique and directed laterally. Usually beginning just distal to the most superior extreme of the tuberosity, it crosses the tuberosity and merges with the fascial expansion of the iliotibial band on the tibia (36,48). Its proximal extent is wider than its distal extent due to the convergence of tendon fascicles towards the midline before their attachment into the tibia (36,48,57). This mirrored by the geometry of the patellar tendon's osseous attachment. There is a transition from the flat frontal plane characteristic of the patellar insertion to a transversely-oriented convex attachment on the tibial tuberosity (48).

Aithal Padur *et al.* studied the lower extremities of 50 cadavers and found that the average length of the patellar tendon was 4.8 cm, while the shortest was about 2 cm (range, 3–6 cm) (57). An evaluation of the mean height of the patella, which the authors define as the linear distance between the superior border and the apex of the patella; reported mean value of 5 cm, which concurred with a separate cadaveric study performed by Schlenzka *et al.* (57,58). Another cadaveric study reported an average length of the PT to be 43 mm (36,59). It has been demonstrated that strength and load-bearing capacity of QT and PT are comparable; according to some authors, the PT is stronger and stiffer than QT (60,61). Around the patella there exists a recognizable circular structure of arteries that enters primarily at the inferior patellar apex (62).

Conclusions

Given the important biomechanical functions of the ACL and the frequency with which injury to this structure occurs, ACLR continues to be a mainstay treatment in orthopedic sports medicine. A solid anatomical understanding of the native ACL and its bony attachments to the femur and tibia are critical for ensuring the success of surgical reconstruction in restoring the native anatomy and biomechanical stability to the knee following ACL injury. Multiple tendinous and ligamentous structures exist around the knee that serve as viable candidates for use as autologous grafts by the operating surgeon. While the biomechanical features, benefits, and drawbacks of these common autograft specimens exist beyond the scope of this review, the anatomy of these distal extents of these structures have been reviewed thoroughly herein. This is equally crucial knowledge for supporting the continued success and improvement of ACLR techniques involving autologous grafts.

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Footnote

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