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The ACL Graft Has Different Cross-sectional Dimensions Compared With the Native ACL

Implications for Graft Impingement

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Background: Impingement of anterior cruciate ligament (ACL) grafts against the femoral notch and the posterior cruciate ligament (PCL) is thought to be influenced primarily by tunnel position and graft orientation. Recent data have implied that the native ACL is ribbon-shaped.

Purpose: To evaluate the 3-dimensional shape and cross-sectional area of the native ACL versus the ACL graft and to compare the degree of impingement against the femoral notch and PCL.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: Bilateral knee magnetic resonance images were analyzed for 27 patients with unilateral bone–patellar tendon–bone (BPTB) ACL reconstruction performed via transtibial or anteromedial portal femoral tunneling techniques. Three-dimensional models of the ACL, PCL, femur, and tibia were digitally rendered. The cross-sectional area and dimensions of the native ACL and the reconstructed graft were determined at 3 equally spaced locations and compared via Wilcoxon-Mann-Whitney and Kruskal-Wallis tests. In addition, impingement of the ACL on the PCL and femoral notch was graded in 3 groups. Chi-square or Fisher exact tests were used to compare the proportional differences of impingement of the native and reconstructed ACL on the PCL and femoral notch, respectively. All analyses were performed using 2-sided hypothesis testing, with statistical significance at $P < .05$.

Results: Cross-sectional areas at all 3 points on the ACL graft were significantly greater than those of the native ACL ($P < .001$). The long- to short-axis ratio for the native ACL was significantly greater at each location compared with the corresponding locations along the ACL graft ($P < .001$), implying that the native ACL is ''flatter'' than is an ACL graft. There were 19 operated knees (70%) with contact or impingement between the ACL graft and the femoral notch compared with zero knees with a native ACL ($P < .001$). In addition, 22 operated knees (81%) showed contact or impingement between the ACL graft and the PCL, compared with 7 knees (26%) with a native ACL ($P < .001$). No significant differences in impingement frequency were noted between the transtibial and anteromedial tunneling techniques for ACL graft specimens ($P > .05$).

Conclusion: Native ACLs have a smaller cross-sectional area, are ''flatter,'' and experience less incidence of impingement compared with anatomically placed BPTB ACL grafts.

Keywords: anterior cruciate ligament (ACL); impingement; cross-sectional dimensions; ACL graft

Anterior cruciate ligament (ACL) graft impingement is associated with poor outcomes after ACL reconstruction (ACLR) and is considered a cause of failure.[6,10,12,17] Studies have shown that while little to no impingement occurs between the native ACL and the femoral notch and/or the posterior cruciate ligament (PCL), nearly 50% of ACLR cases show impingement of the ACL graft.[5,14] Impingement of the ACL graft against the PCL or the femoral notch is related to tunnel position and graft orientation, and it is most frequently reported during full extension of the knee.[5,11,13,14,27]

Prior anatomic studies have described the native ACL as a flat structure at its midsubstance, C-shaped at the tibial insertion, and flat or ribbon-like near the femoral

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insertion.[21,25,28] Triantafyllidi et al[28] suggest that the unique flat 3-dimensional (3D) shape of the native ACL prevents impingement between the ACL and PCL within the femoral notch. Studies have shown that the size of the notch is inversely correlated with the risk of ACL injury, corroborating this theory and highlighting the clinical importance of anatomic differences between the native ACL and ACL graft.[26] Several authors have asserted that the native ACL differs in size and shape compared with standard ACL graft types, with some suggesting that bone–patellar tendon–bone (BPTB) and double-bundle hamstring grafts better approximate the structure of the native ACL compared with single-bundle hamstring grafts.[15,23,28] ACL grafts with dimensions differing from those of the native ACL are therefore at higher risk for impingement and subsequent ACLR failure.

Three-dimensional high-resolution magnetic resonance imaging (MRI) has been shown to be an effective tool in evaluating the impingement of native ACLs and ACL grafts against the femoral notch and PCL.[1,5,9,18,19] The purpose of this study was to use MRI to compare impingement of the native ACL against the PCL and femoral notch with that of BPTB ACL autograft. The secondary objective was to use MRI to compare the size and dimensions of the native ACL with those of the ACL graft. We hypothesized that (1) the BPTB ACL graft would exhibit a higher degree of impingement versus the native ACL and (2) the dimensions of the ACL graft would be significantly different from those of the native ACL.

METHODS

Subject Selection

This study was exempt based on 45 CFR 46.101 (b) Category 4(b) by our institutional review board (study No. 2015-261). Patient selection, surgical technique, and data collection protocols have been previously described in a prospective study.[4] In brief, patients between the ages of 16 and 40 years who underwent primary ACL reconstruction with BPTB autograft were included. Patients who underwent previous knee surgery, concomitant bony procedures (ie, osteotomy, meniscal transplant, osteoarticular allograft or autograft), and/or multiligament reconstruction were excluded from the study, as were those unable or unwilling to undergo postoperative MRI.

Surgical Technique

Patients underwent single-bundle ACL reconstructions using a transtibial (TT) or anteromedial (AM) portal femoral tunnel reaming technique. Procedures were performed by 1 of 8 high-volume, fellowship-trained sports medicine surgeons. In TT reconstruction, the tibial tunnel was created within the tibial footprint using a tibial aiming guide. Coronal angulation of the guide and the resultant tibial positioning were selected to allow access to an appropriate femoral position. A femoral over-the-top guide was then passed through the tibial tunnel to ensure that a 2-mm back wall of the femoral socket was maintained. The rigid femoral reamer was passed through the tibial tunnel before reaming the femoral socket. In AM reconstruction, the tibial tunnel and the femoral socket were reamed independently per a previously described technique.[3] Positioning of the femoral tunnel was based on the anatomic center of the native ACL footprint in both TT and AM techniques. Flexible guide wires were passed through the AM portal with the knee held in hyperflexion, and femoral tunnel preparation was performed using a flexible reaming system (Smith & Nephew). Notchplasty was performed as per the surgeon's discretion during both TT and AM techniques.

3D MRI Reconstructions

Postoperative bilateral knee MRIs were performed 5 to 25 weeks after reconstruction on a clinical 3-T scanner (GE Healthcare). During scanning, all knees were placed in a high-resolution, 8-channel, phased-array transmit/receive knee coil in full extension and neutral rotation. Three-dimensional MRI reconstructions of the femur, tibia, native ACL, ACL graft, and PCL were created from segmented images using Mimics 13.1 software (Materialise).[4] The 3D models were then exported to Geomagic Studio 11 (Geomagic). Mirror images of the left side were created so that the knees from the same patient could be analyzed in the same orientation. Multiple corresponding anatomic points between the 2 femurs were registered, and the mirrored left side was rotated and translated for a best-fit overlay onto the right femur as previously described by Bowers et al.[4]

MRI Dimensional Measurement

This study retrospectively analyzed the 3D models to determine (1) cross-sectional area and (2) dimensions of 3 equally spaced locations on the native ACL and reconstructed graft. Models were exported to Geomagic Studio, where the cross section of the footprints and 3 evenly spaced cross-sectional images of the ligament or graft were sampled. The centroid of each image was identified, and a reference line passing through the centroid of all sections was generated along the entire length of the native or graft ACL. The PTC Creo Parametric (PTC) software package was then used to determine 25% (proximal), 50% (midpoint), and 75% (distal) of the ligament's overall length (from the femoral attachment to the tibial attachment). A perpendicular plane (relative to the central reference line) was isolated at each of these points (proximal, midpoint, and distal along the ligament's length) to create cross-sectional slices (Figure 1).

Slices were then quantified by (1) cross-sectional area, (2) long- and short-axis length in the transverse plane (Figure 1C), and (3) long- to short-axis (LSA) ratio. The cross-sectional area provides information regarding the size of

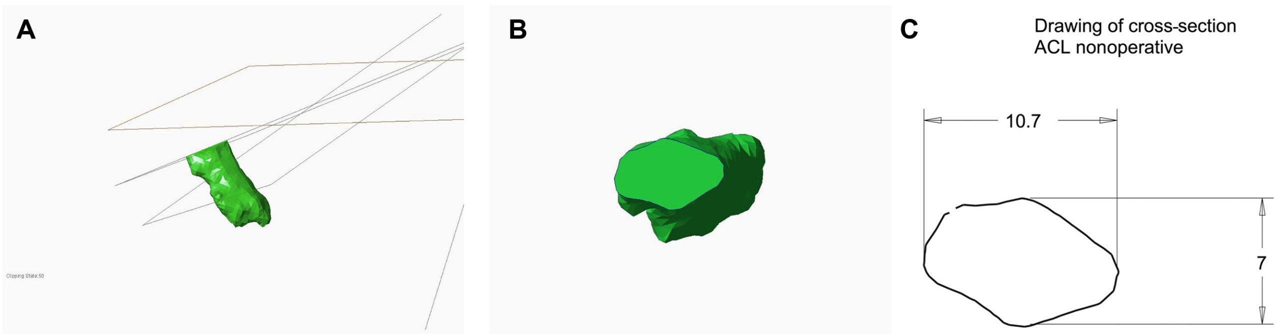

Figure 1. (A) Three-dimensional reconstruction of the ACL (green) showing the transverse planes at 25%, 50%, and 75% of the ligament length at which cross-sectional measurements were obtained. (B) A transverse section along the longitudinal axis of the ACL (green) for dimensional measurement. (C) Measurement of the long and short axes of a transverse section. ACL, anterior cruciate ligament.

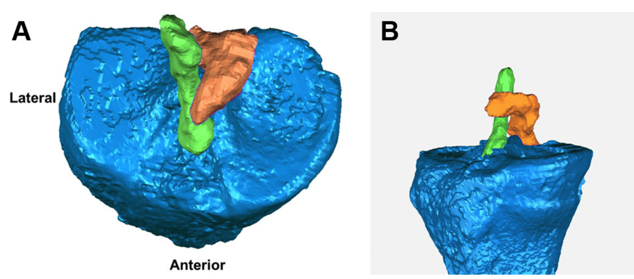

Figure 2. (A) Three-dimensional reconstruction of the tibia (blue), the native ACL (green), and the native PCL (orange) with subtraction of the femur, viewed in a superoinferior direction. This illustrates grade 1 impingement. (B) Three-dimensional reconstruction of the tibia (blue), the native ACL (green), and the native PCL (orange) with subtraction of the femur, viewed from the anteromedial perspective. This illustrates grade 1 impingement. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

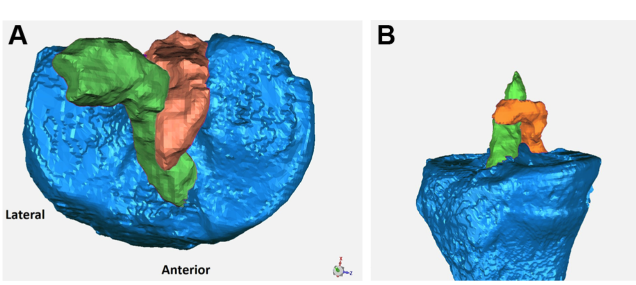

Figure 3. (A) Three-dimensional reconstruction of the tibia (blue), the ACL graft (green), and the native PCL (orange) with subtraction of the femur, viewed in a superoinferior direction. This illustrates grade 2 impingement. (B) Three-dimensional reconstruction of the tibia (blue), the ACL graft (green), and the native PCL (orange) with subtraction of the femur, viewed from the anteromedial perspective. This illustrates grade 2 impingement. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

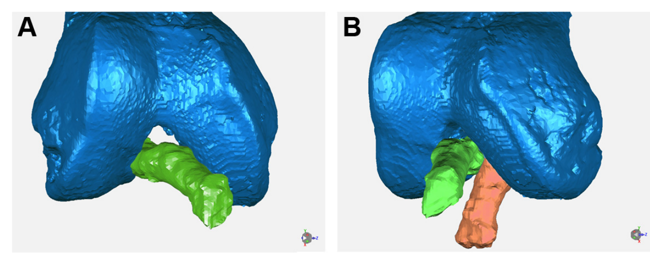

Figure 4. (A) Three-dimensional reconstruction of the femur (blue) and the ACL graft (green) with subtraction of the tibia and native PCL, viewed in an anteroposterior direction. This illustrates grade 3 impingement. (B) Three-dimensional reconstruction of the femur (blue), the ACL graft (green), and the native PCL (orange) with subtraction of the tibia, viewed from the inferomedial perspective. This illustrates grade 3 impingement. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.

the native ACL versus ACL graft. The LSA ratio provides insight into the shape of the native ACL versus ACL graft, whereby mismatch between the long and short axis results in a large ratio and implies a flat ligament (symmetric long and short axes result in a 1:1 ratio, representing a round or square ligament) (Figure 1C).

Impingement

Impingement of the native ACL and the ACL graft against the PCL and the femoral notch was graded in 3 categories as suggested previously by Fujimoto et al.[5] Grade 1 includes knees in which space is present between the ACL and PCL (grade 1p) or between the ACL and femoral notch (grade 1n) (Figure 2). Grade 2 includes knees in which the ACL contacts the PCL (grade 2p) or femoral notch (grade 2n) but does not show any dimples (Figure 3). Grade 3 includes knees in which the ACL is dimpled as a result of contact with the PCL (grade 3p) or femoral notch (grade 3n) (Figure 4).

TABLE 1
Cross-sectional Area and Dimensions[a]

	Mean ± SD	Range	*P* Value: Wilcoxon-Mann-Whitney Test[b]	*P* Value: Kruskal-Wallis Test[c]
Total cross-sectional area				
ACL graft				
Proximal	113.82 ± 37.81	44.30-211.20	<.001	.0341
Midpoint	89.22 ± 31.27	31.31-149.09	<.001	
Distal	95.60 ± 26.45	50.97-155.84	<.001	
Native ACL				
Proximal	69.54 ± 20.37	41.26-118.56		.001
Midpoint	49.32 ± 13.92	25.80-93.38		
Distal	63.01 ± 22.59	22.91-129.77		
Long- to short-axis ratio				
ACL graft				
Proximal	1.29 ± 0.33	1.02-2.62	<.001	.108
Midpoint	1.35 ± 0.24	1.08-2.02	<.001	
Distal	1.24 ± 0.17	1.00-1.59	.007	
Native ACL				
Proximal	2.07 ± 0.28	1.67-2.85		<.001
Midpoint	1.72 ± 0.28	1.12-2.16		
Distal	1.42 ± 0.24	1.04-1.87		
Long axis				
ACL graft				
Proximal	14.20 ± 3.04	8.23-20.41	.667	.076
Midpoint	12.96 ± 3.24	8.31-22.00	.003	
Distal	12.73 ± 2.04	9.75-19.16	.0003	
Native ACL				
Proximal	13.96 ± 2.03	10.83-20.32		<.001
Midpoint	10.61 ± 2.03	7.75-16.52		
Distal	10.82 ± 2.05	7.22-16.95		
Short axis				
ACL graft				
Proximal	11.33 ± 2.72	6.02-17.02	<.001	.048
Midpoint	9.69 ± 1.97	5.14-13.01	<.001	
Distal	10.35 ± 1.68	6.51-13.97	<.001	
Native ACL				
Proximal	6.85 ± 1.28	4.72-9.69		.0004
Midpoint	6.21 ± 0.92	4.44-8.61		
Distal	7.74 ± 1.60	4.48-11.38		

[a]ACL, anterior cruciate ligament.
[b]Comparing ACL graft and native ACL for each slice.
[c]Comparing ACL graft across the 3 slices.

Statistical Analysis

Descriptive statistics were reported in terms of frequencies for discrete variables, as well as means and SDs for continuous variables such as impingement (defined as grades 2 and 3) and the cross-sectional dimensions (cross-sectional area, long- and short-axis lengths, and LSA ratio). The degree of PCL and notch impingement by the native ACL or ACL graft was compared using the Fisher exact test.

Comparison of the cross-sectional area, long axis, short axis, and LSA ratio between the ACL graft and the native ACL at the proximal, midpoint, and distal slices was performed using the Wilcoxon-Mann-Whitney test. Cross-sectional dimensions across the 3 slices within each ACL graft specimen were compared using the Kruskal-Wallis test. Univariate analysis of the cross-sectional dimensions between TT and AM tunnel techniques was performed using the Wilcoxon-Mann-Whitney test. Ordinal logistic regression using the 3 grades of impingement as the outcome was used to assess the effect of ACL cross-sectional dimensions on the likelihood of PCL and/or femoral notch impingement.

RESULTS

A total of 30 subjects who met the inclusion/exclusion criteria underwent bilateral knee MRIs for this study. Three subjects had MRIs that were not conducive to 3D MRI reconstruction, so bilateral knee MRIs for a total of 27 patients were analyzed in this study. Of these, 12 patients underwent TT and 15 underwent AM portal femoral

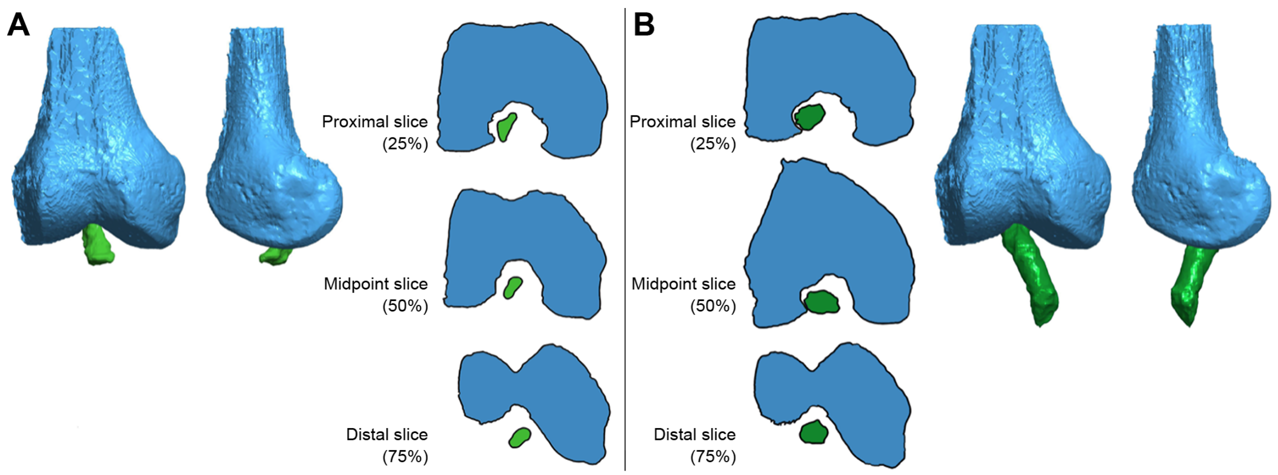

Figure 5. (A) Three-dimensional reconstruction of the femur (blue) and the native ACL (green), with transverse sections at 25%, 50%, and 75% of the ligament length. (B) Three-dimensional reconstruction of the femur (blue) and the ACL graft (green), with transverse sections at 25%, 50%, and 75% of the ligament length.

tunnel reaming techniques. As reported previously,[4] all tunnels were placed within the anatomic footprint of the native ACL on both the femoral and tibial sides.

The cross-sectional area of the ACL graft was significantly greater than that of the native ACL at all 3 locations (proximal, midpoint, and distal; $P < .001$) (Table 1). The long and short axis at each cross-section was significantly greater for the ACL graft as compared with the native ACL ($P < .001$). Moreover, the LSA ratio for each cross-section of the native ACL was significantly greater than the LSA ratio for the ACL graft ($P < .001$ [proximal], $P < .001$ [midpoint], and $P = .007$ [distal]) (Table 1), implying that the native ACL is flatter than is the ACL graft at all 3 points along the ligament (Figure 5).

Furthermore, the LSA ratio of the native ACL was higher at the proximal femoral region ($P < .001$). Both ratios (proximal and midpoint) were significantly higher compared with the LSA ratio near the tibial insertion (Table 1). This implies a flattening of the native ACL in its proximal and midportion region with a more rounded region distally as it inserts on the tibia. No significant differences were observed in the LSA ratios between any of the 3 cross-sectional points for the ACL BPTB graft ($P > .05$). No significant differences were noted between the TT and AM tunneling techniques at any slice point for the ACL graft samples ($P > .05$) (Table 2).

Impingement between the native ACL or ACL graft and the PCL and femoral notch is summarized in Table 3. Grades 3p and 2p impingement against the PCL were present in 14 and 8 specimens, respectively, with the ACL graft versus 1 and 6 knees, respectively, with the native ACL ($P < .001$). Grades 3n and 2n impingement against the femoral notch were observed in 8 and 11 ACL graft specimens, respectively, compared with zero knees with the native ACL ($P < .001$). No impingement on either the PCL or femoral notch was observed in 74.1% of native ACLs, compared with just 3.7% of ACL grafts. No significant differences in impingement frequency were noted between the TT and AM tunneling techniques for ACL graft specimens ($P > .005$) (Table 4).

Seventy-eight percent (n = 21) of all knees underwent notchplasty, of which 76% (n = 16) experienced persistent notch impingement after this procedure. In patients who did not have a notchplasty, 50% of knees (n = 3) experienced impingement. The mean impingement volume (±SD) was 14.3 ± 28.4 mm^3.

DISCUSSION

The findings demonstrate that the native ACL is significantly flatter than is the BPTB ACL graft along its course inside the joint (Figure 5). Moreover, the ACL graft impinges significantly more on both the PCL and the femoral notch as compared with the native ACL.

Recent cadaveric studies have shown that although the ACL attachments are considered broad, the midsubstance of the ligament is flat.[20,25,28] Moreover, histological studies have shown that the broad attachments are built from 2 different types of fibers with different histological features that gather into a flat structure. Sasaki et al[24] and Iwahashi et al[16] studied the femoral attachment of the native ACL, describing 2 different components: direct fibers that attach to a narrow area along the lateral ridge of the lateral condyle and indirect fibers that connect to the femur between the ridge and the posterior cartilage. Mochizuki et al[20] termed the fibers that attach near the lateral ridge the "mid-substance fibers" and named the fibers that attach to the area between the ridge and the cartilage the "fan-like extension fibers" based on their macroscopic appearance. Although these fibers have a broad attachment to the femur, studies have shown that they tend to converge into a flat-shaped ligament within a few millimeters of the ACL femoral attachment.[28]

While cadaveric studies have helped elucidate the shape of the native ACL, to our knowledge, there is no in vivo, 3D

TABLE 2
ACL Graft Cross-sectional Area and Long- to Short-Axis Ratio by Slice and Tunnel Technique[a]

ACL Graft	n (%)	Mean ± SD	Range	*P* Value[b]
Cross-sectional area				
Proximal				
AM	15 (57.69)	103.30 ± 32.92	44.30-164.11	.129
TT	12 (46.15)	126.09 ± 40.78	52.29-211.20	
Midpoint				
AM	15 (57.69)	81.81 ± 29.28	31.31-149.09	.157
TT	12 (46.15)	97.85 ± 32.53	39.47-134.36	
Distal				
AM	15 (57.69)	87.83 ± 18.79	50.97-114.05	.157
TT	12 (46.15)	104.66 ± 31.73	58.12-155.84	
Long- to short-axis ratio				
Proximal				
AM	15 (57.69)	1.35 ± 0.44	1.07-2.62	.63
TT	12 (46.15)	1.22 ± 0.09	1.02-1.34	
Midpoint				
AM	15 (57.69)	1.37 ± 0.24	1.08-1.80	.55
TT	12 (46.15)	1.32 ± 0.26	1.11-2.02	
Distal				
AM	15 (57.69)	1.27 ± 0.18	1.05-1.59	.43
TT	12 (46.15)	1.21 ± 0.16	1.00-1.55	
Long axis				
Proximal				
AM	15 (57.69)	13.45 ± 2.63	8.23-19.16	.19
TT	12 (46.15)	15.07 ± 3.37	9.09-20.41	
Midpoint				
AM	15 (57.69)	12.29 ± 2.56	8.39-18.96	.29
TT	12 (46.15)	13.74 ± 3.87	8.31-22.00	
Distal				
AM	15 (57.69)	12.30 ± 1.38	10.02-14.80	.47
TT	12 (46.15)	13.24 ± 2.58	9.75-19.16	
Short axis				
Proximal				
AM	15 (57.69)	10.41 ± 2.29	6.02-13.86	.13
TT	12 (46.15)	12.39 ± 2.88	7.62-17.02	
Midpoint				
AM	15 (57.69)	9.11 ± 1.91	5.14-12.51	.08
TT	12 (46.15)	10.36 ± 1.89	6.35-13.01	
Distal				
AM	15 (57.69)	9.84 ± 1.38	6.51-11.34	.28
TT	12 (46.15)	10.95 ± 1.85	8.41-13.97	

[a]ACL, anterior cruciate ligament; AM, anteromedial; TT, transtibial.
[b]Wilcoxon-Mann-Whitney test comparing AM and TT within each slice.

quantitative description of the morphologic characteristics and orientation of the native ACL within the knee. Nishimori et al[22] evaluated ACL-PCL impingement but reported only qualitative differences noted on MRI between the native ACL and a hamstring ACL graft. The authors reported clear space between the native ACL, which was described as "spindle-like," and the PCL. However, when analyzing the interaction between the hamstring ACL graft, which was described as an oval structure, and the PCL, no clear space was noticed.[22] The authors did not report quantitative or qualitative differences between single- and double-bundle grafts.[22]

Using computer-modeling technology, we were able to create a 3D model of both the native ACL and ACL graft in vivo to measure their sizes and shapes. Not surprisingly, our findings corroborate cadaveric studies evaluating the native ACL. We found the native ACL to be flat, with an LSA ratio of up to 2.07. We also found a significant difference in shape between the BPTB ACL autograft and the native ACL. Comparing different types of grafts, Triantafyllidi et al[28] found that the BPTB graft better approximates the shape of the native ACL as compared with a single-bundle hamstring ACL graft. However, their measurements were obtained in nonphysiologic, time-zero conditions after the tendons were harvested and just before implantation. In contrast, 3D reconstructions in the present study were based on imaging obtained at least 5 weeks after ACLR. The difference in dimensional measurements

TABLE 3
Frequency and Type of Impingment Seen in the Native ACL and ACL Grafts (N = 27 Patients)[a]

Grade	n (%)	Mean ± SD	95% CI	*P* Value[b]
PCL				<.001
Native ACL				
Grade 1	20 (74.07)			
Grade 2	6 (22.22)			
Grade 3	1 (3.70)			
Impingement	7 (25.93)	2.143 ± 0.378	1.793-2.492	
ACL graft				
Grade 1	5 (18.52)			
Grade 2	8 (29.63)			
Grade 3	14 (51.85)			
Impingement	22 (81.48)	2.636 ± 0.492	2.418-2.855	
Notch				<.001
Native ACL				
Grade 1	27 (100.00)			
Grade 2	0 (0.00)			
Grade 3	0 (0.00)			
Impingement	0 (0.00)			
ACL graft				
Grade 1	8 (29.63)			
Grade 2	11 (40.74)			
Grade 3	8 (29.63)			
Impingement	19 (70.37)	2.421 ± 0.507	2.177-2.666	

[a]ACL, anterior cruciate ligament; PCL, posterior cruciate ligament.
[b]Fisher exact test comparing the distribution across impingement grades between ACL graft and native ACL.

TABLE 4
ACL Graft Impingement Frequency
(N = 27 Patients)[a]

Grade	n (%)	*P* Value[b]
PCL		.8791
TT		
Grade 1	2 (7.41)	
Grade 2	3 (11.11)	
Grade 3	7 (25.93)	
Impingement	10 (37.04)	
AM		
Grade 1	3 (11.11)	
Grade 2	5 (18.52)	
Grade 3	7 (25.93)	
Impingement	12 (44.44)	
Notch		>.999
TT		
Grade 1	4 (14.81)	
Grade 2	5 (18.52)	
Grade 3	3 (11.11)	
Impingement	8 (29.63)	
AM		
Grade 1	4 (14.81)	
Grade 2	6 (22.22)	
Grade 3	5 (18.52)	
Impingement	11 (40.74)	

[a]ACL, anterior cruciate ligament; AM, anteromedial; PCL, posterior cruciate ligament; TT, transtibial.
[b]Fisher exact test comparing the distribution across impingement grades between the TT and AM approaches for ACL graft.

may be a function of the orientation of the implanted graft, influence of the fixation method on graft configuration (fixed around a screw in the tibia), and the physiological conditions inside the joint.

Analysis of cross sections consistently revealed that neither the native ACL nor the ACL graft is perfectly round. Rather, each has a distinct long and short axis. Comparison of LSA ratios revealed that the native ACL is flatter, particularly near the femoral insertion. This shape may permit the native ACL to maintain a proper anatomic relationship with the PCL within a narrow proximal portion of the femoral notch.

A higher incidence of impingement on the PCL and/or the femoral notch was detected after ACLR versus knees with an intact native ACL. These results are consistent with the existing literature. A few studies have reported minimal impingement of the native ACL against the PCL, while others have reported minimal impingement of the native ACL against the femoral notch.[2,5,22] However, significant impingement was reported for almost all types of ACL grafts against the PCL or the femoral notch.[13] Most authors have suggested that tunnel position and ligament orientation are the main risk factors for graft impingement. Iriuchishima et al[14] reported that the double-bundle ACL graft displays minimal impingement as compared with the single-bundle graft, attributing these differences to tunnel positioning. However, the findings of the present study suggest that the flatter shape of the double-bundle graft may also influence the magnitude of impingement. Indeed, Triantafyllidi et al[28] demonstrated that the double-bundle graft has a similar shape to that of the native ACL. Finally, our data suggest that notchplasty performed in these knees was not an effective means of preventing notch impingement. More than 75% of post-ACLR knees continued to demonstrate some degree of notch impingement in extension, despite undergoing notchplasty.

Tunnel position and graft orientation are important risk factors for graft impingement. In a previous report,[4] we demonstrated that the tunnel positions for the ACL grafts in this study were anatomically placed. As such, the present findings suggest that mismatch in the size and shape between the graft and native ACL is a likely mechanistic reason for the impingement. A larger, thicker graft perturbs the structural relationship between the PCL and the ACL, especially in the proximal femoral notch. As such, we believe that suboptimal graft dimensions must be considered alongside tunnel positioning as a causative factor in notch and PCL impingement.

There are limitations to the present study. First, procedures were performed by 8 sports medicine surgeons, which may cause inconsistency and variability in ACLR when compared with a single-surgeon study. However, all ACL grafts were different from the native ACL, 70% of ACL grafts presented with impingement in the notch (compared with 0% of the native ACLs), and 82% of grafts presented with impingement with the PCL (compared with 26% of the native ACLs). Second, impingement between the native ACL or ACL graft, PCL, and femoral notch was graded by qualitative methods. We are not aware of any quantitative scale for impingement measurement at this time. Third, the range of time from surgery to postoperative MRI (5-25 weeks) was long enough that a graft may undergo modifications in its anatomy and ligamentization. Fourth, the size and shape of the ligaments were calculated using reconstructed 3D MRI images that may have been subject to operator error. However, this remains the only available method to evaluate the shape, size, and impingement of the ligaments in vivo. Finally, the present study does not detail the clinical implications of the impingement. However, it has been reported that impingement leads to inferior clinical outcomes and higher failure rates.[7,8]

In conclusion, we present novel data describing the shape of the native ACL and ACL graft in their in vivo positions within the knee. The native ACL is significantly flatter than is the BPTB ACL graft after implantation in the knee. We believe this different shape interferes with the anatomic relationship between the ligaments and the bone, which may lead to a higher impingement rate.

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