ACL Roof Impingement Revisited

Does the Independent Femoral Drilling Technique Avoid Roof Impingement With Anteriorly Placed Tibial Tunnels?

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Background: Anatomic femoral tunnel placement for single-bundle anterior cruciate ligament (ACL) reconstruction is now well accepted. The ideal location for the tibial tunnel has not been studied extensively, although some biomechanical and clinical studies suggest that placement of the tibial tunnel in the anterior part of the ACL tibial attachment site may be desirable. However, the concern for intercondylar roof impingement has tempered enthusiasm for anterior tibial tunnel placement.

Purpose: To compare the potential for intercondylar roof impingement of ACL grafts with anteriorly positioned tibial tunnels after either transtibial (TT) or independent femoral (IF) tunnel drilling.

Study Design: Controlled laboratory study.

Methods: Twelve fresh-frozen cadaver knees were randomized to either a TT or IF drilling technique. Tibial guide pins were drilled in the anterior third of the native ACL tibial attachment site after debridement. All efforts were made to drill the femoral tunnel anatomically in the center of the attachment site, and the surrogate ACL graft was visualized using 3-dimensional computed tomography. Reformatting was used to evaluate for roof impingement. Tunnel dimensions, knee flexion angles, and intra-articular sagittal graft angles were also measured. The Impingement Review Index (IRI) was used to evaluate for graft impingement.

Results: Two grafts (2/6, 33.3%) in the TT group impinged upon the intercondylar roof and demonstrated angular deformity (IRI type 1). No grafts in the IF group impinged, although 2 of 6 (66.7%) IF grafts touched the roof without deformation (IRI type 2). The presence or absence of impingement was not statistically significant. The mean sagittal tibial tunnel guide pin position prior to drilling was 27.6% of the sagittal diameter of the tibia (range, 22%-33.9%). However, computed tomography performed post-drilling detected substantial posterior enlargement in 2 TT specimens. A significant difference in the sagittal graft angle was noted between the 2 groups. TT grafts were more vertical, leading to angular convergence with the roof, whereas IF grafts were more horizontal and universally diverged from the roof.

Conclusion: The IF technique had no specimens with roof impingement despite an anterior tibial tunnel position, likely due to a more horizontal graft trajectory and anatomic placement of the ACL femoral tunnel. Roof impingement remains a concern after TT ACL reconstruction in the setting of anterior tibial tunnel placement, although statistical significance was not found. Future clinical studies are planned to develop better recommendations for ACL tibial tunnel placement.

Clinical Relevance: Graft impingement due to excessively anterior tibial tunnel placement using a TT drilling technique has been previously demonstrated; however, this may not be a concern when using an IF tunnel drilling technique. There may also be biomechanical advantages to a more anterior tibial tunnel in IF tunnel ACL reconstruction.

Keywords: ACL; roof impingement; tibial tunnel position; transtibial; independent femoral drilling

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The importance of anatomic femoral tunnel placement in anterior cruciate ligament (ACL) reconstruction to maximize postoperative knee biomechanics and function has gained widespread agreement.[5,12] Although the ideal location of the femoral tunnel for the ACL graft has been studied extensively, this has not been the case for the tibial tunnel. Recent data suggest that more anterior placement of the tibial tunnel relative to the center of the native attachment site may improve knee biomechanics, but the potential for impingement remains problematic.

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The exact anatomic location of the tibial attachment site to the native ACL has been investigated in numerous studies. In the sagittal plane, it has become customary to express this position relative to a percentage of the midsagittal tibial diameter measured from the anterior aspect. Staubli and Rauschning[13] found the center of the tibial attachment site was located at 41.2% in fresh cadaveric specimens, and 43.3% in cryoplaned specimens. The anterior limits of the footprint were found to be 27.5% and 24.6% in fresh and cryoplaned specimens, respectively. Another study using an optimized computed tomography (CT) protocol found a slightly more anterior center of the native tibial footprint at 37%.[10] Several cadaveric and biomechanical studies have investigated tibial tunnel placement and its effect on the biomechanics of the reconstructed knee. Staubli and Rauschning[13] advocated placing the center of the tibial tunnel at 44% of the tibia diameter posterior and parallel to the individual intercondylar roof inclination angle. However, biomechanical testing has also shown that more anterior placement of the tibial tunnel can improve Lachman and pivot-shift test results.[7] Additionally, a clinical study of anterior tibial tunnel placement confirmed improved stability without loss of extension.[2]

A major concern with anterior tibial tunnel placement is roof impingement with the knee in full extension. Direct contact between the ACL graft and the roof of the notch has been theorized to cause graft abrasion, pathologic stretching, arthrofibrosis, and, potentially, graft failure. Howell[8] popularized the concept of roof impingement in transtibial (TT) ACL reconstructions with anterior tibial tunnels by comparing postoperative lateral radiographs with clinical results. He found that tibial tunnel placement anterior to the Blumensaat line with the knee in full extension resulted in impingement of the ACL graft and inferior clinical results.[8]

The purpose of this study was to determine whether ACL graft roof impingement occurs with anteriorly placed tibial tunnels with either TT or independent femoral (IF) drilling. We hypothesized that TT drilling in conjunction with an anterior tibial tunnel would lead to an increased rate of graft impingement on the intercondylar roof and that IF drilling would not.

METHODS

Six matched pairs (n = 12 knees) of fresh-frozen cadaveric knees obtained through the university's cadaver program were used for this study. Each pair was randomized to undergo arthroscopically assisted TT drilling on one side and IF drilling via an accessory medial portal approach on the other side. There was equal representation of right and left knees for each drilling technique. All surgical procedures were directly supervised by the senior author (M.D.M.). All subsequent radiographic analyses were performed independently by 2 fellowship-trained sports medicine surgeons blinded to the drilling technique.

Transtibial Technique

Medial and lateral parapatellar arthroscopic portals were made with portals placed immediately adjacent to the patellar tendon. In all specimens, the ACL was debrided using a shaver, with care taken to leave remnant fibers at both the femoral and tibial attachment sites. The tibial tunnel guide pin position was selected using an external tibial tunnel drill guide (Acufex; Smith & Nephew Endoscopy) set at 55°, which is the senior author's (M.D.M.) standard ACL reconstruction technique in clinical practice. The final guide pin position was in the anterior third of the tibial ACL stump in a central position with regard to the medial-to-lateral width of the attachment site. Externally, a longitudinal incision was made along the medial tibia, and the cannulated sleeve was placed approximately 1 cm anterior to the anterior fibers of the superficial medial collateral ligament. Finally, a 2.4-mm pin was drilled through the tibia with the guide placed as inferiorly as the contour of the guide and proximal tibia would allow.

After placement of the tibial tunnel guide pin, a fluoroscopic image was obtained using a C-arm with the knee in a true lateral position. The anterior-to-posterior position of the pin was measured using the Staubli technique (Figure 1).

Guide pins were considered acceptable if the Staubli percentage was <35%; otherwise, the pin was redrilled more anteriorly. Once the tibial tunnel guide pin position was accepted, a cannulated 8-mm fully fluted drill was passed over the guide pin in bicortical fashion. The intra-articular tibial aperture was cleared free of debris using a motorized shaver.

The ACL femoral tunnel position was determined using a 6.5-mm transtibial ACL femoral offset guide (Arthrex), introduced through the tibial tunnel and placed over the posterior aspect of the lateral femoral condyle. In each specimen, using what remained of the femoral footprint, the surgeon attempted to place the guide pin as close to the native ACL footprint as possible. The placement and positioning of the offset guide were carried out in whatever degree of knee flexion would allow the guide to reach the posterior wall, generally between 45° and 90°. Otherwise, all of these steps were accomplished with the knee in 80° to 90° of flexion. Because of the inherent restraints of the TT technique, the desired anatomic femoral tunnel position was not achieved for most specimens. When this occurred, no adjustments were made to the tibial tunnel position, and the best possible femoral tunnel position was accepted. A guide pin was advanced through the lateral femoral condyle and then overdrilled with a half-moon-shaped 8-mm

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Ethical approval for this study was obtained from The University of Virginia IRB-HSR.

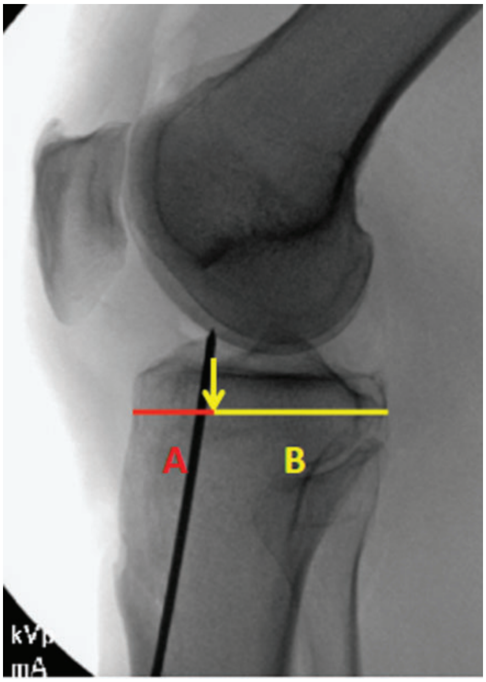

Figure 1. Measurement of the tibial tunnel guide pin using the Staubli technique. A line is drawn perpendicular to the tibial axis at the widest portion of the tibial plateau (A + B). Next, a perpendicular line is dropped from the articular entry point of the guide pin. The percentage of plateau diameter is determined as follows: A ÷ (A + B).

tip reamer in bicortical fashion. Care was taken to manually push or oscillate the reamer through the tibial tunnel rather than drilling under power to reduce the risk of widening the tibial tunnel or aperture.

Independent Femoral Technique

The arthroscopy setup and initial portals were similar for the IF technique. The femoral tunnel was drilled first to prevent extravasation. First, an accessory low anteromedial portal was established using a spinal needle for localization, typically 1 to 2 cm medial and inferior to the standard anteromedial portal. The arthroscope was inserted into the knee joint through an anteromedial portal to allow an orthogonal view of the lateral wall of the notch. A microfracture awl was used to create a pilot hole at the center of the attachment site. A guide pin was then introduced in the pilot hole and left in place while the knee was maximally hyperflexed to at least 120°. The guide pin was then advanced through the lateral femoral condyle, and then both cortices were reamed using an 8-mm reamer. Clinically, the lateral cortex would not typically be drilled, but for the purposes of this study, the lateral cortex was drilled to allow passage of the Gore-Tex smoother. Care was taken during the entire femoral tunnel drilling process to protect the medial femoral condyle. The tibial tunnel was then drilled independently using similar instruments and steps as in the TT specimens.

Figure 2. A radiopaque wire mesh tunnel smoother is shown after being passed into position through the drilled tunnels.

Gore-Tex Smoother Insertion

After tunnel drilling was complete, a No. 5 passing suture was used to pull a 7.9-mm wire-mesh tunnel smoother (Gore Smoother; Smith & Nephew) into the tunnels to serve as a radiopaque surrogate graft during imaging (Figure 2).

Computed Tomography Technique

All knee specimens underwent dual-energy CT scanning with a technique optimized for metal artifact suppression. Scanning was performed using a 0.625-mm detector configuration, and axial images at 0.625 mm with 50% slice overlap were constructed. Care was taken to position the knees as close to full extension and in a perfect lateral position as possible using CT scout images. With the knee positioned in maximal extension, a clamp was affixed under tension to the free ends of the tunnel smoother in an attempt to prevent laxity of the graft within the knee.

Radiographic Measurement

Three independent orthopaedic surgeons reviewed the radiographic data using a standardized method. The Staubli percentage of the center position of the tibial tunnel was measured using the midsagittal CT image by drawing a digital line on the widest part of the tibial plateau and perpendicular to the tibial mechanical axis, and then dropping a second line perpendicular to the joint surface to bisect the first line (Figure 1). Grading of roof impingement for each knee was performed using the Impingement

TABLE 1
Impingement Review Index[a]

Type 1. *Impingement*: The ACL graft touches the roof and the graft shape is deformed (pathological impingement)
Type 2. *Touch:* The ACL graft touches the roof and the graft shape is not deformed (physiological impingement)
Type 3. *Nontouch:* The ACL graft does not touch the roof

[a]The Impingement Review Index, described by Iriuchishima et al,[9] is an objective assessment of ACL graft-roof impingement that is performed using 3-dimensional computed tomography. The 3 types of graft-roof interaction were clearly distinguishable with the radiopaque surrogate graft that was used in the present study. ACL, anterior cruciate ligament.

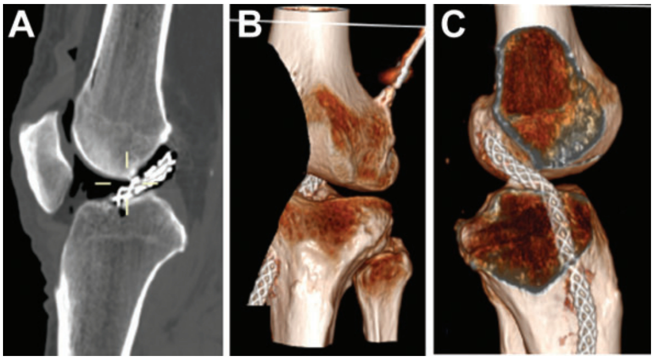

Figure 3. (A) Midsagittal computed tomography (CT) slice depicting the surrogate graft and roof morphology. (B) A reformatted coronal 3-dimensional CT scan demonstrating the volume subtraction tool to permit an unobstructed view of the graft-roof interaction. (C) Tunnel assessment and impingement review were performed using the sagittal sequence and confirmed in all other planes; in this case, no impingement occurred for this independent femoral specimen.

Review Index (IRI), as described by Iriuchishima et al[9] (Table 1), which uses 3-dimensional CT (3D CT) to investigate the graft-roof relationship.

The evaluation of graft-roof contact was facilitated by the data subtraction capabilities of 3D CT, which allowed an unobstructed view from any angle. Prior studies utilizing 3D CT relied on the axial plane evaluation of the graft position at the most distal point in the intercondylar notch roof. In the present study, the sagittal plane (Figure 3) was the most useful view and was obtained by bisecting the radiopaque graft in a sagittal plane subtraction to allow unobstructed visualization of the entire intra-articular course of the graft.

The axial plane was then used to confirm the findings, and there was no disparate grading using this method. Additional variables including knee extension angle, intercondylar roof inclination angle (RIA), tunnel lengths, and sagittal graft angle (SGA) (Figure 4) were measured using CT. The SGA compares the anatomic axis of the femur (AAF) with the intra-articular trajectory of an ACL graft. A line connecting the center of both the tibial and femoral tunnel apertures is extended until it intersects the AAF, yielding the SGA. While 0° would be parallel to the femur (ie, "vertical"), a larger angle, up to a maximum of 90°, corresponds to a more "horizontal" graft.

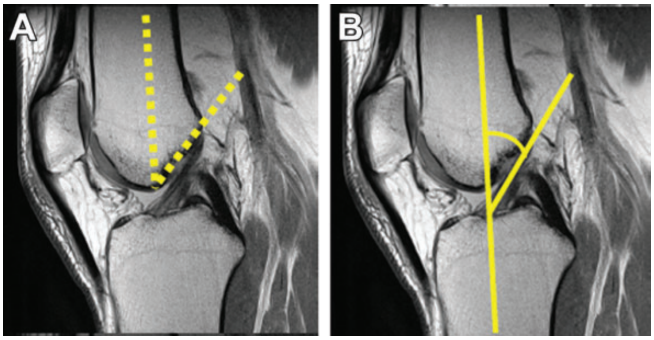

Figure 4. (A) The roof inclination angle (dotted line) measures the inclination of a line along the intercondylar roof and a second line along the midsagittal femoral shaft axis. (B) The sagittal graft angle (smooth line) measures the intra-articular course of the graft in the sagittal plane with respect to the midsagittal femoral shaft axis. The measurement is performed in full extension by plotting a straight line between the center of the tibial and femoral insertions of the graft. This measurement allows direct comparison of the graft geometry and intercondylar roof.

Statistical Analysis

Data are presented as mean and range. Several statistical tests were used to compare the 2 drilling techniques. Categorical data from the IRI were analyzed using a 2-tailed Fisher exact test. Continuous, normally distributed data, including knee extension angle, intercondylar RIA, and tunnel lengths, were assessed using independent-sample t tests. The sagittal graft angle values were compared using a Mann-Whitney U test as these data were not normally distributed. Tests were considered statistically significant if the P values were .05 or less.

RESULTS

Impingement

For the primary outcome measure of radiographic impingement (Table 2), 2 of 6 (33.3%) TT grafts impinged on the intercondylar roof and sustained angular deformation (IRI type 1) (Figure 5). This outcome was not statistically significant ($P = .45$).

The remaining 4 TT grafts made no contact with the roof (IRI type 3), although 2 of these grafts may have impinged but for a 6-mm posterior enlargement of the tibial tunnel that possibly occurred during femoral tunnel drilling despite careful technique. In the IF group, no grafts demonstrated IRI type 1 impingement with deformation, but 2 of 6 (33.3%) were observed to touch the intercondylar roof (IRI type 2) (Figure 6).

TABLE 2
Comparative Assessment of Impingement Between the IF and TT Techniques[a]

	Type 1 (Impinge)	Type 2 (Touch)	Type 3 (Nontouch)
IF technique	0	2	4
TT technique	2	0	4

[a] Values represent the primary outcome measure of anterior cruciate ligament graft-roof impingement based on the Impingement Review Index. Of the 6 cadaveric specimens in each group, 2 of the TT grafts impinged while none of IF grafts impinged. IF, independent femoral; TT, transtibial.

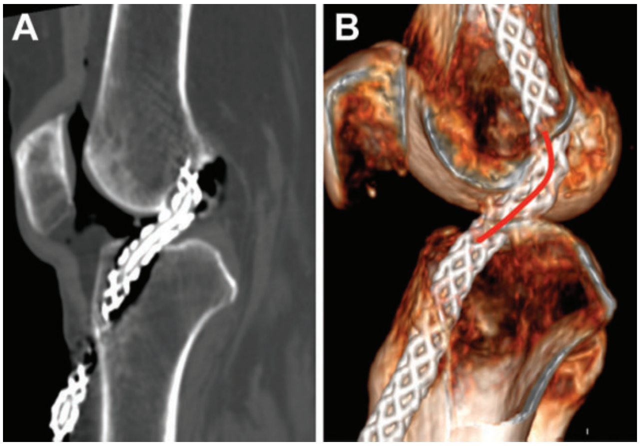

Figure 5. (A) A sagittal computed tomography (CT) slice and (B) 3-dimensional CT volume subtraction of a transtibial specimen that sustained impingement with angular deformation (Impingement Review Index type 1). The center of the tibial tunnel had a Staubli measurement of 29.3.

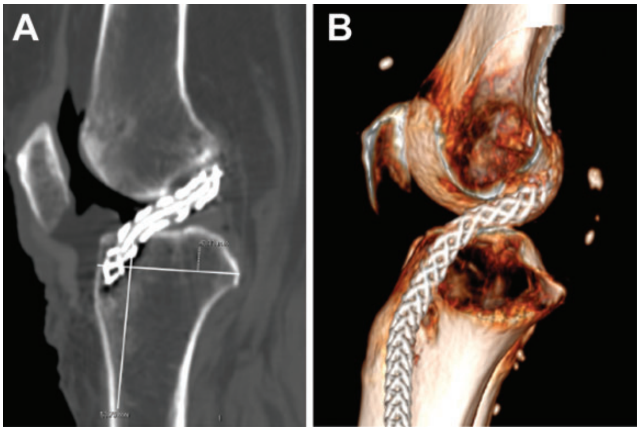

Figure 6. (A) A midsagittal computed tomography (CT) slice and (B) 3-dimensional CT reformatted image after volume subtraction of the independent femoral specimen that was the matched pair to the specimen in Figure 5. Note a more horizontal graft trajectory and touch—but no impingement—with the intercondylar roof.

The remaining 4 IF grafts did not touch the roof (IRI type 3). There was no measurable tibial tunnel enlargement in the IF group.

Tibial Tunnel Position

Secondary outcome measures and results are summarized in Table 3.

The initial anterior-posterior tibial guide pin position, as assessed by fluoroscopy, and the resulting sagittal tibial tunnel position were measured using CT. Staubli's measurement was originally described using a midsagittal magnetic resonance imaging cut taken through the intercondylar notch.[13] Only an approximation was possible for the fluoroscopic analysis of the tibial guide pin position. The mean position along Staubli's line was 27.6%. The mean midsagittal measurement based on a CT scan was 31.6%. As noted, 2 of 6 (33.3%) tibial tunnels in the TT group enlarged $\geq$6 mm posteriorly during reaming of the femoral tunnel, causing the central position to "migrate" from initial guide pin measurements of 27.3% and 32.5% to 50.4% and 42.8%, respectively. In the 2 TT grafts that did impinge, the tunnels were placed at 28.6%, whereas the IF grafts that touched had a mean of 26.6%. No statistical significance or correlation was found between tunnel position and impingement status or drilling technique.

Additional Measurements

The mean RIA for both drilling techniques was 39.6°. This was similar to prior studies[6,8,13] and was essentially identical between groups given the matched pair setup. Femoral tunnel lengths were greater for the TT group, with a mean of 46.6 mm compared with 34.9 mm in the IF group ($P < .001$). Tibial tunnel lengths were equivalent between groups. The sagittal graft angle was 18° more horizontal with the IF technique compared with the TT technique (47.3° ± 4.2° vs 29.1° ± 8°, $P < .001$). Since the roof inclination also references from the AAF, it was possible to determine whether an individual graft geometrically converged or diverged with the intercondylar roof in full extension. Universally, all 6 IF grafts were divergent with the roof, and all 6 TT grafts were convergent (Table 4; Figure 7).

DISCUSSION

The ideal position for the tibial tunnel in ACL reconstruction remains controversial, with an acceptable range of Staubli measurements reported as 30% to 55% in 1 large multicenter study.[15] Several recent studies have suggested that stability,[2,4] biomechanics,[1] and clinical outcomes[7] are superior with an ACL graft placed in the anterior part of the ACL tibial attachment site. However, placing the tibial tunnel too anteriorly has been shown to result in intercondylar roof impingement and inferior clinical outcomes.[8,11] Our study used a cadaveric knee model and 2 accepted ACL femoral tunnel drilling techniques to understand the effect of positioning the ACL tibial tunnel in the anterior part of the tibial attachment site on roof impingement. To our

TABLE 3
Cumulative and Comparative Radiographic Measurements of Secondary Outcome Measures[a]

	Guide Pin Staubli, %	CT Staubli, %	Roof Inclination Angle, deg	Knee Flexion Angle, deg	Tibial Plateau Length, mm	Tibial Tunnel, mm	Femoral Tunnel, mm	Sagittal Graft Angle, deg
Group (n = 12)	27.6 (22 to 33.9)	31.6 (22.8 to 50.4)	39.6 (32.9 to 43)	1.1 (−2.1 to 4.7)	51.6 (42.9 to 64.5)	35.3 (29.6 to 46.8)	40.8 (30.8 to 52)	38.2 (18.8 to 51)
IF (n = 6)	27.2 (22 to 33.9)	28.7 (22.8 to 33.3)	39.9 (32.9 to 43)	0.1 (−2.1 to 1.9)	51.4 (43.1 to 58.5)	34.3 (29.6 to 44.8)	34.9 (30.8 to 40.3)	47.3 (41.6 to 51)
TT (n = 6)	27.9 (26.3 to 32.5)	34.6 (27.8 to 50.4)	39.3 (35.8 to 43)	2.1 (−1.9 to 4.7)	51.8 (42.9 to 64.5)	36.4 (30.9 to 46.8)	46.6 (40.9 to 52)	29.1 (18.8 to 37)
P value	.73	.2	.76	.14	.92	.57	**.0006**	**.0006**

[a] Values given as mean (range), with statistical significance noted between groups with regard to femoral tunnel length and sagittal graft angle (boldfaced entries). CT, computed tomography; IF, independent femoral; TT, transtibial.

TABLE 4
Comparison of Sagittal Obliquity of the Graft and Intercondylar Roof[a]

	SGA, deg	RIA, deg	RIA − SGA, deg
IF (n = 6)	47.3	39.9	−7.4
TT (n = 6)	29.1	39.3	10.2
P	.0006	.76	.0003

[a] Both SGA and RIA are measurements of obliquity in relation to the anatomic axis of the femur (AAF). Thus, a greater value equates to a more horizontal trajectory relative to the AAF. The third column is a simple arithmetic calculation of whether a graft is geometrically converging (positive value) or diverging (negative value) when it traverses from the tibial tunnel to the femoral tunnel. IF, independent femoral; RIA, roof inclination angle; SGA, sagittal graft angle; TT, transtibial.

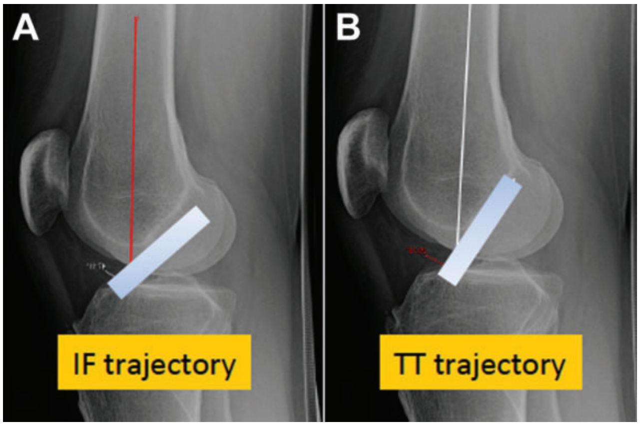

Figure 7. Superimposed graphical depiction of the mean sagittal graft angle (SGA). The mean SGA for the independent femoral (IF) specimens (47.3°) indicates they were more horizontal than that of the independent femoral specimens (29.1°). TT, transtibial.

knowledge, our study is the first to use 3D CT to evaluate graft impingement properties after single-bundle ACL reconstruction.

With regard to the primary outcome measure of roof impingement, the observed difference of 2 out of 6 (33.3%) impinged grafts in the TT and 0 out of 6 in the IF group was not statistically significant. We believe that impingement was averted artificially in 2 additional TT grafts by posterior enlargement of the tibial tunnel that occurred during femoral tunnel reaming. This phenomenon denotes the difficulty we faced in placing accurate femoral tunnels transtibially. Despite the 2 TT specimens with posteriorly enlarged tibial tunnels, the post–tunnel drilling CT confirmed the successful placement of the tibial tunnel in the anterior third of native ACL footprint at 31.6%. Whereas one-third of TT grafts impinged, the IF technique appears to be protective against impingement in the setting of far-anterior tibial tunnels. That 0 of 6 IF specimens sustained pathologic impingement even with such an anterior tibial tunnel position defies previous assumptions regarding graft roof impingement.

Significant differences in the secondary outcome measures did emerge between the 2 groups. One plausible explanation for this arises from an analysis of graft geometry, tunnel position, and the anatomy of the intercondylar roof in full extension. For ACL grafts with anterior tibial tunnels, our data support the conclusion that TT grafts impinge because of convergence with the intercondylar roof angle in the sagittal plane owing to a nonanatomic femoral tunnel that is too proximal (Table 4; Figure 7). Essentially, the most distal point of the roof becomes an obstacle in the straight-line trajectory between the 2 tunnels. This conclusion is supported by the well-established fact that TT grafts centered in the posterior half of the tibial footprint avoid impingement with the roof,[8,11] as this starting position is more posterior than the tip of the roof of the intercondylar notch.

Conversely, the IF technique more accurately places the femoral tunnel in the anatomic footprint[14] and does so irrespective of the tibial tunnel. In our study, the IF technique was associated with a more horizontal sagittal graft angle, which diminished the risk for roof impingement. The difference in graft angles between TT and IF specimens in our study is consistent with the findings of Bowers et al,[3] who reported that TT grafts were an average of 14.9° more vertical than their IF counterparts. In their study, the 2 techniques achieved similar femoral tunnel aperture positions, but this came at the expense of an average tibial tunnel positioned 6 mm more posteriorly.

In our study, we noted that 2 of 6 tibial tunnels enlarged 6 mm in the posterior direction during transtibial drilling, even though the tibial guide pin was placed in the anterior third of the native ACL tibial attachment site.

Our study is not the first to assess the risk of roof impingement with the IF technique. In a study of 24 patients who underwent anatomical double-bundle ACL reconstruction, Iriuchishima et al[9] utilized 3D CT to evaluate for impingement. The average sagittal tibial position of the anteromedial bundle in the study was 34.2. Zero grafts impinged in full extension, although 12 of 24 were noted to make contact without deforming (IRI type 2). The authors concluded that surgeons can perform anatomic ACL reconstruction without risk for impingement. In our study, there was no impingement in the IF group despite an even further anterior position of the tibial tunnel at 28.7.

The results of our study are in agreement with those of Hantes et al,[6] who investigated the sagittal geometry of the native ACL using MRI. They described the "ACL angle," which measures the angle of a line along the intact ACL with regard to the long axis of the tibia. This was noted to have a mean of 52° (45°-56°). Bearing in mind that the ACL angle references from the tibia, it provides a complementary angle to the SGA, which references the femur. By extrapolation, the study by Hantes et al[6] yields an average SGA of 38° (34°-45°). Hence, our study found that the TT grafts demonstrated a more vertical angle to that of a native ACL while the IF grafts were more horizontal. For example, an ACL graft at 38° in the sagittal plane would traverse the knee in a near perfect parallel to Staubli's reported roof inclination angle of 39.8°. Accordingly, the study by Hantes et al[6] validates Staubli's recommendation to "[place] the center of the tibial tunnel at 44% of the tibia diameter posterior and parallel to the individual intercondylar roof inclination angle." Although placing the tibial tunnel at 44% along the Staubli line will decrease the risk of roof impingement when a TT or IF technique is used to drill the ACL femoral tunnel, the findings of our study demonstrate that when an IF technique is used to drill the ACL femoral tunnel, ACL grafts centered in the anterior part of the native ACL tibial attachment site are also safe from roof impingement. It is important to note that our study used an 8-mm tunnel to simplify measurements and accommodate the tunnel smoother size. An 8-mm tunnel is not appropriate for all clinical situations or graft types, and caution is advised in the placement of a tibial tunnel in the far anterior position if a much larger tunnel is needed.

Limitations

The small sample size may have contributed to an inability to find statistical significance for the primary outcome. We acknowledge the inherent limitations of the cadaveric design of the study. While a novel radiographic tool, the Gore-Tex smoother used as a surrogate for an ACL graft may not accurately represent the intra-articular properties of a biologic graft. We did not assess whether any specimens lost knee extension after graft passage and "fixation," which could contribute to any differences noted in motion postprocedure. Furthermore, the mean knee extension angle during CT scanning for all specimens was 1.1° (range, −2.1° [hyperextension] to 4.7°) (Table 3). The mean for the TT group (2.1°) was higher than the IF group (0.1°, $P = .14$). Three TT specimens had >4° of residual flexion in the CT scanner, and we surmise the possibility of a preexisting flexion contracture in the cadaver specimen. Theoretically, this may have inhibited roof impingement or touch that otherwise would have occurred in the TT group.

CONCLUSION

When the tibial tunnel was intentionally placed in the anterior third of the native ACL tibial attachment site, ACL graft impingement upon the intercondylar roof occurred with a transtibial drilling technique but did not occur with an independent femoral drilling technique. With the knee in full extension, the sagittal trajectory of the transtibial grafts was convergent with the Blumensaat line, but for independent femoral grafts it was divergent. Despite guide pin placement in the anterior third of the tibial attachment site, the transtibial drilling technique was associated with posterior enlargement of the tibial tunnel during drilling of the femoral tunnel. The importance of anatomic femoral tunnel placement, unquestionably a strength of the IF technique, is highlighted by our findings. Further work is necessary to further delineate the complex interaction between tunnel position and impingement in the clinical setting.

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