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Coverage of the Anterior Cruciate Ligament Femoral Footprint Using 3 Different Approaches in Single-Bundle Reconstruction

A Cadaveric Study Analyzed by 3-Dimensional Computed Tomography

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Investigation performed at North Mayenne Hospital, Mayenne, France

Background: Performing a single-bundle anterior cruciate ligament (ACL) reconstruction within the femoral footprint is important to obtain a functional graft and a stable knee.

Hypothesis: There will be a significant difference in the ability of 3 ACL reconstruction techniques to reach and cover the native femoral footprint.

Study Design: Controlled laboratory study.

Methods: The percentage of the ACL footprint covered by the femoral tunnel was compared after 3 different techniques to target the footprint: transtibial (TT), inside-out/anteromedial (IO), and outside-in/transfemoral (OI). Fourteen cadaveric knee specimens with a mean age of 67.5 years were used. For each knee, the TT technique utilized a 7.5-mm offset guide, the IO technique was performed through an accessory anteromedial portal, and the OI technique was carried out through the femur from the external wall of the lateral condyle. Entry points in the footprint were spotted with markers, and orientations (sagittal and frontal) of each drill guide were noted. The distal femurs were sawed and scanned, and 3-dimensional image reconstructions were analyzed. The virtual drilled area (reamer diameter, 8 mm) depending on the entry point and the sagittal/frontal orientation of the drill guide was calculated and reported for each of the 3 techniques. The distance from the tunnel center to the ACL center, percentage of the femoral tunnel within the ACL footprint, and percentage of the ACL footprint covered by the tunnel were calculated and statistically compared (analysis of variance and *t* test).

Results: The average distance to the native femoral footprint center was 6.8 $\pm$ 2.68 mm for the TT, 2.84 $\pm$ 1.26 mm for the IO, and 2.56 $\pm$ 1.39 mm for the OI techniques. Average percentages of the femoral tunnel within the ACL footprint were 32%, 76%, and 78%, and average percentages of the ACL footprint covered by the tunnel were 35%, 54%, and 47%, for the TT, IO, and OI techniques, respectively. No significant difference was observed between the IO and OI techniques (P = .11). The TT approach gave less satisfactory coverage on all testing criteria.

Conclusion: The IO and OI techniques allowed for creation of a tunnel closest to the ACL femoral footprint center. Despite this fact and even if the average percentage of the drilled area included in the femoral footprint was close to 80% for these 2 techniques, the average percentage of the ACL footprint covered by the tunnels was <55% for all 3 techniques. Coverage of the ACL footprint depended on the entry point, orientation, and diameter of the drilling but also on the size of the footprint.

Clinical Relevance: To improve the coverage of the native femoral footprint with a single-bundle graft, in addition to the entry point it may also be necessary to consider the orientation of the drilling to increase the dimensions of the area while respecting the anatomic constraints of the femoral bone and graft geometry.

Keywords: anterior cruciate ligament; femoral footprint; anatomic reconstruction; transtibial, outside-in; inside-out; 3D CT

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Over the past few years, the focus of anterior cruciate ligament (ACL) reconstruction has evolved from a priority placed on isometric reconstruction to an approach that focuses more on anatomic considerations to improve the kinematics of the reconstructed knee.[2,9,11,34] Anatomic reconstructions may have improved clinical results.[17] In the absence of anatomic reconstruction, the kinematics of the knee is modified, and the risk of developing osteoarthritis has been shown to be higher over the long term.[5,26,29]

During a single-bundle reconstruction, the goal is typically to position the graft between the center of the 2 footprints of the 2 bundles ("mid-mid" technique)[19] and cover the native femoral and tibial insertions, thereby reproducing the orientation and function of the native ACL.[45] Many anatomic studies have precisely described the insertion sites of the ACL compared with osseous landmarks used during arthroscopic surgery.[8,33] There is significant variability in the dimensions of the insertion sites and direction of the femoral footprint.[25] The goal for surgeons is to best reproduce the anatomy of each patient by identifying the center, boundaries, and area of the footprint.[47] Orientation of the footprint is different for the femur and the tibia and is at the origin of respective movements of each bundle, anteromedial and posterolateral, during flexion-extension. The anterograde or retrograde drilling of the femur, usually in an oblique way, creates an oval-shaped opening, more or less close to the anatomic footprint obliquity. The femoral attachment site has a greater effect than the tibial attachment site on graft length changes in flexion and extension, and minor alterations of the femoral footprint may be significant.[20,32] In this cadaveric study, we are interested in evaluating the coverage of the native femoral footprint for a single-bundle reconstruction using 3 common surgical approaches: transtibial (TT), anteromedial portal/inside-out (IO), and transfemoral/outside-in (OI). For the IO and OI techniques, femoral and tibial drillings are independent, while the TT technique is dependent and constrained by the tibial tunnel. The TT technique is commonly used, especially in the United States,[27,43] but does not appear to be accurate or reproducible in accessing the majority of the femoral footprint.[12,36,42] Regardless of technique, in a single-bundle reconstruction, surgeons are directing the drill to the footprint, but dimensions and orientation of the drilling area are dependent on many factors including frontal and coronal obliquity of the drill guide, diameter of the drill, and degree of knee flexion. These parameters influence the orientation of the shape of the opening obtained with the drilling and determine the percentage of coverage of the native footprint. The goal is to obtain maximum coverage of the femoral footprint and to have a maximum number of fibers recruited during flexion-extension and pivot movements.[22] If only a part of the footprint is covered, only some fibers will be functional. In theory, the higher the percentage of the individual footprint that is restored, the better expected the functional outcome for the patient.[38] For this work, 3-dimensional (3D) reconstructions by computed tomography (CT) have been used, which is the gold standard to evaluate bony morphological structures.[21] The ability to isolate specific anatomic images after rotation makes 3D CT a powerful tool for visualizing the femoral tunnel location.[21]

The goals of this cadaveric study were to measure the distance of the tunnel center to the native ACL center, the percentage of the femoral tunnel within the ACL footprint, and the percentage of the ACL footprint covered by the tunnel using the IO, OI, and TT techniques. To the best of the authors' knowledge, there has not been any prior cadaveric study evaluating this comparison, but there is a theoretical work by Hensler at al[15] about the influence of drilling parameters on the femoral tunnel. The hypothesis was that these 3 techniques would not access the center of the native femoral footprint or cover it in the same way.

MATERIALS AND METHODS

The study was performed by using 14 fresh-frozen human cadaveric knee specimens (midfemur to midtibia; 9 right knees, 5 left knees) with a mean age of 67.5 years (range, 57-82 years). Written consent for their use for educational and research purposes was obtained from the donor for each specimen. All cadaveric knees had an intact ACL and minor cartilage and meniscal lesions, except one (femur 6, which was excluded). Specimens were obtained from the Anatomic Laboratory of Rennes and were preserved at −20°C and thawed at room temperature 1 day before experimental testing. Femurs were secured on the laboratory table with a vise to maintain the axis of the femur horizontally and keep the tibia free (knees in 90° of flexion). A lateral parapatellar portal was used for the insertion of the 30° scope. A traditional anteromedial portal was used for debridement of the ACL with a basket grasper, leaving the femoral footprint intact. A short cuff of tissue was left for visual evaluation of the location, shape, and size of the footprint.[4,24] The 3 techniques were performed on each specimen by a senior surgeon (H.E.R.), and the sequence among the 13 specimens of the 3 techniques used was randomized.[10] After each step, the pin was recessed in the lateral condyle by 5 to 7 mm to not interfere with the subsequently placed pin. At the end of the 3 steps, the 3 drill guides corresponding to the 3 techniques were repositioned in the lateral condyle, flush with the notch wall. No reaming was done in the cortex of the lateral condyle.

Surgical Techniques

Transtibial Technique. For the TT technique, the knee was placed at 90° of flexion, and an ACL tibial aimer (Arthrex, Naples, Florida) was used to place a guide pin in the center of the native tibial ACL insertion.[26,27] The

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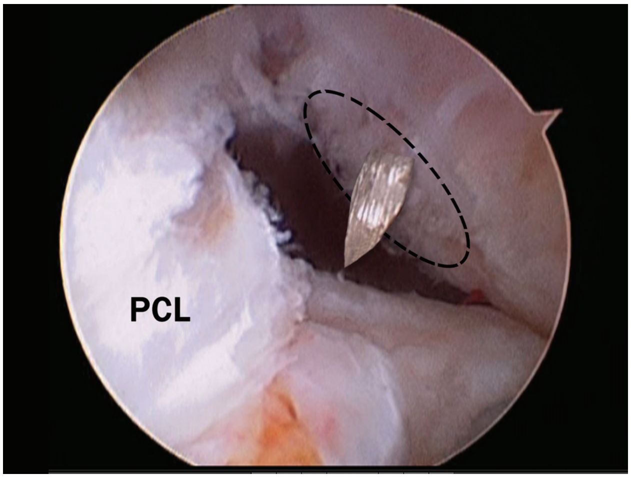

Figure 1. Arthroscopic view of the outside-in technique. The pin was placed as close as possible to the center of the femoral footprint.

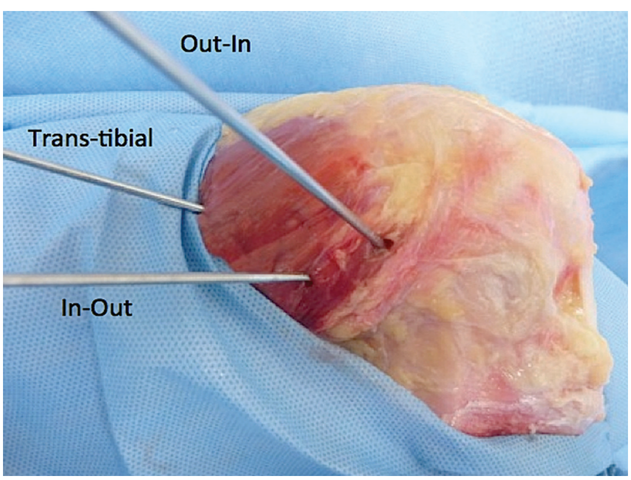

Figure 2. Lateral view of a right knee with the 3 pins.

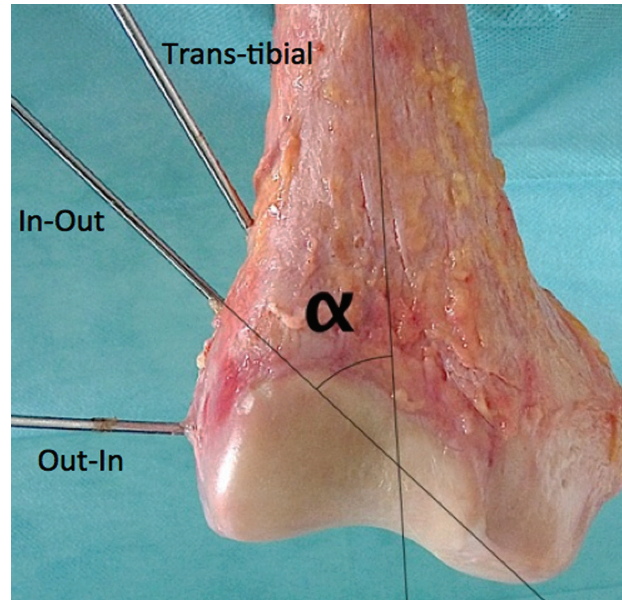

Figure 3. Frontal angle (α) between each pin and the long axis of the femur.

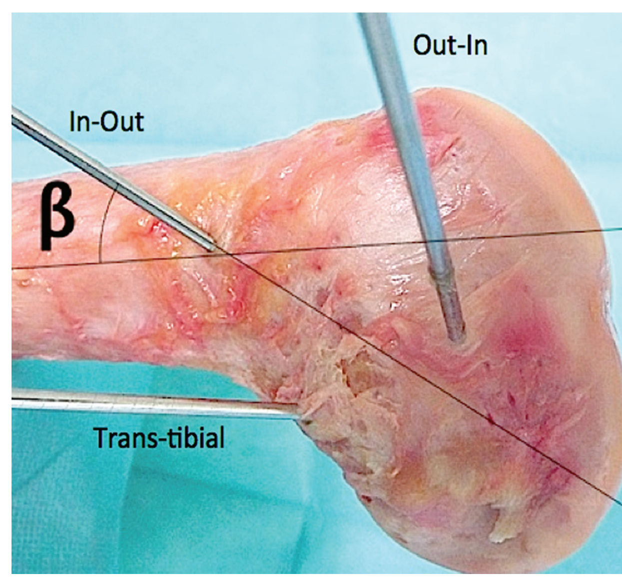

Figure 4. Sagittal angle (β) between each pin and the long axis of the femur.

starting point on the tibia was placed a mean 21.1 ± 4.2 mm from the anterior margin of the medial collateral ligament and 31.8 ± 3.6 mm from the edge of the medial tibial plateau, according to Piasecki et al.[35] The guide pin was inserted at approximately a 65° angle within the tibial plateau. An 8 mm–diameter cannulated drill was used to create the tibial tunnel (Arthrex). A 7.5-mm offset guide (Arthrex) was introduced and placed over the posterior aspect of the lateral femoral condyle, generally between 45° and 90° of knee flexion, and then the knee was flexed to 80° to 90°. The offset was then laterally rotated so as to position the drill guide as close to the center of the ACL footprint as possible. A guide wire (2.4-mm diameter) was then advanced through the lateral femoral condyle.

Inside-Out Technique. The IO technique was performed more inferior (5 mm) and medial (1 to 2 cm) than the traditional anteromedial technique.[7,14] A pilot hole was created by a chondral pick at the center of the footprint according to its visual limits. A guide pin was inserted through the accessory portal into the pilot hole with the knee flexed to 120° and advanced through the lateral femoral condyle.[10]

Outside-In Technique. The OI technique was conducted with a 115° femoral drill guide (FH Orthopedics, Chicago, Illinois) introduced into the anteromedial portal with the knee fixed at 90° of flexion. The tip of this guide was placed as close as possible to the center of the ACL femoral footprint with an extra-articular visual angulation of 45°

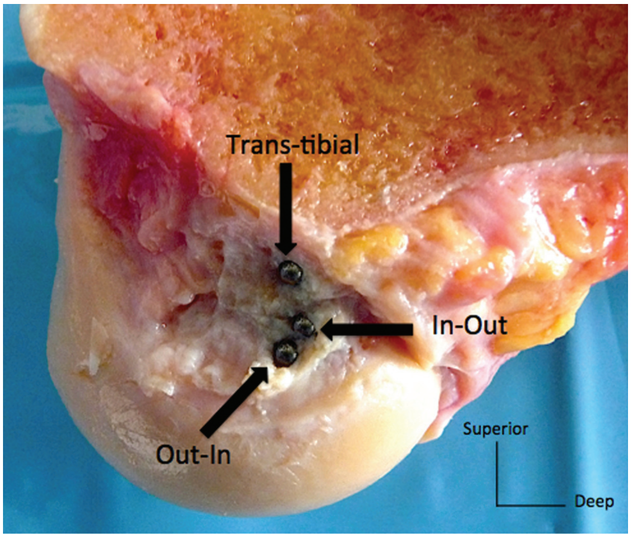

Figure 5. Each entry point of the 3 pins in the medial wall of the lateral condyle was spotted with a 2-mm nonmetallic marker. The positions of the markers were located according to common arthroscopic terminology.

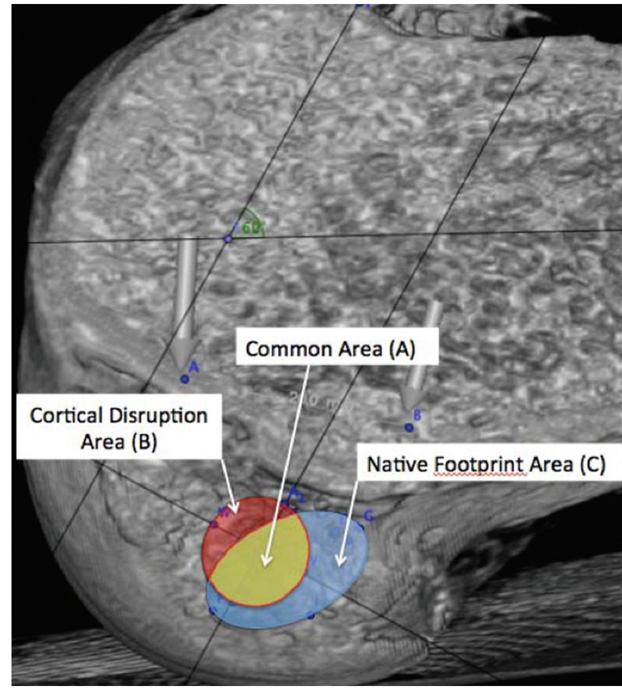

Figure 6. The area of the native femoral footprint was reproduced on the profile view (C) according to the anatomic size. The percentage of the cortical disruption included in the native femoral footprint was the ratio A/B. The percentage of the native femoral footprint covered by the cortical disruption was the ratio A/C.

relative to the frontal and sagittal axes of the distal thigh.[6] A small incision on the lateral thigh through the iliotibial band allowed for insertion of the guide wire sleeve into the bone. The entry point was situated above and behind the lateral epicondyle. The pin was then advanced until it reached the tip of the femoral aimer (Figure 1).

When the 3 pins had been inserted in the femur (Figure 2), all musculature surrounding the joint was removed. Frontal (α) (Figure 3) and sagittal (β) (Figure 4) angles between each pin and the long axis of the femur were registered. The medial femoral condyle was then carefully removed with an oscillating saw, avoiding any perturbation on CT. The exposure after splitting gave an excellent view of the ACL footprint and the 3 pins. Each entry point of the 3 pins in the medial wall of the lateral condyle was spotted with a 2-mm nonmetallic marker and named a "tunnel center" (Figure 5).[10] The anterior-posterior and medial-lateral dimensions of the femoral footprint of the native ACL were measured using a digital caliper (Avenger Products, Boulder City, Nevada) with a resolution of 0.1 mm and an accuracy of 0.05 mm.[43]

Data Analyses

The CT scans using thin 1-mm cuts and 3D reconstructions of the distal femur of each specimen were obtained using an Aquilion 16 scanner (Toshiba Medical Systems Europe BV, Zoetermeer, the Netherlands). On a Vitrea 2 postprocessing workstation (Vital Images, Minnetonka, Minnesota), a 3D view of the femoral condyle was obtained (3D CT images). The analysis was performed on a scanned image in the plane of the medial wall of the lateral condyle that replicated a profile view. The knees were studied in 90° of flexion, reproducing the arthroscopic position. The 3D profile views were studied with Geogebra 4.0.38.0 software (Geogebra, Salzburg, Austria). A femoral coordinate system was created with a proximal-distal axis (x-axis) defined parallel to the long axis of the femur (line passing through the midpoints of the anterior and posterior cortices) and an anterior-posterior axis (y-axis) defined perpendicular to the proximal-distal axis in the medial part of the lateral condyle plane (Figure 6). The area of the native femoral footprint was reproduced on the profile view (Figure 6, "C") according to the anatomic size already collected with a caliper, and the center of the footprint was marked (ACL center). The distance between the tunnel center and the ACL center was registered using this coordinate system.

A virtual femoral tunnel was projected on the native femoral footprint. The shape of the virtual tunnel can be assimilated to an ellipse, with the minor axis (d) constantly equivalent to the diameter of the drill bit and with the major axis (D) dependent on the orientation of the guide pin. This major axis can be calculated with the frontal angle (α) of each guide pin with the following equation: $D = d/\sin \alpha$ (Figure 7).[15,22] The area of the ellipse (E) was calculated with the following equation: $E = \pi \times (D/2) \times (d/2)$, with a diameter of the drill bit (d) of 8 mm.[22] The virtual ellipse was then projected on the femoral footprint, centered on the tunnel center, and sagittally oriented according to the β angle. For each technique, the percentage of the femoral tunnel included in the native footprint (A/B) and the percentage of the femoral footprint covered by the tunnel (A/C) were calculated (Figure 6).

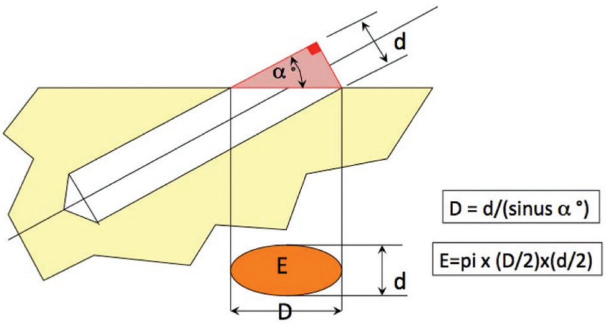

Figure 7. The area of the ellipse (E) was calculated with the following equation: E = $\pi \times (D/2) \times (d/2)$, with a diameter of the drill bit (d) of 8 mm.

Statistical Analyses

Normality tests were conducted to confirm the normal distribution. All values were expressed as mean ± standard deviation. Values were continuous variables and were compared with *t* tests and analysis of variance (ANOVA). A *P* value of .05 was considered statistically significant. Statistical analysis was performed by use of Stata (StataCorp, College Station, Texas).

RESULTS

Frontal and Sagittal Angulations of the Guide Pin

The frontal orientations (α angle) of the guide pin had an average of 30.61° ± 5.45° (range, 21°-37°) for the TT, 51.84° ± 6.64° (range, 45°-65°) for the IO, and 72.08° ± 10.34° (range, 55°-90°) for the OI techniques. Concerning the sagittal orientations (β angle) of the guide pin, the TT technique had an average of 39.84° ± 12.22° (range, 17°-40°), 21.31° ± 19.91° (range, 0°-40°) for the IO technique, and 52.61° ± 18.49° (range, 25°-80°) for the OI technique (Tables 1 and 2).

Location of the Tunnel Center Relative to the ACL Footprint Center

The marker for the TT technique was the farthest from the native femoral footprint center at an average of 6.8 ± 2.68 mm (range, 3.9-12.7 mm), followed by the IO technique at 2.84 ± 1.26 mm (range, 0.1-6.1 mm). The OI technique was the closest at an average of 2.56 ± 1.39 mm (range, 0-4.8 mm). With the IO and OI techniques, no tunnel center was out of the target, while 5 tunnel centers with the TT technique were outside the target area (Table 3).

Native Femoral Footprint and Drilled Areas for the 3 Techniques

The length of the minor axis of the native femoral footprint had an average of 9.2 ± 0.9 mm (range, 8.1-10.7 mm), and the major axis had an average of 16.3 ± 1.2 mm (range, 14.2-18.7 mm). The average area of the femoral footprint was 118 ± 11.3 mm^2 (range, 100.6-138.9 mm^2). The average cross-sectional areas calculated at the aperture of the femoral tunnels created by the TT, IO, and OI techniques were 127.5 ± 24.3 mm^2 (range, 94.6-177.2 mm^2), 84.2 ± 7.3 mm^2 (range, 72-98.2 mm^2), and 69.5 ± 6 mm^2 (range, 63.3-83 mm^2), respectively.

Percentage of the Femoral Tunnel Within the ACL Footprint

The lowest average percentage of the drilled area included in the femoral footprint was with the TT technique and was 32.47% ± 19.28% (range, 9.1%-69.8%). Average percentages were close to 80% for the 2 other techniques: 75.62% ± 11.71% (range, 58.1%-93.3%) for the IO and 77.6% ± 17.5% (range, 33.6%-99%) for the OI techniques. The difference was significant between the TT and IO ($P < .001$) and OI techniques ($P < .001$) but not between the IO and OI techniques ($P = .73$) (Table 4).

Percentage of the Femoral Footprint Covered by the Tunnel

The average percentage of the femoral footprint covered by the drilled area was 35.39% ± 19.79% (range, 8.4%-64.3%) for the TT technique. It averaged 53.97% ± 7.78% (range, 40.2%-65.5%) for the IO technique and 46.87% ± 12.89% (range, 20.7%-71.6%) for the OI technique ($P = .11$). The difference was significant between the TT and IO techniques ($P = .006$) but not between the TT and OI techniques ($P = .09$) and not between the IO and OI techniques ($P = .1$) (Table 5).

DISCUSSION

This experimental study demonstrated several interesting observations. The independent techniques, IO and OI, were able to cover more of the ACL femoral footprint than the TT technique. The center of the tunnels created by the OI and IO techniques was closer to the anatomic ACL center footprint than the center of the TT technique's tunnel. However, none of the 3 techniques meets all the conditions: centering, orientation of the guide pin in the 2 planes, reamer diameter identical to the diameter of the footprint, and no technique able to cover a large portion (80% or more) of the femoral footprint.[46]

As a result of many studies, the anatomy of the femoral footprint is now well described.[8,33,39] The entire ACL insertion area is located in the posterior third of the medial wall of the lateral femoral condyle and lies nearly horizontal with the anteromedial insertion proximal to the posterolateral insertion. The footprint has the shape of an ellipse, more or less elongated, oblique relative to the axis of the femur. According to different authors, the width of the footprint varies from 8 to 11 mm and the length from 11 to 21 mm, which explains the variations in the footprint area from the single to double (from 83 to 197 mm^2).[23,25,38] Sagittal obliquity of the footprint relative to

TABLE 1
Frontal Orientation of the Guide Pin (α Angle)[a]

	α Angle, deg													
Technique	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 7	Femur 8	Femur 9	Femur 10	Femur 11	Femur 12	Femur 13	Femur 14	Mean ± SD
Transtibial	30	35	25	28	30	37	35	37	30	32	21	22	36	30.6 ± 5.4
Inside-out	50	60	50	49	60	47	50	45	45	65	45	50	58	51.8 ± 6.6
Outside-in	60	75	65	55	80	75	80	85	75	90	62	70	65	72.1 ± 10.3

[a]*P* values for all comparisons (transtibial vs inside-out, transtibial vs outside-in, outside-in vs inside-out) were <.001.

TABLE 2
Sagittal Orientation of the Guide Pin (β Angle)[a]

	β Angle, deg													
Technique	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 7	Femur 8	Femur 9	Femur 10	Femur 11	Femur 12	Femur 13	Femur 14	Mean ± SD
Transtibial	40	35	55	50	17	52	60	37	39	30	43	25	35	39.8 ± 12.2
Inside-out	23	30	40	40	0	35	10	0	9	40	10	0	40	21.3 ± 16.9
Outside-in	60	30	80	50	35	65	76	25	33	45	50	75	60	52.6 ± 18.5

[a]*P* values: transtibial vs inside-out = .004; transtibial vs outside-in = .05; outside-in vs inside-out = .001.

TABLE 3
Distances to the Native Femoral Footprint Center from the Markers[a]

	Distance to the Native Femoral Footprint Center from the Markers, mm													
Technique	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 7	Femur 8	Femur 9	Femur 10	Femur 11	Femur 12	Femur 13	Femur 14	Mean ± SD
Transtibial	3.97	12.67	8.05	8.01	6.14	11.17	4.53	4.72	3.86	6.04	7.55	6.13	5.58	6.80 ± 2.68
Inside-out	2.07	2.91	3.00	3.07	2.70	2.52	0.96	4.96	0.11	3.38	3.75	3.64	3.87	2.84 ± 1.26
Outside-in	2.07	3.60	3.00	1.30	4.80	2.52	3.45	4.35	2.65	0.00	0.98	1.29	3.32	2.56 ± 1.39

[a]*P* values: transtibial vs inside-out < .001; transtibial vs outside-in < .001; outside-in vs inside-out = .6.

TABLE 4
Percentages of the Cortical Disruption Included in the Native Femoral Footprint[a]

	Percentages of the Cortical Disruption Included in the Native Femoral Footprint, %													
Technique	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 7	Femur 8	Femur 9	Femur 10	Femur 11	Femur 12	Femur 13	Femur 14	Mean ± SD
Transtibial	50.04	9.10	40.18	10.88	21.90	16.76	47.88	40.55	69.83	20.97	11.15	29.70	53.18	32.47 ± 19.28
Inside-out	74.40	87.07	63.92	83.76	64.34	84.64	88.04	62.20	93.31	66.69	72.33	83.94	58.41	75.62 ± 11.71
Outside-in	78.40	65.00	68.55	88.26	33.64	89.88	69.08	74.72	88.75	96.10	99.01	89.40	68.04	77.6 ± 17.5

[a]*P* values: transtibial vs inside-out < .001; transtibial vs outside-in < .001; outside-in vs inside-out = .73.

TABLE 5
Percentages of the Femoral Footprint Covered by the Cortical Disruption[a]

	Percentages of the Native Femoral Footprint Covered by the Cortical Disruption, %													
Technique	Femur 1	Femur 2	Femur 3	Femur 4	Femur 5	Femur 7	Femur 8	Femur 9	Femur 10	Femur 11	Femur 12	Femur 13	Femur 14	Mean ± SD
Transtibial	61.63	8.40	55.72	11.03	26.25	15.61	47.41	36.87	64.30	24.10	16.32	39.24	53.20	35.39 ± 19.79
Inside-out	60.33	50.64	48.73	52.23	45.50	65.39	65.50	47.32	61.01	58.83	52.91	53.02	40.16	53.97 ± 7.78
Outside-in	60.93	35.57	41.85	51.17	20.66	53.88	40.34	40.85	41.29	71.61	59.58	47.08	44.47	46.87 ± 12.89

[a]*P* values: transtibial vs inside-out = .006; transtibial vs outside-in = .09; outside-in vs inside-out = .11.

the axis of the femur varies from 0° to 24° with an average of 12°.[39]

The IO and OI techniques allowed a positioning of the drill guide very close to the center of the ACL, except for one case (femur 6, IO technique). The accessory approach that was performed is a more medial and more favorable approach than the classic anteromedial approach.[34] Markers of the entry points for the TT technique were always the farthest from the anatomic center of the footprint (6.8 ± 2.68 mm) and were predominantly (11/14 cases) superior and deep according to common arthroscopic terminology, leading to a vertical and nonanatomic graft. This observation is in agreement with other studies evaluating the location of the TT technique's tunnel with respect to the ACL center.[2,18,21,40,43,44] This is likely because the IO or OI techniques employed independent femoral drilling, in contrast to the TT technique.[18,22] The independent techniques allow surgeons to individualize the tunnel placement and to ideally place it in the ACL center. Difficulties exist with the IO approach, particularly the need for knee hyperflexion, that make visualization challenging and cause potential risks to the peroneal nerve.[31] The OI technique can be a good solution for centering, and it allows a versatility in the direction of the drill guide and avoids the pitfalls of the IO approach.[11,18,27] A potential disadvantage of the OI technique can be the existence of an abrupt turn between the femoral tunnel and the direction of the intra-articular graft.

The percentage of the ACL footprint covered by the tunnel is dependent on the entry point and the orientation and diameter of the drill. Average percentages of the drilled area included in the native femoral footprint were high for the OI and IO approaches (78% and 76%, respectively) because of the placement of the pilot hole. Our results are similar to those of Gadikota et al,[10] who reported 89% and 86% for the OI and IO techniques, respectively. The percentages of the femoral footprint covered by the drilled area were less than 55% for the 3 techniques. The maximum coverage was achieved by the IO technique, followed by the OI technique (P = .11), and these 2 techniques are better than the TT technique ($P < .05$). These results are similar to those of Gadikota et al[10] and Hensler et al.[15] For the TT technique, the coverage of the footprint was poor (35.4%), as in the study of Strauss et al[43] (30%).

In practice, the width (minor axis) of the virtual femoral tunnel corresponds to the diameter of the drill, and the length (major axis) depends on the frontal inclination (α angle). For an inclination with an α angle equal to 90° (drill guide is perpendicular to the footprint), the tunnel is a cylinder with a section that is a circle, but if the α angle decreases, the section becomes an ellipse. As the drill guide is increasingly oblique, the major axis of this ellipse becomes longer.[15] Frontal orientation is thus the dominant factor on the length of the ellipse. The α angle was 51.8° for the IO technique in our study, as recommended by Hensler et al.[15] In contrast, Siebold et al[39] advocated a frontal angulation between 65° and 75°, which seems to put the cartilage of the medial femoral condyle at risk in the absence of a flexible guide wire and reaming system.[4,41] Yet, in the IO technique, drilling with a frontal angle of 30° might damage the cartilage of the posterior aspect of the lateral condyle and can lead to a posterior blowout. Secondly, an elongated tunnel increases the ratio between the footprint and the cross-sectional area of the graft, which might adversely affect ACL function.[13] For the OI technique, we measured an average of frontal angulation of 72.1°, which is higher than recommended (45°).[6] This excessive angulation explains the smaller area of the virtual ellipse for the OI technique than for the IO technique (difference of 14.7 mm^2). It also explains the smaller percentage of the femoral tunnel within the ACL footprint (difference of 4.42 mm^2) between the 2 techniques. Excessive frontal angulation exposes the graft to an abrupt turn, which may injure the ligament fibers ("ACL killer turn"), as has been observed at the tibial tunnel exit in posterior cruciate ligament reconstruction. A high α angle places the femoral aimer above and behind the epicondyle, while an angle less than 45° requires crossing the lower muscular part of the vastus lateralis. With the OI technique, a frontal angulation close to 45° is possible to improve the area of the ellipse, without risk for the lateral condyle. On the contrary, with the TT technique, frontal orientation is low (30.6° on average), which increases the major axis and thus the area of the ellipse. This low angulation is secondary to the parasagittal position of the tibial tunnel. The sagittal angulation (β angle) is important for the orientation of the tunnel and the recovery of the femoral footprint. Hensler et al[15] proposed a theoretical model: a frontal (α) angle of 50° with an IO approach and a sagittal (β) angle of 12°, with the knee being flexed at 90°. The same result is obtained if the knee is flexed at 102° with a horizontal position of the drill guide. The authors proved the unfavorable role of the increase in flexion of the knee on the length of the ellipse.[15] The decrease in the sagittal angle leads to the same effect. Our study found a lower sagittal angulation (average of 21°) for the IO technique relative to the other techniques (40° for the TT and 53° for the OI). With the TT technique, the orientation of the femoral drill guide is imposed by the tibial tunnel, but this orientation is free for the OI technique and can be decreased to adapt to the native femoral footprint. It seems to us that an OI approach with a β angle between 10° and 20° would be more favorable than 45°, as recommended in the technical note, because it would allow a slightly oblique drilling, in the axis of the femoral footprint.[6]

Basdekis et al[3] studied the effect of knee flexion angle on tunnel orientation and length when drilling through the anteromedial portal. They noted that knee flexion angles of 90° led to a higher risk of posterior wall blowout and a shorter tunnel.[3] Tunnels drilled at 130° resulted in a vertical tunnel, which increased the contact pressure of the graft and the tunnel wall. This situation may erode the anterior portion of the femoral tunnel, resulting in tunnel enlargement.[37] Basdekis et al[3] concluded that tunnels should be drilled at 110° of flexion to obtain an obliquity of the tunnel of 32° (β angle) and an average intraosseous tunnel length of 40 mm.

This study has several strengths. First, we studied high-resolution images using 3D scans, allowing us to rotate the knee and therefore obtain exact reconstruction in the sagittal, frontal, and axial planes. This is not possible with 2D radiographs or photographic imaging.[30] Plain radiographs are merely 2D projected images of 3D structures, and thus, significant errors may be introduced in measured tunnel positions. Second, this is the first study comparing the 3 approaches on a large number of knees while considering orientations in the sagittal and frontal planes.

There are several limitations of the study. First, it is a cadaveric study. The cadaveric knees were older than typical of athletes undergoing ACL reconstruction. It is possible that ACL anatomy is slightly different than in a healthy young population. Second, only one traditional TT technique was studied with a specific tibial starting point, identical to the starting point used in the Piaseki et al[35] or Strauss et al[43] studies. It is possible that when the tibial starting point is meticulously aligned with the native ligament's axis and moved to a more proximal and medial position, femoral access can be improved.[10,35] Yet, such a starting point may cause some damage to the medial collateral ligament and the medial tibial plateau. It also leads to a short tibial tunnel, which may create the difficult clinical situation of graft length/tunnel mismatch and the tibial-side bone plug protruding out the tibial tunnel. Third, the average shape of the ACL footprint in the sagittal plane was not strictly elliptical. Instead, it widened in the anteroposterior direction, moving proximally to distally. This fact has no consequence on the centering of the drill guide but can slightly modify recovery calculations.

Recent biomechanical studies have suggested that grafts positioned centrally within the native tibial and femoral footprints will more closely re-create the normal ligament's stability and graft tension relationship than traditionally oriented single-bundle grafts.[19,28] Clinical studies also confirm the importance of the anatomic reconstruction in a single bundle.[16] Alentorn-Geli et al[1] compared 21 TT cases and 26 IO cases. The IO group had significantly better anteroposterior and rotational stability and higher International Knee Documentation Committee scores.[1]

To improve the coverage of the native femoral footprint with a single-bundle graft, it would be necessary to better consider the femoral orientation of the drilling to increase the dimensions of the drilling area while respecting anatomic constraints. It is also very important to fill the tunnel with a graft whose size replicates the size of the tunnel. The choice of the graft, hamstring tendon, patellar tendon, or quadriceps tendon should be made according to the area of the tunnel to maximize the percentage of the footprint that is restored.[38]

CONCLUSION

To date, many studies have focused on the value of replicating the location of the femoral tunnel and not the morphological orientation of the femoral tunnel aperture to the native footprint. This study shows the importance of the sagittal and frontal angulations of the drill guide as we aim to reproduce the anatomy and allow for maximum coverage of the native femoral footprint and therefore better knee kinematics.

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