Technique for Creating the Anterior Cruciate Ligament Femoral Socket: Optimizing Femoral Footprint Anatomic Restoration Using Outside-in Drilling

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Purpose: The purpose of this study was to investigate and optimize anterior cruciate ligament (ACL) femoral outside-in drilling technique with a goal of anatomic restoration of the footprint morphologic length, width, area, and angular orientation. **Methods:** Ex vivo, computer navigation was used to create virtual 3-dimensional maps of femoral bone tunnels for ACL drill guide pin insertion paths on small, medium, and large models of averaged femora considering various pin insertion angles to the femur. We then determined which pin insertion angle resulted in an ACL femoral footprint optimally matching normal human anatomic length, width, area, and angular orientation of the footprint long axis. **Results:** During outside-in drilling of the ACL femoral socket, a guide pin entrance angle of 60° to a line perpendicular to the femoral anatomic axis, combined with a guide pin entrance angle of 20° to the transepicondylar axis, results in the closest approximation of the gold standard of normal anatomic morphology of the human knee ACL femoral footprint length, width, area, and angular orientation. **Conclusions:** During outside-in drilling of the ACL femoral socket, a guide pin entrance angle of 60° to a line perpendicular to the femoral anatomic axis, combined with a guide pin entrance angle of 20° to the transepicondylar axis, results in optimal reconstruction of the normal human anatomic ACL femoral footprint length, width, area, and angular orientation. **Clinical Relevance:** We describe arthroscopic landmarks for anatomic ACL femoral socket creation that may be considered by practicing arthroscopic surgeons in the operating room, without open dissection or fluoroscopy and unaffected by type of drill guide or variations in the thickness of the femoral soft-tissue envelope.

Options for creating the femoral socket during surgical reconstruction of the knee anterior cruciate ligament (ACL) include transtibial techniques, anteromedial (AM) portal techniques, and outside-in techniques.[1-7] Recently, as a result of new, minimally invasive, retrograde socket drilling technology, where outside-in socket creation no longer requires "2-incision" surgical dissection,[8-14] interest in an outside-in technique for creation of the ACL femoral socket has been renewed. This interest in the outside-in technique is also motivated by possible disadvantages of the transtibial technique, which results in nonanatomic, vertical grafts, and AM portal techniques, which result in shorter tunnels.[1-7,15-23] However, the optimal method for outside-in drilling of the ACL femoral socket has not been determined.

The purpose of this study was to evaluate surgical techniques for outside-in drilling of the ACL femoral socket. We specifically investigated the effect of ACL femoral outside-in drill guide pin sleeve position on ACL femoral footprint length, footprint width, footprint area, and angular orientation of the footprint long axis. Our hypothesis was that drill guide pin sleeve position can be optimized in a manner where ACL femoral length, width, area, and angular orientation (morphology) reproduce normal human anatomy.

Methods

For this ex vivo analysis, testing was performed on synthetic replicas of actual human, femoral cadaveric specimens representing small-, medium-, and large-sized

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left femora (Sawbones; Pacific Research Laboratories, Vashon, WA). We then used computer-digitized data acquisition, recording, and analysis similar to surgical navigation to create virtual (computer-simulated) 3-dimensional maps on which we were then able to create, measure, and analyze virtual ACL femoral sockets.

By use of a MicroScribe 3-dimensional digitizer (MicroScribe G2; Immersion, San Jose, CA), calibrated with Rhinoceros software (version 3.0 SR3; McNeel North America, Seattle, WA), points along the femoral axis and on the medial and lateral femoral epicondyle were recorded as anatomic reference landmarks, used to define the "femoral anatomic axis" (Fig 1) and "femoral transepicondylar axis" (Fig 2).

An ACL femoral guide (FlipCutter guide, ACL marking hook, and guide pin sleeve; Arthrex, Naples, FL) was held with the point of the marking hook at the anatomic centrum[24] of the ACL footprint and the guide pin sleeve on the lateral wall of the condyle. The guide pin sleeve was positioned perpendicular to the femoral axis (Fig 1) and parallel to the transepicondylar axis (Fig 2).

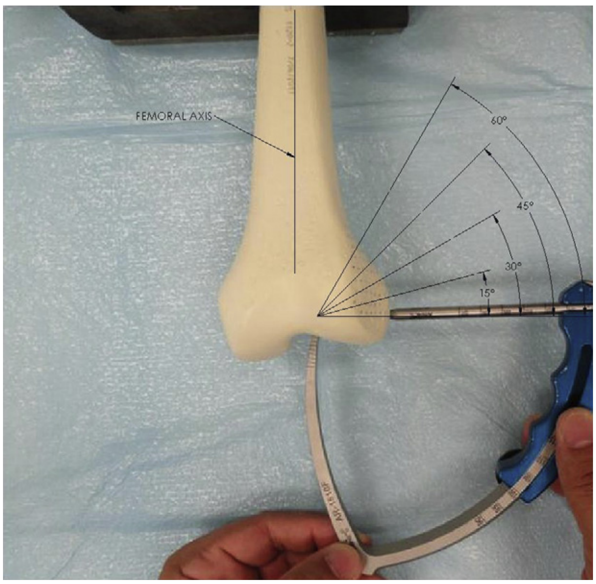

Fig 1. Left femoral Sawbones model viewed from anterior to posterior. The femoral anatomic axis is represented by a vertical line (arrow). An ACL femoral guide (FlipCutter guide, ACL marking hook, and guide pin sleeve) is positioned with the point of the marking hook at the anatomic centrum of the ACL footprint and the guide pin sleeve on the lateral wall of the condyle. The guide pin sleeve is positioned perpendicular to the femoral axis. The contact point between the guide pin sleeve and the condyle represents the point of origin for 3-dimensional digitization and mapping, and a grid of points, 4 to 5 mm apart, proximal and anterior to the point of origin, is also marked (small dots) on the distal-lateral femoral condylar surface. Five coronal-plane angles to a line perpendicular to the femoral axis are evaluated (0°, represented by the guide pin sleeve, and 15°, 30°, 45°, and 60).

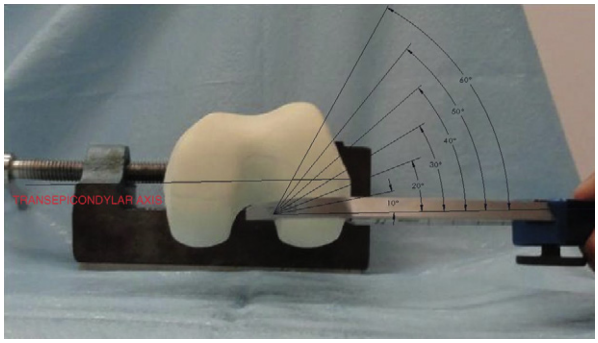

Fig 2. Left femoral Sawbones model viewed from distal to proximal. The transepicondylar axis is represented by a horizontal line. An ACL femoral guide (FlipCutter guide, ACL marking hook, and guide pin sleeve) is positioned with the point of the marking hook at the anatomic centrum of the ACL footprint and the guide pin sleeve (obscured by the marking hook) on the lateral wall of the condyle. The guide pin sleeve is positioned perpendicular to the femoral axis. Six axial-plane angles to a line parallel to the transepicondylar axis are evaluated (0°, represented by the guide pin sleeve, and 10°, 20°, 30°, 40°, and 50°).

The contact point between the guide pin sleeve and the condyle was marked with a fine-tip marker, and this point represents the point of origin for additional measurements (Fig 3).

Next, a grid of points, 4 to 5 mm apart, proximal and anterior to the point of origin, were marked on the distal-lateral femoral condylar surface and used for anatomic surface mapping (Fig 3). By use of a MicroScribe device, each point on the condyle was digitized and recorded relative to the point of origin, the ACL footprint, the femoral axis, and the transepicondylar axis. The surface of the ACL femoral footprint on the

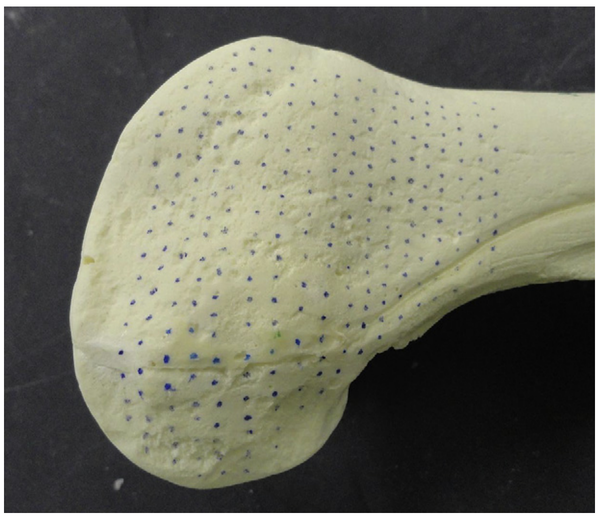

Fig 3. Left femoral Sawbones model viewed from lateral to medial. A grid of points, 4 to 5 mm apart, proximal and anterior to the point of origin (additional small dots), is marked on the distal-lateral femoral condylar surface.

lateral wall of the intercondylar notch was digitized by similar methods. The grid of points was opened by use of SolidWorks Office Premium software (version SP2.1; SolidWorks, Concord, MA).

Finally, a 9-mm femoral socket was projected on the lateral wall of the femoral intercondylar notch. We measured and recorded socket length, width, area, and orientation. We compared these results with normal human anatomy to evaluate which femoral outside-in angle technique best reproduced normal anatomy.

Data were measured and recorded for angle combinations of 0°, 15°, 30°, 45°, and 60° to a line perpendicular to the femoral axis in the coronal plane (Fig 1) and 0°, 10°, 20°, 30°, 40°, and 50° to a line parallel to the transepicondylar axis in the axial plane (Fig 2). These angle combinations replicate various drill guide pin sleeve positions that might be used for an ACL femoral socket outside-in surgical technique.

The primary outcome measures were ACL footprint morphologic measurements of length (in millimeters), width (in millimeters), area (in square millimeters), and footprint major axis orientation angle to the femoral axis for each combination. Figure 4 illustrates our method for defining outcome.

Rationale for Experimental Design

The rationale for our experimental design is dictated by a translational research goal of translating an ex vivo analysis to a clinically useful recommendation regarding optimal outside-in drill guide pin sleeve position (coronal- and axial-plane angle combinations) for creating the ACL femoral socket.

Results

Results for small, medium, and large femora are reported in Table 1 for each combination of guide pin sleeve angles (Figs 1 and 2). Results marked with dashes represent extreme angle combinations that did not fit the anatomic models.

The results were compared to normal anatomy (Table 2).[24-26] Working from our data (Table 1) to determine what came closest to normal (Table 2), we then made boldface the Table 1 combinations closest to normal human anatomy for all sizes. The boldface combinations of entrance angles of 60° to a line perpendicular to the femoral axis in the coronal plane (Fig 1) by 20° to the transepicondylar axis in the axial plane (Fig 2) overlap to determine our results (boldface and italic in Table 1 where boldface overlap).

Discussion

Our methods tested guide pin entrance angles for ACL femoral socket outside-in technique. Our results used normal human anatomy as the gold standard. The outcome measures were (1) socket width, (2) length, (3) area, and (4) angle. (It should be noted that the outcome measure "angle" is the angle of the femoral socket, not the guide pin entrance angle.)

Previous publications describing ACL femoral outside-in drilling are conflicting with regard to technique. Some studies recommend drill guide placement at a specific point on the femur, but these recommendations vary widely: "3 to 4 cm proximal to the [lateral] epicondyle,"[27] "just anterior to the lateral epicondyle,"[13] "just proximal

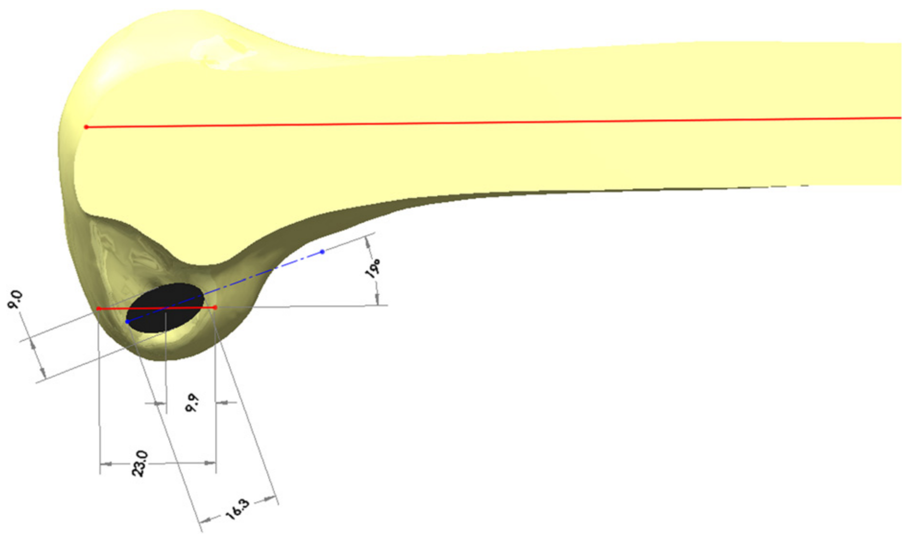

Fig 4. Right femur, ACL femoral footprint arthroscopic view (distal is left, anterior is up, proximal is right, posterior is down) illustrating methods for positioning centrum (red line) and for defining outcome measures (length, width, and angle to femoral axis [blue line]). In the example illustrated, the total distance from proximal where the cartilage ends to the distal cartilage border (red line) equals 23.0 mm; the anatomic centrum is 43% from proximal,[24] which equals 9.9 mm (horizontal-oriented measurements illustrated in gray at bottom of figure). Also illustrated are examples of a socket width of 9.0 mm, length of 16.3 mm, and angle to the femoral axis of 19°. It should be noted that the outcome measure "angle" is the angle of the femoral socket, not the guide pin entrance angle.

Table 1. Outcomes Regarding ACL Femoral Guide Pin Bone Tunnels for Outside-in Technique for Creating ACL Femoral Socket for Small, Medium, and Large Femora

	0° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	15° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	30° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	45° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	**60° Angle to Line Perpendicular to Femoral Axis in Coronal Plane**
Small femur (transepicondylar distance of 62.95 mm)					
Area of drill tunnel ellipse on ACL footprint plane (mm^2)					
0° angle to transepicondylar axis in axial plane	80.02	73.10	—	—	—
10° angle to transepicondylar axis in axial plane	69.80	68.80	72.17	—	—
20° angle to transepicondylar axis in axial plane	68.53	66.03	69.48	77.95	***101.41****
30° angle to transepicondylar axis in axial plane	64.50	64.03	67.37	80.03	98.90
40° angle to transepicondylar axis in axial plane	65.57	64.18	69.00	84.54	—
50° angle to transepicondylar axis in axial plane	67.74	66.34	74.95	—	—
60° angle to transepicondylar axis in axial plane	70.22	70.40	85.97	—	—
Major ellipse diameter (mm)					
0° angle to transepicondylar axis in axial plane	11.32	10.35	—	—	—
10° angle to transepicondylar axis in axial plane	9.88	9.74	10.22	—	—
20° angle to transepicondylar axis in axial plane	9.70	9.34	9.83	11.03	***14.35****
30° angle to transepicondylar axis in axial plane	9.13	9.06	9.54	11.32	13.99
40° angle to transepicondylar axis in axial plane	9.28	9.08	9.81	11.96	—
50° angle to transepicondylar axis in axial plane	9.59	9.39	10.61	—	—
60° angle to transepicondylar axis in axial plane	9.94	9.97	12.16	—	—
Angle of ellipse large diameter to femoral axis (°)					
0° angle to transepicondylar axis in axial plane	77.4	103.8	—	—	—
10° angle to transepicondylar axis in axial plane	72.4	98.0	131.5	—	—
20° angle to transepicondylar axis in axial plane	51.2	118.9	157.9	161.3	***18.0****
30° angle to transepicondylar axis in axial plane	54.2	159.8	166.5	15.6	21.0
40° angle to transepicondylar axis in axial plane	156.0	47.8	24.7	32.4	—
50° angle to transepicondylar axis in axial plane	132.3	74.4	52.7	—	—
60° angle to transepicondylar axis in axial plane	109.4	79.9	59.5	—	—
Medium femur (transepicondylar distance of 76.03 mm)					
Area of drill tunnel ellipse on ACL footprint plane (mm^2)					
0° angle to transepicondylar axis in axial plane	67.34	65.12	66.69	—	—
10° angle to transepicondylar axis in axial plane	67.04	63.68	66.45	—	—
20° angle to transepicondylar axis in axial plane	66.18	64.34	67.08	75.57	***106.86****
30° angle to transepicondylar axis in axial plane	71.22	69.19	71.78	85.63	105.45
40° angle to transepicondylar axis in axial plane	76.79	75.80	83.09	107.22	—
50° angle to transepicondylar axis in axial plane	82.92	86.96	94.77	—	—
60° angle to transepicondylar axis in axial plane	99.77	105.49	—	—	—
Major ellipse diameter (mm)					
0° angle to transepicondylar axis in axial plane	9.53	9.21	9.44	—	—
10° angle to transepicondylar axis in axial plane	9.49	9.01	9.41	—	—
20° angle to transepicondylar axis in axial plane	9.36	9.13	9.79	10.69	***15.12****
30° angle to transepicondylar axis in axial plane	10.08	9.73	10.16	12.11	14.92
40° angle to transepicondylar axis in axial plane	10.87	10.73	11.75	15.17	—
50° angle to transepicondylar axis in axial plane	11.73	12.30	13.41	—	—
60° angle to transepicondylar axis in axial plane	14.11	14.92	—	—	—

(continued)

Table 1. Continued

	0° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	15° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	30° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	45° Angle to Line Perpendicular to Femoral Axis in Coronal Plane	**60° Angle to Line Perpendicular to Femoral Axis in Coronal Plane**
Angle of ellipse large diameter to femoral axis (°)					
0° angle to transepicondylar axis in axial plane	38.8	76.5	139.9	—	—
10° angle to transepicondylar axis in axial plane	160.2	87.6	21.1	—	—
20° angle to transepicondylar axis in axial plane	144.4	97.8	48.2	30.9	***30.8****
30° angle to transepicondylar axis in axial plane	125.3	90.2	58.5	44.7	38.2
40° angle to transepicondylar axis in axial plane	118.0	85.0	62.0	48.0	—
50° angle to transepicondylar axis in axial plane	108.2	86.3	66.7	—	—
60° angle to transepicondylar axis in axial plane	103.3	83.5	—	—	—
Large femur (transepicondylar distance of 89.18 mm)					
Area of drill tunnel ellipse on ACL footprint plane (mm^2)					
0° angle to transepicondylar axis in axial plane	66.21	67.50	71.67	—	—
10° angle to transepicondylar axis in axial plane	64.32	65.01	68.63	—	—
20° angle to transepicondylar axis in axial plane	64.16	65.09	73.96	88.55	***129.59****
30° angle to transepicondylar axis in axial plane	65.79	66.92	76.40	95.82	126.80
40° angle to transepicondylar axis in axial plane	69.97	74.23	83.46	117.04	—
50° angle to transepicondylar axis in axial plane	77.28	80.96	95.18	—	—
60° angle to transepicondylar axis in axial plane	88.54	96.49	117.32	—	—
Major ellipse diameter (mm)					
0° angle to transepicondylar axis in axial plane	9.37	9.56	10.14	—	—
10° angle to transepicondylar axis in axial plane	9.10	9.20	9.72	—	—
20° angle to transepicondylar axis in axial plane	9.08	9.21	10.47	12.52	***18.30****
30° angle to transepicondylar axis in axial plane	9.31	9.47	10.81	13.56	17.93
40° angle to transepicondylar axis in axial plane	9.90	10.50	11.81	16.55	—
50° angle to transepicondylar axis in axial plane	10.94	11.45	13.47	—	—
60° angle to transepicondylar axis in axial plane	12.52	13.65	16.59	—	—
Angle of ellipse large diameter to femoral axis (°)					
0° angle to transepicondylar axis in axial plane	72.3	130.1	157.0	—	—
10° angle to transepicondylar axis in axial plane	44.9	154.8	170.4	—	—
20° angle to transepicondylar axis in axial plane	148.3	28.6	18.8	17.6	***17.8****
30° angle to transepicondylar axis in axial plane	110.1	54.7	33.1	31.5	23.7
40° angle to transepicondylar axis in axial plane	97.4	68.5	46.1	39.3	—
50° angle to transepicondylar axis in axial plane	101.9	72.8	56.8	—	—
60° angle to transepicondylar axis in axial plane	97.3	75.1	60.6	—	—

NOTE. Area of socket footprint, footprint major ellipse diameter (length in millimeters), and footprint orientation angle (of ellipse large diameter) to femoral axis are reported for each combination of guide pin sleeve positions, defined as an angle to a line perpendicular to the femoral axis by an angle to the transepicondylar axis. Results marked with dashes represent extreme angle combinations that did not fit the anatomic models. For all samples, the minor diameter (width in millimeters) for all sockets was defined as 9.00 mm (virtual drill diameter) as described in the Methods.

*Boldface and * indicate those outcome combinations most closely approximating normal anatomy for small, medium, and large sizes.

Table 2. Anatomic Normal Values for Human Knee ACL Femoral Footprint Anatomy (Used as Gold Standard)[24-26]

	Data
Width (mm)	8.9*; range, 7-10†
Length (mm)	16.3*; range, 13-19†
Area (mm^2)	136*
Socket angle (ellipse long-axis orientation) to femur (°)	19‡

*Data from Hensler et al.[25]
†Data from Piefer et al.[24]
‡Data from Steckel et al.[26]

to the lateral epicondyle,"[7] "behind the posterior cortex of the lateral femoral condyle,"[28] or "the distal metaphysis of the (lateral) femur."[29] In addition to being conflicting and imprecise, none of these recommendations describe the effect of the technique on socket length or angle. Furthermore, these recommendations are predicated on dissection through the skin, subcutaneous tissue, iliotibial band, and vastus lateralis to precisely identify bony landmarks, and by use of currently available, less invasive retrograde drilling technology,[8-14] this dissection is no longer necessary or preferred.

Previous publications describing ACL femoral outside-in socket drilling using less invasive retrograde drilling technology are also conflicting with regard to technique and even show inconsistent technique descriptions by the same authors, such as the "distal midlateral femoral metaphyseal flare, 4 cm proximal to the lateral epicondyle,"[2] "the level of the skin at a point approximately 1 cm anterior to the posterior border of the iliotibial band and 2.5 cm proximal to the lateral femoral condyle,"[10] or "a small incision over the lateral femoral cortex just anterior to the iliotibial tract."[14] Again, in addition to being conflicting and imprecise, none of these recommendations describe the effect of the technique on socket length or angle. Furthermore, reliance on bony landmarks absent invasive soft-tissue dissection is imprecise and will result in varying entrance points depending on the thickness of the soft-tissue envelope.

Some previous publications also base technical recommendations for ACL femoral outside-in drilling on the guide angle or position, including the following: "the point is dictated by the femoral guide,"[22] "110° angle of the guide is arbitrary but an angle used often in our clinical experience,"[2] or the "guide ring [is set] at an angle of approximately 100° to 110°."[10] Yet again, in addition to being inconsistent, vague, or imprecise, none of these recommendations describe the effect of the technique on socket length or angle. Furthermore, reliance on guide ring angles is not reproducible absent consistent recommendations with regard to the angles at which the guide is positioned. This bears repeating: Guide ring angle settings are not clinically relevant as outcome measures because of diverse guides, portal positions, patient sizes, surgeon hand positioning and force, or other uncontrolled variables.

We evaluated ACL femoral outside-in drilling techniques with regard to the clinically relevant outcome measure of normal human ACL footprint anatomy. In addition, we described guide pin entrance angles with regard to the femoral anatomic and transepicondylar axes. These landmarks are unaffected by the thickness of the femoral soft-tissue envelope, the configuration or properties of diverse commercially available guides, or more invasive, open dissection and drilling. As such, our results may be relevant to diverse surgeons with an interest in ACL femoral outside-in drilling.

Alternative techniques for creating the ACL femoral socket are the AM portal technique[3,22] and the transtibial technique. However, Hensler et al.[25] reported that the AM portal technique results in ACL femoral socket morphology length, width, area, and orientation results that are quantitatively less anatomic than our results for all variables tested. The AM portal technique also results in shorter bone tunnels than the outside-in technique.[2] In addition, the transtibial technique for creating the ACL femoral socket is nonanatomic.[14,30-33]

Limitations

Our study has limitations. Ours is an in vitro evaluation. However, all research is specific to the methods tested. Translational research dictates that basic science investigation must be translated to clinically practical application, requiring additional ex vivo, cadaveric, and ultimately, in vivo clinical research.[34]

Conclusions

During outside-in drilling of the ACL femoral socket, a guide pin entrance angle of 60° to a line perpendicular to the femoral anatomic axis, combined with a guide pin entrance angle of 20° to the transepicondylar axis, results in the closest approximation of the gold standard of normal anatomic morphology of the human knee ACL femoral footprint length, width, area, and angular orientation.

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