The Shape and the Thickness of the Anterior Cruciate Ligament Along Its Length in Relation to the Posterior Cruciate Ligament: A Cadaveric Study

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Purpose: The purpose of this study was to evaluate the shape of the native anterior cruciate ligament (ACL) along its length in relation to the posterior cruciate ligament (PCL) and compare it with the size of the 3 commonly used autografts (bone—patellar tendon—bone [BPTB], single-bundle hamstring, and double-bundle hamstring). **Methods:** With the knee in extension, we filled the intercondylar notch with paraffin, fixing the cruciate ligaments in their natural position, in 8 cadaveric specimens. The ACL-PCL tissue specimen, embedded in paraffin, was removed en bloc. Gross sections were prepared in the coronal plane and were evaluated histologically. The width, thickness, and cross-sectional area of both the ACL and PCL were determined. The dimensions of the semitendinosus tendon (ST), gracilis tendon (GT), and BPTB grafts were measured and compared with those of the native ACL. **Results:** The PCL occupies the largest part of the intercondylar area, leaving only a small space for the ACL in knee extension. The ACL midsubstance has a width of 5 mm, resembling a band shape. Only before its tibial insertion does the ACL fan out and take the form of its tibial attachment. The BPTB graft has a thickness of 5.8 mm, whereas the ST and GT grafts have a thickness of 6.25 mm and 4.5 mm, respectively, and are comparable to the midsubstance of the ACL but undersized in the tibial insertion ($P = .0016$ for BPTB graft, $P = .002$ for ST graft, and $P = .0003$ for GT graft). A quadruple-looped ST-GT graft, with a diameter of 8 mm, is oversized in the midsubstance ($P = .0002$) but fits better in the tibial attachment. **Conclusions:** The ACL midsubstance has a width of 5 mm, resembling a band shape. Before its tibial insertion, the ACL fans out like a trumpet, taking the form of its wide tibial attachment. **Clinical Relevance:** The dimensions of the native ACL have to be considered in graft selection for anatomic ACL reconstruction.

Anatomic anterior cruciate ligament (ACL) reconstruction aims to restore the biomechanics of the knee joint in ACL-deficient patients fully and consequently improve functional outcome and prevent the progression of osteoarthritis.[1-4] In the literature, several issues have been considered important, initiating a discussion on ways to improve the ACL reconstruction technique, aiming toward a more anatomic approach.[5-9] The discussion is mainly focused either on the choice of graft or on tunnel position, which are the main considerations in an anatomic ACL reconstruction. In the first aspect, bone—patellar tendon—bone (BPTB) and hamstring graft (either single-bundle [SB] or double-bundle [DB] graft) are the most commonly used; they have comparable properties to the native tissue, and their effectiveness has been proven.[8,10-13] The second concept regarding where to place the femoral and tibial tunnels has been well discussed. Most recent evidence suggests positioning of the graft at the anatomic insertions of the native ACL.[14-16]

A more detailed description of the anatomy of the ACL was considered necessary in an attempt to replicate the exact anatomy and behavior of the ACL.[17-19]

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The authors report that they have no conflicts of interest in the authorship and publication of this article.

Received June 6, 2013; accepted September 12, 2013.

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0749-8063/13376/$36.00
http://dx.doi.org/10.1016/j.arthro.2013.09.007

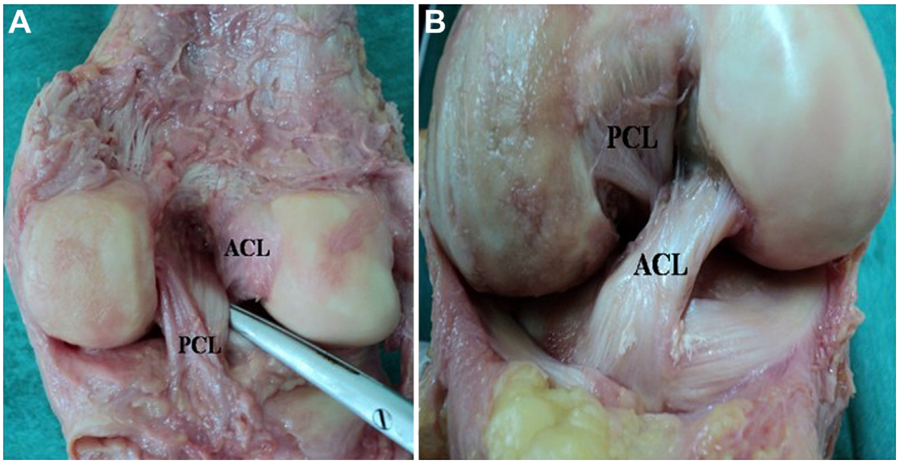

Fig 1. Anatomic preparation of knee joint. (A) Posterior view of knee joint (right knee). In full extension the PCL occupies the largest part of the intercondylar notch, leaving only a small space for the ACL. (B) Anterior view of knee joint in flexion (left knee). Because of the rolling of the anteromedial and posterolateral bundles of the ACL and the rolling of the femoral attachment posteriorly, we have the impression that the ACL is wide and occupies the largest part of the intercondylar notch.

Despite the evolution toward anatomic ACL reconstruction, the fact that the dimensions of the graft should preferably resemble those of the native ACL has not received adequate attention. Previous studies described in detail the shape of the attachment areas.[1,20] In these studies the cross-sectional area of the ACL was approximately 3 times the area at the midsubstance. Similarly, Harner et al.[21] reported that the posterior cruciate ligament (PCL) has a similar shape with a thinner midsubstance and wider insertions. However, it seems that the PCL has the opposite distribution, with the tibial insertion being smaller. Recently, Mochizuki et al.[22] described the configuration of the natural ACL, which looks like “lasagna,” measuring about 15 mm in length and 5 mm in width. In addition, it has been suggested that the femoral origin is of a similar size to the midsubstance.[23,24]

To our knowledge, there is no anatomic study that evaluates the shape of the ACL along its length. Most of the studies evaluating the ACL focus on the cross-sectional area, or they evaluate the ACL after its separation from the tibial and femoral attachment areas. Therefore it is difficult to measure the shape and size of the native ACL. As a consequence, the importance of the shape of the intact ACL in anatomic ACL reconstruction has not received adequate attention. In the ideal anatomic ACL reconstruction, the geometry of the ACL graft should resemble that of the native ACL to avoid ACL—intercondylar notch impingement.[6,25-27]

The purpose of this study was to evaluate the shape of the native ACL along its length in relation to the PCL and compare it with the size of the 3 commonly used autografts (BPTB, SB hamstring, and DB hamstring). We hypothesized that the native ACL and PCL do not have the same shape along their length starting from the femoral attachment. Close to the tibial insertion, the ACL widens to transform its shape to match the wide tibial “footprint” attachment.

Methods

This research was evaluated and approved by the institutional review board. Eight fresh-frozen, non-paired human cadaveric knees from adult patients aged between 50 and 70 years (mean age, 59 years) were assessed; 4 male and 4 female knees (right and left) were dissected. The cadaveric knees had no major macroscopic arthritic lesions and no signs of instability, deformity, or any other lesion.

Anatomic Preparation of Knee Joint

Initially, the skin and subcutaneous tissues were removed, leaving only the muscle groups and the ligaments. Then, the quadriceps femoral muscle, the iliotibial band, the biceps femoris, the popliteus muscle, and the lateral and medial heads of the gastrocnemius muscle were dissected (leaving intact a part of the muscle approximately 1 to 2 cm from its tendon insertions). The pes anserinus (sartorius, gracilis, and semitendinosus) was surgically prepared and reserved for further evaluation. All the other ligaments were dissected, apart from the extensor apparatus, leaving intact the following extracapsular and intracapsular ligaments: the quadriceps tendon, the patella, the retinaculum patellae laterale and mediale, the patellar tendon, the lateral collateral ligament, the medial collateral ligament, the oblique collateral ligament, the 2 cruciate ligaments, and the 2 menisci.

After all the ligaments and the insertions of the muscles underwent preparation, the capsule of the knee joint was opened posteriorly and most of the loose synovial tissue was carefully removed, by use of magnification loupes, to avoid damaging the surface of both cruciate ligaments. This was undertaken to create a free connection between the posterior and anterior space of the intercondylar notch, which was very essential for the second step of the study. At the end of this procedure, the knee only contained the tibia and

Fig 2. Knee in full extension, inside silicone rubber mold (posterior view). The asterisk indicates solidified paraffin from the intercondylar notch to the tibial plateau, filling the intercondylar area of interest and fixing the cruciate ligaments absolutely in their natural position.

femur, the extensor apparatus, the ligament structures (ACL, PCL, and medial and lateral collateral ligaments), and both menisci.

During this step, we took photographs from the posterior view of the intercondylar notch showing the relation of the PCL and ACL in full extension using a Sony DSC-S2000 Cyber-shot camera (Sony, Tokyo, Japan) (Fig 1). The specimens, in full extension, were then fixed by immersion in neutral-buffered formalin (4% formaldehyde; pH, 7.2 to 7.4) for 24 hours, before they were processed, to prevent tissue degeneration or drying out.

Paraffin Embedding

Twenty-four hours later, the knees were removed and toweled from the formalin. Then, they were placed in prone position and in extension inside a silicon rubber mold, which had similar dimensions to the specimen examined each time. In this position, using a typical 10-mL syringe, we filled the area extending from the intercondylar notch to the tibial plateau with hot molten paraffin (70°C). The intact extensor apparatus (patella and ligaments) prevented the flow of the liquid paraffin into the bottom of the mold, filling the intercondylar area and fixing absolutely the cruciate ligaments in their natural position. A few minutes later, the molten paraffin became more solid at room temperature (20°C) (Fig 2).

After this procedure was completed, the specimens were left in the freezer (−20°C) to become solid. The specimens were then removed from the freezer and left for another 24 hours at room temperature (20°C) to become softer for further processing.

Dissection of Paraffin-Embedded ACL-PCL Tissue Specimen

With a sharp surgical scalpel (No. 11), we removed the ACL-PCL tissue specimen from the intra-articular space embedded in paraffin very carefully en bloc. It was thoroughly removed from its femoral and tibial attachment sites, with care taken to ensure that the blade's edge was always in contact with the bone. Initially, the PCL was removed carefully from its tibial insertion. Then, the ACL and PCL were carefully separated from their femoral insertions. Later, the extensor mechanism of the knee was removed (which was also reserved for further evaluation), as was the fat pad. In the same manner, on the anterior side of the knee, the ACL was carefully extracted from its tibial insertion.

Finally, the ACL-PCL tissue specimen, removed from the intercondylar area (Fig 3), was placed in a small box, which was filled with hot molten paraffin. This was made with the aid of a paraffin wax bath that ensured complete coverage of the fixed cruciate ligaments with paraffin. The box was placed in the freezer as described earlier to solidify the contents and was then carefully removed, leaving the ACL-PCL tissue specimen ready for further evaluation. This procedure was undertaken to have a larger amount of paraffin surrounding the ligaments. This method facilitated the cutting of the paraffin-embedded tissue and guaranteed no change in the ligaments' geometry due to the fixation technique.

In the end, using a surgical scalpel, we carefully prepared the gross sections in the coronal plane, devoting a long time so that we did not break the paraffin or injure the ligaments internally. The axis of the ACL and PCL was determined to calculate the thickness of the ligaments at a plane perpendicular to the ACL axis (Fig 4). The slices had a mean width of 4 to 5 mm in the coronal plane from posteriorly to anteriorly. Therefore we obtained about 5 to 6 slices each time from every specimen (Fig 5). To calculate the cross-sectional area of the ligaments, data from subsequent slides were combined.

Measurements

Measurement of ACL-PCL. The width, thickness, and cross-sectional area of the cruciate ligaments were calculated for every section, along their length (from the femoral to the tibial insertion). For this purpose, the previously mentioned dimensions were measured

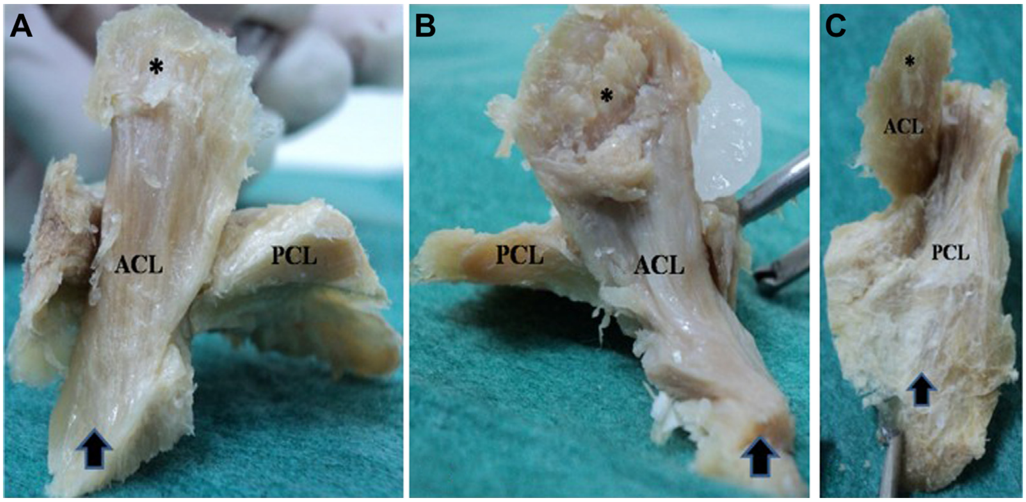

Fig 3. ACL-PCL fixed tissue specimens removed en bloc from intercondylar areas. (A) Anterolateral view of fixed cruciate ligaments in left knee. (B) Anterolateral view of fixed cruciate ligaments in right knee. (C) Posterior view of fixed cruciate ligaments in left knee. The asterisks indicate the ACL femoral insertion, and the arrows indicate the ACL tibial insertion.

at 4 different topographies: femoral attachment, midsubstance region located at one-third of the total ACL length (midsubstance 1), midsubstance region at two-thirds of the ACL length (midsubstance 2), and tibial attachment.

We identified the ligaments' geometry by observing the shape, the surface, and the anatomic relation between them. This was achieved with the use of a stereo-microscope (Leica MZ75; Leica Microsystems, Heerbrugg, Switzerland). Afterward, the image information was digitized (with a resolution of 12 bits) by a digital microscope camera (Leica DFC425/DFC425C LED Illumination, Trinocular Tube, SmartTouch, and PC System with Leica LAS Software; Leica Microsystems), leading to excellent noise suppression and perfect acquisition of the specimen's image for analysis and documentation.

Finally, we used the ImageJ program (http://rsbweb.nih.gov/ij/docs/intro.html) (National Institutes of Health, Bethesda, MD) to analyze the figures, measuring the distances of the ligaments, and saved the images as TIFF files. Spatial calibration was available and provided real-world dimensional measurements in millimeters.

Measurement of Other Knee Anatomic Structures. Using the same method, we measured the dimensions of the intercondylar fossa of every knee at 4 levels with respect to the measurements of the ACL and PCL. These data were used to calculate the percentage of width and cross-sectional area that the ACL and PCL occupy in the intercondylar fossa. In addition, we calculated the distance between the 2 ligaments, as well as the cross-sectional area between them, in an attempt to evaluate impingement.

Finally, from the pes anserinus (sartorius, gracilis, and semitendinosus) complex, which was prepared as described earlier, the semitendinosus tendon (ST) and gracilis tendon (GT) were prepared with a similar technique to that during surgery. For determining the double bundle graft, the ST and GT grafts were duplicated separately. For determining single bundle reconstruction graft, the ST and GT graft were calculated together quadrupled. This assumption was made since in

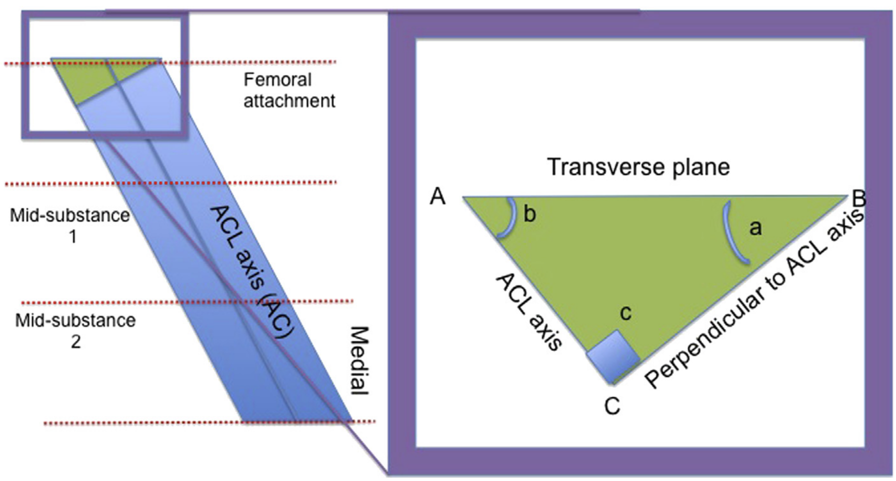

Fig 4. ACL axis, axis perpendicular to ACL, and transverse axis. The 4 different topographies of the measurements are also depicted. (AC, anterior cut.)

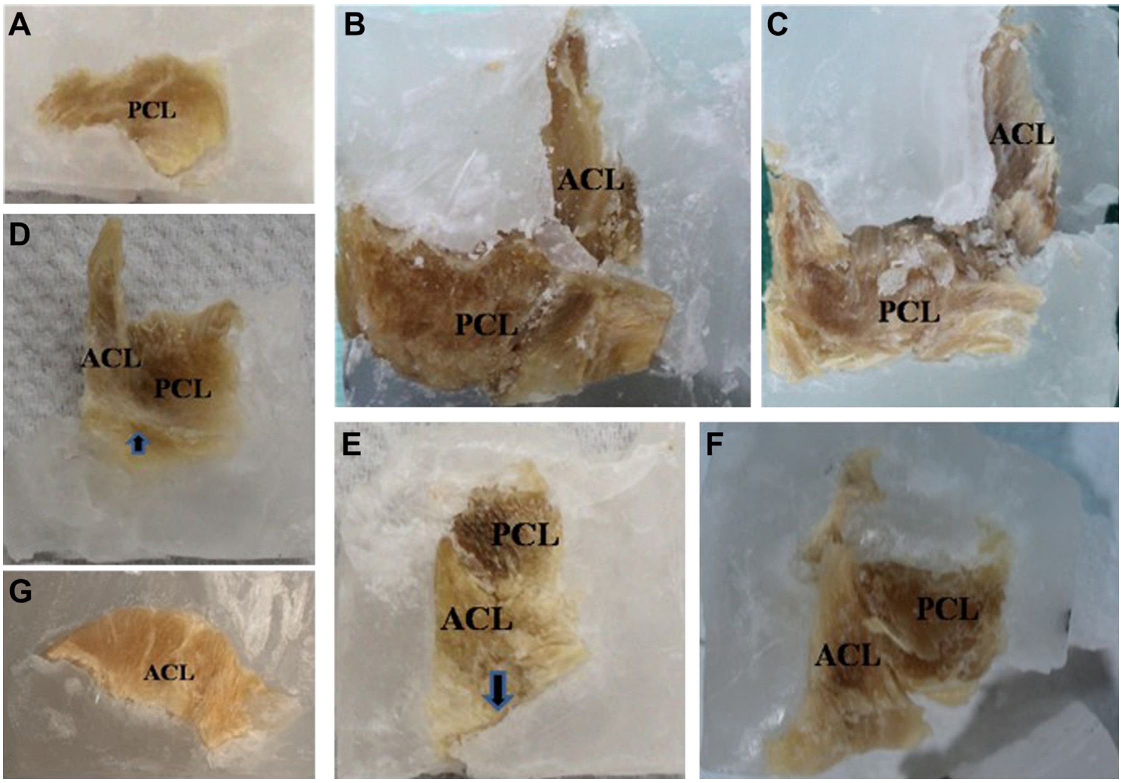

Fig 5. Paraffin gross sections of similar thickness, in coronal plane, from posterior to anterior side of intercondylar notch. (A) PCL tibial insertion (left knee). (B) ACL femoral insertion and midsubstance and PCL tibial insertion (2 bundles distinguished) (right knee). (C) ACL midsubstance and PCL (right knee). (D) ACL midsubstance and PCL (left knee). The arrow indicates ACL tibial widening. (E) PCL femoral insertion (left knee). The arrow indicates the ACL tibial insertion. (F) PCL femoral insertion and ACL tibial insertion (left knee). (G) ACL tibial insertion (right knee).

extension the AM and PL bundles are parallel. From the reserved patellar tendon, the medial one-third of the patellar tendon was isolated with a technique similar to that used clinically for BPTB graft preparation. We measured the width and cross-sectional area of the BPTB graft in 4 topographies along its length according to its positioning during ACL reconstruction. A correlation between the dimensions of the different anatomic structures was performed.

Histologic Preparation of Paraffin-Embedded ACL-PCL Tissue Specimens (Gross Sections)

Specimen sections were placed in labeled cassettes. They were then dehydrated and cleaned in an automatic embedding machine (Histokinette [Leica Microsystems, Wetzlar, Germany] and Tissue-Tek VIP [Sakura, Torrance, CA]) by passing through multiple changes of dehydrating and cleaning solvents for about 15 hours. Specimen sections were subsequently cut at a thickness of 3 to 5 μm by a rotate microtome (MICROM-HM355 S; Microm International GmbH, Walldorf, Germany) and picked up onto glass microscopic slides. The sections were then stained by an automated stainer (MICROM-HM5740; Microm International GmbH), with the routine tissue stain hematoxylin-eosin, and covered by glass coverslips (RCM 7000 coverslipping machine; MEDITE, Burgdorf, Germany). Finally, tissue sections were ready for microscopic evaluation under a light microscope.

Histologic Evaluation

In the beginning, at different section levels (femoral attachment, midsubstance, and tibial attachment), the portions of the 2 ligaments were distinguished on the stained sections with glass coverslips. The relation between them along their length was calculated, and they were compared with the images obtained by the stereomicroscope. The histologic evaluation of tissue sections was performed by 2 independent observers using of a Nikon Eclipse 50i light microscope (Nikon, Tokyo, Japan).

Statistical Analysis

A 2-way analysis of variance with Tukey post hoc statistical analysis was performed for data comparison among the different groups. Statistical significance was considered present at $P < .05$.

Results

Macroscopic Evaluation of Knee Joint

With the knee joint in full extension, the PCL occupies the largest part of the intercondylar area close

Table 1. Cross-Sectional Area of ACL, PCL, and Space Between ACL and PCL (Percentage of Intercondylar Fossa Space)

Specimen	Femoral Insertion Mean Cross-Sectional Area (mm^2)	Femoral Insertion %	Midsubstance 1 Mean Cross-Sectional Area (mm^2)	Midsubstance 1 %	Midsubstance 2 Mean Cross-Sectional Area (mm^2)	Midsubstance 2 %	Tibial Insertion Mean Cross-Sectional Area (mm^2)	Tibial Insertion %
ACL	29.1	13.1	35.4	15.7	39.4	15.7	127.1	43.2
PCL	87.4	39.2	53.2	23.6	74.9	29.8	110.7	37.7
Space between ACL and PCL	35.1	15.7	0.08	0.04	0.08	0.03	41.45	14.1
Intercondylar fossa	222.5	100	224.6	100	251.14	100	293.89	100

to the femoral insertion, leaving only a small space for the ACL. This can be clearly seen mainly on the posterior side of the knee joint in extension (Fig 1A). At the midsubstance, the PCL occupies a higher percentage of the intercondylar fossa area (Table 1). On the contrary, close to the tibial insertion, the ACL occupies the largest part of the fossa (Table 1).

Gross Morphology of ACL in Comparison With Other Grafts

Using paraffin gross sections, we made an anatomic approach in the cruciate ligaments over their entire length (from the femoral to the tibial attachment and mainly in the midsubstance), identifying all of their parts and the anatomic relation between them (Fig 6). The ACL, not only in the insertions but over the entire midsubstance, had a thickness of about 5 mm, more closely resembling a band shape (Figs 5B-5D and 6C-6E, Table 2). Only about 5 mm before the tibial insertion does the ACL fan out to finally take the form of the wide tibial insertion (Figs 5D-5F and 6F-6H, Tables 1 and 2). In addition, in our sections the thickness of the PCL was about 21 mm in the posterior (tibial) part and about 9 mm in the anterior (femoral) part (Table 2).

Simulating a DB ACL reconstruction, using an ST-GT graft, the diameters of the anteromedial and posterolateral grafts were 6.25 mm (SD, 0.86 mm) and 4.5 mm (SD, 0.57 mm), respectively. Simulating an SB ACL reconstruction, using an ST-GT graft, the diameter of the quadrupled graft was about 8 mm (SD, 0.81 mm). Finally, simulating a BPTB ACL reconstruction, using patellar tendon, the thickness of the graft was about 5.81 mm (SD, 0.46 mm) (Figs 7A and 8). Figure 7B shows the cross-sectional area of the different grafts in comparison with the native ACL. The GT graft was significantly smaller whereas the ST and ST-GT grafts, when used for SB ACL reconstruction, were remarkably oversized. The shape of the different grafts in comparison with the native ACL is shown in Fig 8.

Histologic Observations

In all of our specimens, in both cruciate ligaments, the specimens remained intact histologically and were characterized by collagen fibers and fusiform and spindle-shaped fibroblasts, oriented in a fairly parallel fashion, especially in the midsubstance of the ACL and PCL (Figs 9A-9C). In addition, in the structure of the bony insertions, a histologic difference between the fan-like extension fibers and the midsubstance was identified. In particular, we observed the fibrocartilaginous and cartilaginous zone in the transition area between the collagen fibers and the bone (Figs 9D-E, and 9G-9J). This observation was a very important finding of our study because the histologic evaluation affirmed that the cruciate ligaments were thoroughly harvested from the intercondylar area and accurately observed during all previous steps.

Discussion

This study shows clearly that the native ACL has a thickness of about 5 mm from its femoral insertion until about 5 to 6 mm before the tibial attachment, where the ACL tends to become wider to match the tibial insertion. This is in agreement with the study of Mochizuki et al.,[22] who found that the ACL midsubstance close to the femoral insertion is rather flat, looking like lasagna, about 5 mm in width. Our finding also adds to the recent published data suggesting that the orientation of the midsubstance fibers changes during knee motion.[28] Our study is more advanced because it proves that the ACL has these dimensions not only close to its femoral insertion but also along its length. On the contrary, approximately 5 to 6 mm before its tibial insertion, the ACL fans out on its wide tibial attachment, having a significantly increased width.

Numerous studies in the past focusing on ACL anatomic reconstruction were based only on a descriptive analysis of the ACL, either measuring the dimensions of the attachment areas separately or evaluating the ACL midsubstance after its removal from the bony insertions.[1,20,23,24,29,30,31] This determination of the exact shape of the ACL along its length is very crucial because of the close proximity of the midsubstance of the ACL to the PCL in full extension or a close-to-extension position of the knee joint. Therefore ACL grafts that are thicker compared with the remaining space between the lateral femoral condyle and the PCL (the actual position of the native ACL) can produce impingement either on the lateral femoral condyle or on the PCL.[3,6,23,32,33]

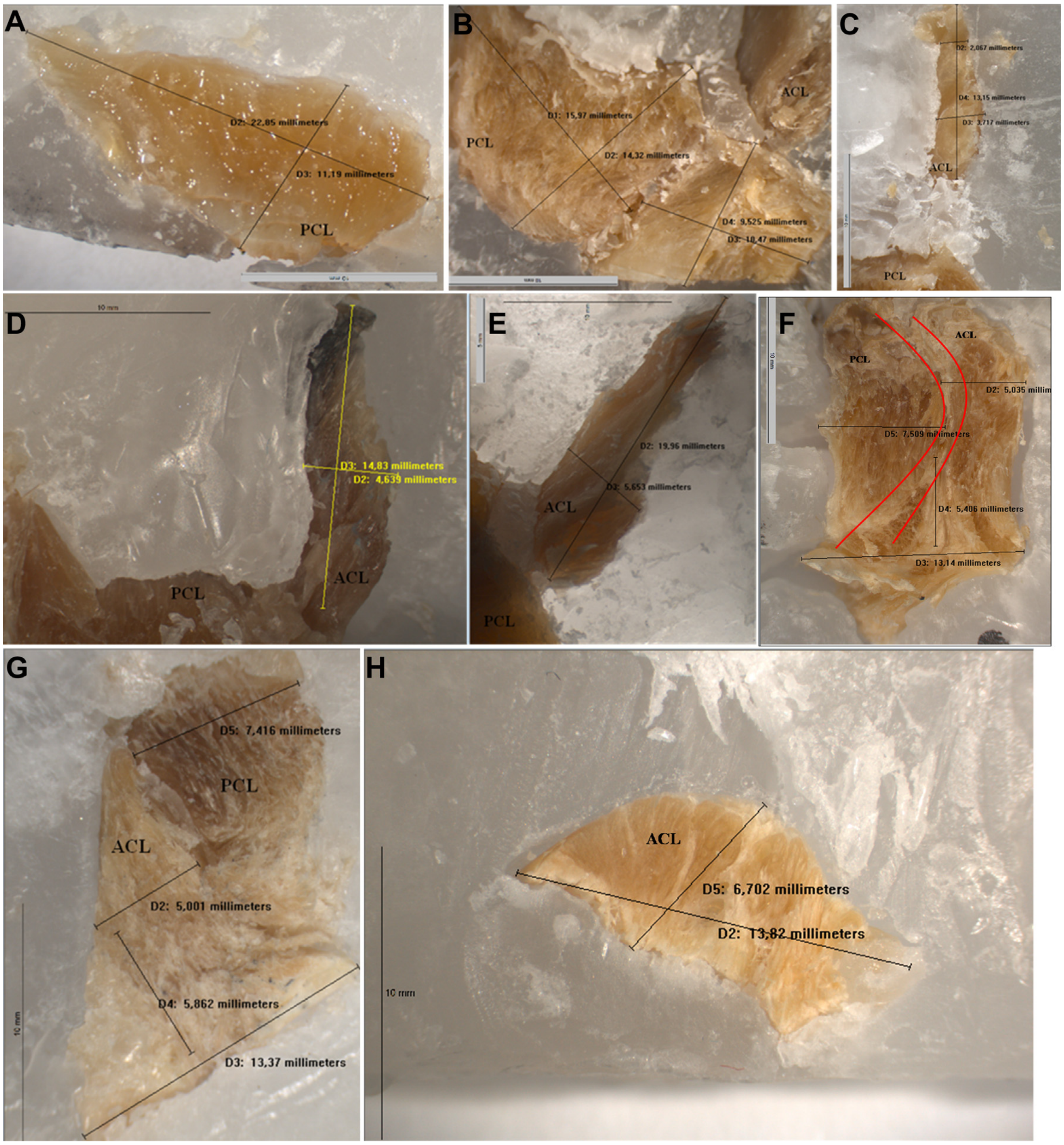

Fig 6. ACL-PCL tissue specimen sections, in coronal plane, from posterior to anterior side of intercondylar notch. Real-world dimensional measurements are given in millimeters. (A) PCL tibial insertion (right knee). (Dimension [D]2, thickness; D3, width.) (B) PCL tibial insertion (right knee) (2 bundles distinguished). (D1 and D3, thickness; D2 and D4, width.) (C) ACL femoral insertion and midsubstance (right knee). (D2, thickness of ACL femoral insertion; D3, thickness of ACL midsubstance.) (D) ACL close to PCL (right knee). In the midsubstance the thickness of the ACL is increased (D2). (E) Thickness of ACL midsubstance (D3) (right knee). (F) ACL (right knee) (D2, thickness) close to PCL (D5, thickness). Between the 2 red lines, we notice the border of the ACL and PCL (right knee). (G) Thickness of ACL midsubstance (D2), width of ACL (D4), thickness of ACL tibial attachment (D3), and thickness of PCL close to femoral insertion (D5) (left knee). (H) ACL tibial insertion (right knee). (D2, thickness; D5, width.)

We chose the position of knee extension to examine the natural geometry of the ACL and its relation to the PCL for several reasons. First, this is the knee position at which the PCL occupies the largest proportion of the intercondylar space. Most surgeons are familiar with the relative positioning of the cruciate ligaments at 90° of flexion from their experience with arthroscopic or open surgery. In this position the PCL femoral attachment leaves adequate space for the wide ACL tibial attachment in the anterior part of the intercondylar notch. Moreover, in knee flexion the rotation of the anteromedial and posterolateral bundles practically widens the ACL in the midsubstance, and the rolling of the ACL femoral attachment posteriorly gives the

Table 2. Thickness, Width, and Cross-Sectional Area of ACL and PCL (at Plane Perpendicular to ACL or PCL Axis)

	Mean (SD)			
Specimen	Femoral Insertion	Midsubstance 1	Midsubstance 2	Tibial Insertion
ACL				
Thickness (mm)	3.54 (0.78)	4.78 (0.59)	4.96 (0.57)	11.71 (1.24)
Width (mm)	8.22 (1.04)	7.41 (0.82)	7.94 (0.78)	10.85 (1.12)
Cross-sectional area (mm^2)	29.1 (3.2)	35.4 (2.5)	39.4 (2.2)	127.1 (7.3)
PCL				
Thickness (mm)	9.12 (0.83)	8.03 (1.02)	19.47 (3.22)	20.69 (0.99)
Width (mm)	9.58 (0.94)	6.63 (0.86)	3.85 (0.7)	5.35 (1.06)
Cross-sectional area (mm^2)	87.4 (4.6)	53.2 (2.9)	74.9 (4.8)	110.7 (5.7)

impression that the ACL is wider than it actually is and occupies the largest part of the intercondylar notch. In addition, virtually all sports are performed with the knee extended, and most injuries occur with the knee in extension. Furthermore, both PCL impingement and roof impingement occur in extension. Lastly, in full extension or a close—to—full extension position of the knee, the in situ loading between the 2 ACL bundles is equal.[19,34] This increases the clinical relevance of the model because the dimensions measured are representative of those acting during normal ACL loading.

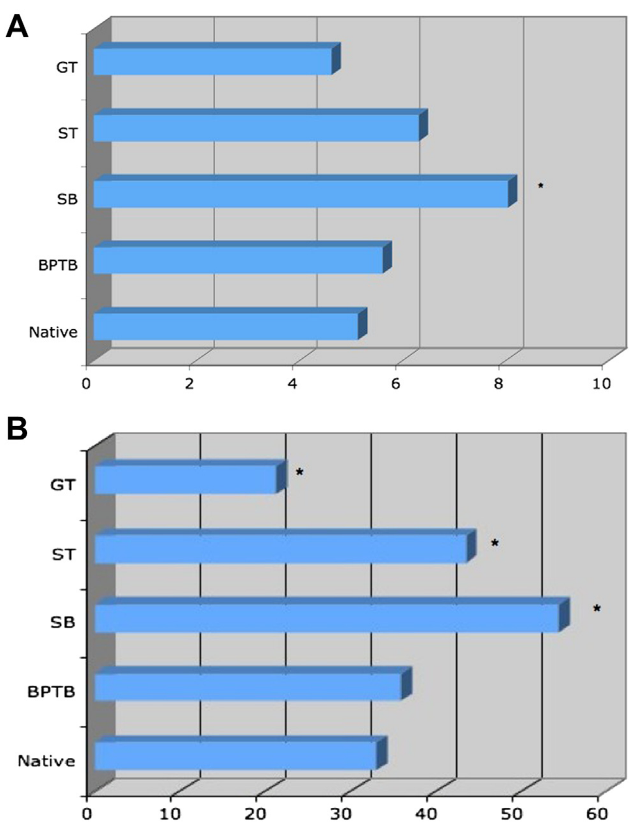

Fig 7. Comparison of dimensions (in millimeters) (A) and cross-sectional area (in square millimeters) (B) of native ACL at midsubstance with the most commonly used grafts. Asterisks indicate statistically significant differences.

Recently, the cross-sectional area of the midsubstance of the ACL and its relation to the cross-sectional area of the 3 possible grafts were evaluated.[23,24] Unfortunately, in these studies the shape of the native ACL was not mentioned because it is difficult to maintain the ACL shape in fresh cadavers. In our study the geometry of the ACL was evaluated throughout its length. The ACL midsubstance was evaluated in relation to the shape and geometry of the ACL attachments. Measuring the dimensions of the 3 possible ACL grafts (hamstring SB, hamstring DB, and medial one-third of patellar tendon), we found that there are 2 different areas of interest, the midsubstance and the tibial attachment. When one is evaluating the midsubstance, it has been shown that only the BPTB graft and SB hamstring graft are suitable for an anatomic reconstruction because they have a thickness similar to the midsubstance of the native ACL. The SB hamstring graft, with a diameter 50% thicker, can potentially produce impingement on either the femoral condyle or the PCL. Fujimoto et al.[25] found that the SB hamstring graft can produce a curving of the PCL as a result of an impingement on the PCL. This is very obvious in the study of Nishimori et al.[27] that showed that in cases of ACL reconstruction without impingement on the PCL, the ACL graft is thin, contrary to reconstructions with PCL impingement, in which the ACL graft is round and thick. Surprisingly, all grafts used for ACL reconstruction fail to resemble the

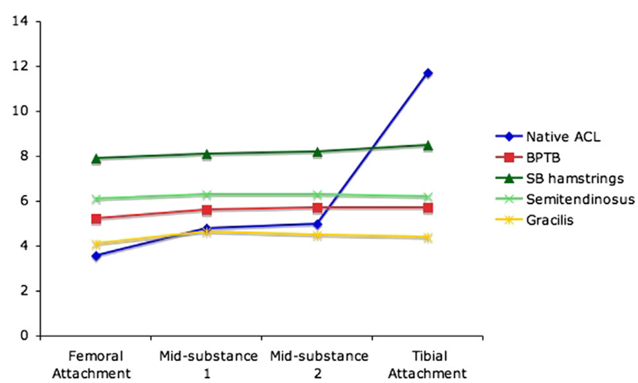

Fig 8. Thickness (in millimeters) of native ACL along its length in comparison with the most commonly used grafts.

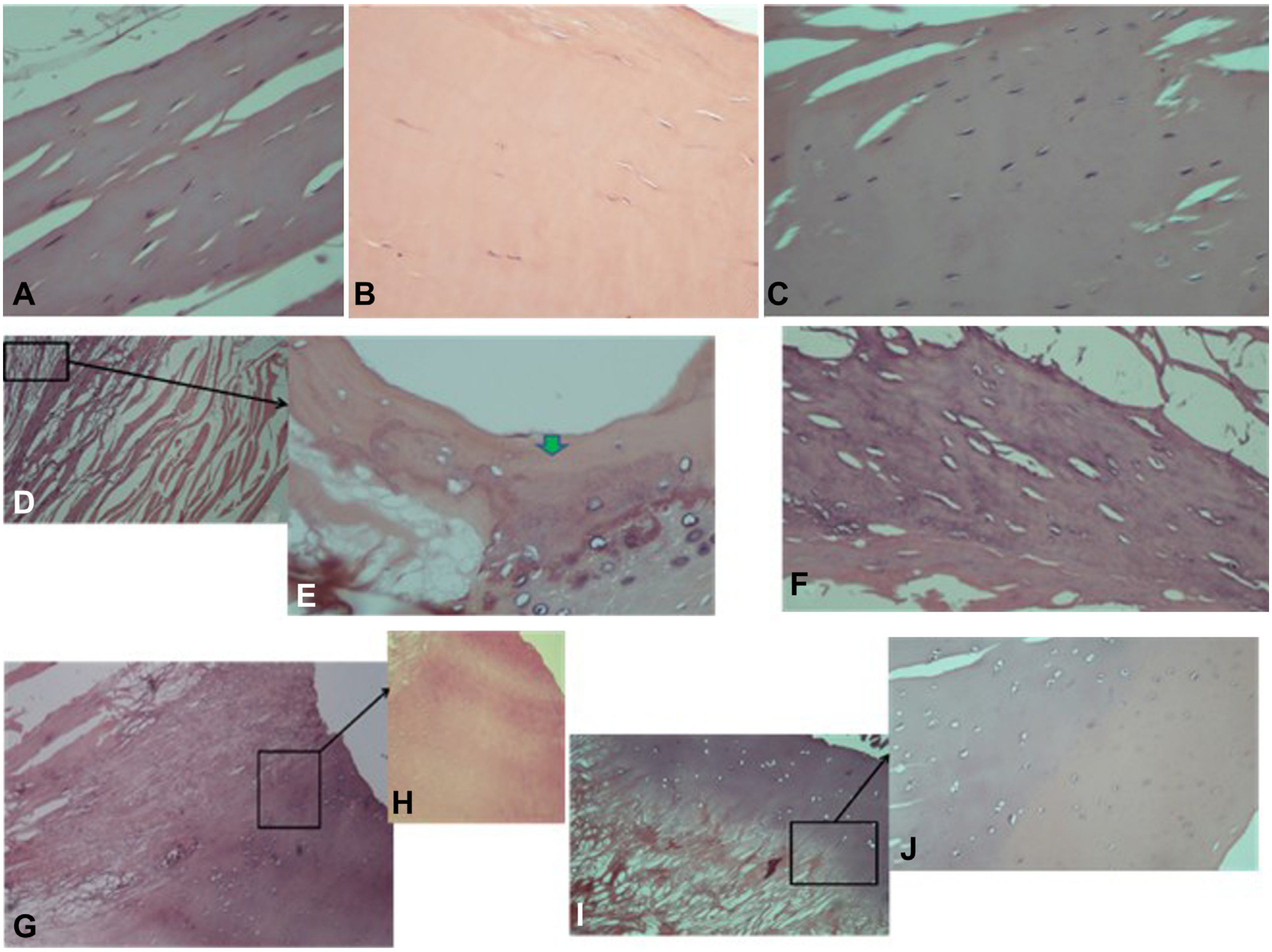

Fig 9. Histologic evaluation of ACL and PCL over their entire length (femoral attachment, midsubstance, tibial attachment) (Nikon ECLIPSE 50i light microscope). (A, B) PCL midsubstance. A high density of collagen fibers and fusiform, spindle-shaped fibroblasts running in a fairly parallel fashion is present. (A, B, H&E stain, magnification ×40.) (C) ACL midsubstance. A highly cellular area of fusiform and spindle-shaped fibroblasts in dense collagen connective tissue is present. (C, H&E stain, magnification ×40.) (D, E) ACL femoral insertion. (D) ACL collagen fibers lie longitudinally next to the femoral cartilaginous attachment with its characteristic basophilic morphology. (D, H&E stain, magnification ×20.)(E) As shown on the close-up view of D, the attachment zone resembles the chondral apophyseal insertions of tendons. At the transition between the bone (arrowhead) and dense connective tissue, there is a zone of fibrocartilage. Close to the bone, the fibrocartilage is mineralized. (E, H&E stain, magnification ×40.) (F) PCL tibial insertion. There is a basophilic cartilaginous attachment area, rich in chondrocytes and collagen bundles. (F, H&E stain, magnification ×20.) (G, H) ACL tibial insertion. (G) The attachment of the ACL to the tibia occurs through the interdigitation of the collagen fibers of the ligament with those of the adjacent bone, through the transitional zone of fibrocartilage and mineralized fibrocartilage. (G, H&E stain, magnification ×4.) (H) The close-up view of G shows cartilaginous tissue in the ACL tibial insertion. (H, H&E stain, magnification ×10.) (I, J) PCL femoral insertion. (I) The fibrocartilage transitional zone is easily distinguished next to the basophilic cartilaginous tissue. (I, H&E stain, magnification ×10.) (J) The close-up view of I shows cartilage rich in chondrocytes. (J, H&E stain, magnification ×20.)

shape of the native ACL as it fans out to become wider and attach on the tibial attachment.

During ACL reconstruction, surgeons pay great attention to avoid impingement of the graft on the intercondylar roof or on the lateral condyle by placing the tunnels in the most anatomic positions. In the literature the importance of tunnel placement with regard to subsequent impingement has been extensively evaluated either arthroscopically or with postoperative magnetic resonance imaging studies.[6,26-28,32,35] In the era of anatomic ACL reconstruction, equally as significant as the correct anatomic placement of the tunnels appears to be the fact that the shape of the ACL graft has to simulate the shape of the native ACL. At present, it is uncertain whether using grafts of different shapes would have any value in ACL reconstruction. It was beyond the scope of this study to evaluate the role of different-shaped grafts in ACL reconstruction, but this is certainly an interesting topic to study in the future.

In our study we tried to present the geometry of the native ACL along its length, focusing on the midsubstance, which is in close relation to the PCL. In addition, we identified another factor responsible for nonanatomic ACL reconstructions: the placement of oversized grafts in the narrow space left between the PCL and the lateral femoral condyle. Similarly, the geometry of the tibial attachment needs to be considered. Therefore the need for an anatomic ACL reconstruction requires the shape and the geometry of the native ACL along its length to be taken into consideration. It is necessary, of course, to place the graft at the femoral and tibial insertions and also in 90° of knee flexion; we have to choose grafts that are similar to the shape of the native ACL. Accordingly, the BPTB graft, with a thickness of about 5 mm, and the ST or GT graft, as a possible DB graft, with a thickness of about 5 to 6 mm, are closer to the thickness of the native ACL and match the small space left between the lateral border of the PCL and the lateral femoral condyle. The quadrupled ST-GT, as a possible SB graft, with a thickness of about 7 to 8 mm, is oversized. Further studies in cadaveric models are necessary to identify the ideal shape of the ACL graft in the most commonly performed reconstructions (SB/DB hamstring or patellar tendon) when placed at the anatomic femoral and tibial attachments.

The most important finding of our study is that the ACL does not have the same dimensions along its length, contrary to what it is believed. At the femoral attachment and the midsubstance, the ACL has a “band-like” shape with a diameter of approximately 5 mm. This confirms findings of recent studies showing that the cross-sectional area at the femoral insertion is comparable to that of the midsubstance.[23,24] However, at the tibial attachment, the size of the ACL is significantly larger. This finding is very important when one is considering ACL reconstruction. BPTB, ST, and GT grafts, as DB grafts, have a comparable size to the midsubstance of the ACL, but they are clearly undersized in the tibial insertion. On the other hand, the quadrupled SB graft fits better at the tibial attachment, but it is oversized in the midsubstance area, creating impingement, which is well recognized as a risk factor for subsequent failure.[36] Another important advantage of our study was that the separation of the ACL from its attachments was performed after fixation of the complex in paraffin, which did not allow further changes in its shape, dimensions, and relative position. This enabled the evaluation of the relative dimensions of the ACL/PCL along its length. The PCL occupies most of the intercondylar space in knee extension, giving a thin rim for the ACL from its femoral insertion until 5 mm before the tibial insertion. This seems to be very critical regarding the decision for tunnel positioning.

Limitations

This study has certain limitations. However, this was not a simple observational cadaveric study, and the data were extracted as part of multiple steps that were carefully designed and meticulously performed. This study design was selected because of its ability to accurately evaluate the shape of the ACL along its length. One limitation of the study is that the cross sections were at the coronal plane. The dimensions of the ACL at a plane that is perpendicular to the ACL axis were calculated to have comparable data to the literature. ACL reconstruction is performed using grafts whose dimensions are measured before reconstruction. One advantage of the present model was the fact that it allowed a direct comparison of the shape of the native ACL after its separation from its attachments with that of the grafts used for reconstruction. Another limitation of our model is that it studied the ACL cross-sectional area only in knee extension. However, the cross-sectional area of the ACL does not change significantly with knee flexion.[28]

Conclusions

The ACL midsubstance has a width of 5 mm, resembling a band shape. Before its tibial insertion, the ACL fans out like a trumpet, taking the form of its wide tibial attachment.

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