EFFECT OF TIBIAL TUNNEL DIAMETER ON ANATOMIC FEMORAL TUNNEL PLACEMENT IN TRANSTIBIAL ENDOSCOPIC SINGLE BUNDLE ACL RECONSTRUCTION

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Introduction:

As anterior cruciate ligament anatomy and kinematics become better understood, a more anatomic approach to ACL reconstruction is increasingly being pursued.[5] ACL deficiency has consistently been demonstrated to give rise to increased anterior translation, medial translation, and internal rotation of the tibia during various loading maneuvers.[4, 11, 12] Knee kinematics and stability have been shown to markedly improve following ACL reconstruction with restoration of native ACL insertion sites and ligament orientation.[7, 8, 10, 19] ACL reconstructive procedures that fail to alleviate knee instability post-operatively often lead to a predictively higher risk for osteoarthritis of the knee, failure to return to previous level of play, and poor subjective and objective knee outcome scores.[16]

Although an understanding of ACL biomechanics and knee kinematics has significantly improved in recent decades, optimal surgical technique in ACL reconstruction remains uncertain; to date, no ACL reconstruction procedure has been shown to exactly replicate the biomechanics of the native ACL.[9, 13, 22] Small variations in femoral tunnel positioning can drastically change ACL length, tensioning patterns as well as alter ACL force vectors and joint kinematics.[1, 2, 14, 18] Grafts placed higher on the femoral wall in ACL reconstruction—a less coronally oblique orientation—less effectively opposes rotatory loads as compared with grafts placed lower on the femoral wall.[18] Decreased sagittal plane obliquity has also been implicated, largely because such an orientation incompletely resists anterior translational loads as compared with the native ACL.[1, 3, 6, 17] Regardless of which ACL reconstruction technique is utilized, a growing body of literature supports the notion that a more anatomic reconstruction better restores knee kinematics than non-anatomic reconstructions.[21, 24]

The modified transtibial endoscopic single bundle ACL reconstruction has been demonstrated to have equal efficacy in improving knee joint biomechanical stability as ACL reconstructions performed via an anteromedial portal technique and an outside-in technique.[23] The most limiting aspect of this technique is the reliance of femoral tunnel positioning on tibial tunnel orientation and position; because the femoral tunnel is drilled through the tibial tunnel, the tibial tunnel represents a potentially unforgiving linear constraint to instrumenting the femur. The ideal scenario for transtibial reconstruction is one where the tibial tunnel is collinear with a line connecting the centers of both femoral and tibial ACL insertions. Such geometry has been shown to be impractical, however. As noted by Heming et al, a guide pin drilled through the center of both insertions will consistently exit the tibia within millimeters of the joint line.[15] A tibial tunnel created with this proximal of a starting point likely would compromise tibial graft fixation and create significant graft-tunnel mismatch problems if a bone-tendon-bone graft was employed. If a more distal, traditional tibial starting position is employed instead, the resultant tunnel will be less aligned with the native ligament and will result in less-than-anatomic femoral tunnel positioning.[20]

In a previous cadaveric study, we noted that tibial and femoral tunnels can be created in a highly anatomic manner using a transtibial technique but requires a fairly proximal, carefully chosen tibial starting position.[20] In that study, however, an 11mm tibial reamer was utilized in all specimens which afforded great flexibility in placing the "over-the-top" femoral guide through the 11mm wide tibial tunnel onto an anatomic position on the femoral ACL footprint. At the present time, a large proportion of bone-tendon-bone and soft tissue grafts used are smaller than 11mm. It is possible that smaller tibial reamers would not allow for such precise anatomic femoral tunnel placement using a transtibial technique because the resultant smaller tibial tunnel would have too small a diameter. If this notion were proved true, a femoral independent drilling technique may need to be pursued for select cases in which a narrow tibial tunnel is anticipated.

The purpose of this study is to identify the impact of tibial reamer size on the ability to place anatomic femoral tunnels via a transtibial approach. It is hypothesized that there is a threshold for tibial tunnel size, under which, the surgeon will be unable to obtain anatomic femoral tunnel placement using a transtibial technique.

Methods

Eight fresh-frozen adult knee specimens (mid thigh to mid knee, 4 right, 4 left) without ligamentous injury or significant degenerative joint disease were thawed over 24 hours. Demographic characteristics for the specimens are provided in **Table 1**. Taking care to preserve soft tissues about the knee joint, skin, muscle and subcutaneous tissue were removed from tibial and femoral diaphyses. Specimens were then mounted in 90° of flexion on a custom designed mount stationary on a laboratory table stabilized to floor (**Figure 1)**. This flexion angle was chosen as it is the most common position of the knee during transtibial reconstruction techniques. In order to ensure that the necessary exposures of the ACL insertions did not destabilize the knee and result in aberrant motion of the tibia and femur, a three-point coordinate system was arbitrarily defined on each specimen by choosing and marking a point on the femur, tibia, and laboratory table. The *x, y,* z coordinates of each of these points were measured and repeatedly referenced throughout the study to assure a static relationship between the femur, tibia, and digitizer (MicroScribe™; CNC Services, Amherst, Virginia) accurate to 0.05 mm.

After fixing the specimen on the custom designed mount, the lateral femoral condyle was further secured to the lateral tibial plateau with 2 divergent K-wires. Extra-articular soft tissues about the knee joint were then dissected off and the intact nature of the articular cartilage, meniscal attachments and cruciate ligaments were confirmed. The superior border of the pes anserinus and anterior edge of the medial collateral ligament (MCL) were marked on the proximal tibia prior to removal. The length of the central third of the patellar tendon was measured with a ruler for each specimen, from distal patella to tendo-osseous junction on the tibial tubercle prior to removal.

To allow a post-hoc three dimensional analyses, the knee joint's surface femoral and tibial anatomy was then recorded using the digitizer to log extensive point cloud arrays of both bones. In addition to articular surfaces and bony landmarks, soft tissue structures such as the anterior horn of the lateral meniscus, the medial meniscus, and the anterior face of the posterior cruciate ligament (PCL) at the posterior edge of the tibial plateau were also digitized to better appreciate the anatomical relationship of the ACL to these structures.

Using an oscillating saw, the medial femoral condyle was then carefully removed with great caution taken to avoid damage to the femoral ACL insertion (**Figure 2**). The ACL was then sharply divided transversely and removed with care to allow the tibial and femoral footprints to be digitized after being marked with a pen. The *x, y,* z coordinates of the three arbitrary points on the tibia, femur, and laboratory were measured once again to confirm the static relationship between the femur, tibia, and digitizer had not changed.

Surgical Technique

As shown by Piasecki and colleagues, there is an optimal tibial tunnel starting point (15.9 mm below the medial plateau, 9.8 mm posteromedial to the medial margin of the tibial tubercle) which best allows for anatomic femoral tunnel drilling using a transtibial technique.[20] Using this idealized tibial tunnel starting point, a guide pin was drilled using a standard ACL tibial aimer (Smith & Nephew Endoscopy, Andover, MA) to the center of the marked tibial footprint (**Figure 3**). Guide pin intersection with the intercondylar notch wall was observed and verified. Cannulated straight tibial reaming was then sequentially performed over the guide wire beginning with a 6 mm full-fluted reamer and proceeding to an 11mm full-fluted reamer (Smith & Nephew Endoscopy, Andover, MA). After each tibial reaming, the guide wire was removed and a 7 mm offset "over the top femoral guide" was placed through the tibial tunnel to a point as low on the femoral wall and central in the femoral ACL insertion's anteroposterior distance as possible. This position on the femur was recorded for each reamer size via the digitizer, and the distance from this point to the native femoral insertion center was calculated. After final straight reaming with an 11 mm reamer, the digitizer was then used to register the periphery of this tibial tunnel entrance within the joint.

The digitizer was used to register the apertures and dimensions of tibial tunnels, and to measure the tunnel location in relation to the native ACL tibial and femoral footprint anatomy. Once these measurements were taken, the guide wire was replaced, and the femoral tunnel was reamed with a standard fluted 10 mm reamer through the tibial tunnel. The digitizer was once again utilized to analyze the tibial and femoral tunnel dimensions, and tunnel location compared with the native anatomy.

Analysis

A number of subsequent analyses were performed using the spatial information recorded with the digitizer. Rhino software (McNeel, Seattle WA) was used to geometrically determine the center of the native femoral footprint and measure in millimeters the relationship of this point with the over-the-top femoral position achieved with each tibial tunnel size. The surface areas of each tibial and femoral insertion were measured using the insertional periphery data recorded with the digitizer. Similar surface areas were calculated for the recorded peripheries of the intraarticular tibial tunnel exit and femoral tunnel. The percentage overlap of the tibial tunnel surface area with that of the native tibial insertion was then directly calculated.

Statistical analysis of continuous variable data was performed with *t* tests with alpha set to 0.05 using GraphPad Software (La Jolla, CA); *P* values below this were deemed significant. Pre-hoc sample size for comparison of tibial tunnel sizes was determined by a power analysis (G*Power 3.0, Dusseldorf, Germany). Assuming a 50% increase in tunnel size and a standard deviation of 0.25 the mean value, to achieve a power of 0.80 with a two-tailed analysis, 6 specimens were required.

Results

All specimens had intact cruciate ligaments and menisci, and none had significant degenerative joint disease. In all cases, the coordinates used to reference the tibia, femur, and laboratory table remained within 0.1 mm as measured by the digitizer throughout the testing protocol. Upon tibial tunnel reaming, no specimen showed compromise of the proximal bone bridge or medial tibial plateau. Tibial starting points were in accordance to those described by Piasecki et al (15.9mm below the medial tibial plateau, 9.8mm posterior to the medial margin of the tibial tubercle).[20]

After use of an 11mm tibial reamer, tibial tunnel length was 32.07±2.62mm (**Table 2**), and tibial-articular ACL footprint area was 111.45±16.40mm^2, compared to the native landmark size of 151.53±28.95mm^2 (**Table 3**). Initial tibial tunnel reaming of 6, 7, 8, 9, and 10mm full cannulated reamers produced increasing areas of the tibial-articular ACL footprints with 35.07±8.06mm^2, 47.34±8.65mm^2, 59.95±9.54mm^2, 78.39±13.21mm^2, and 96.30±10.53mm^2 respectively. Of note, upon reaming the femoral tunnel with an "over the top" guide centered on native femoral insertion and a 10mm full cannulated reamer; the tibial-articular aperture increased in size to 189.84±22.13mm^2.

In 6 knees, a 9mm tibial tunnel was necessary for the center of the femoral ACL footprint to be reached. In 2 knees, the center of the femoral footprint was reached with an 8mm tunnel. After reaching the anatomic center of the femoral ACL footprint in these specimens, it was shown that subsequent reaming with 10mm and 11mm (in 6 knees) or 9, 10, and 11 mm (in 2 knees) allowed placement of the guided pin not only on the native center, but also inferior and slightly anterior or posterior to the native insertion on the condylar wall as needed (**Figure 4**). Comparisons between guide tip positions in 9, 10, and 11mm tibial tunnels was significantly lower than guide tip positions in 6, 7, and 8mm tunnels as shown in **Table 4**. A 6mm or 7mm tibial tunnel did not allow for anatomic positioning in any specimen (**Figure 5**). The 6 mm and 7 mm tunnels produced errors that were superior and slightly posterior to the native femoral ACL center with an average elevation distance of 4.42±1.76mm and 2.94±0.54mm, respectively (**Table 4**).

In comparing the location of the ACL femoral-articular footprint with relation to joint anatomy, distances from each landmark were digitized from the center and periphery of the native and 10mm full cannulated reamed footprints (**Table 5**). The native ACL femoral footprint had an area that measured 107.79±37.30mm compared to that of the 10mm reamed femoral tunnel intra-articular aperture, which digitized to 115.27±8.56mm. While the center of the native footprint was digitized to be 18.54±1.66mm from the anterolateral corner of the PCL footprint on the femur ("notch distance"), the center of the footprint of the 10mm full reamer measured 18.85±2.62mm from the PCL.

Finally, the distance from the center of the ACL's native femoral footprint to the inferior intra-articular cartilage surface measured 7.59±1.93mm, compared to 7.68±1.32mm from the 10mm reamed center. Additionally measurements were taken to the "back wall" of the femur from the center and posterior aspect of each footprint; while the native was digitized at 9.83±2.30mm (from center) and 3.63±1.75mm (from posterior), the 10mm full reamer measured 9.69±2.24mm and 3.02±1.61mm respectively. Of note, throughout the entirety of the testing protocol in no specimen was there an observation of compromise to the "back wall" or intra articular surface on the femur. Additional values demonstrating the anatomical relationships of the ACL femoral footprints are provided in **Table 5**.

Discussion

Current understanding of ACL biomechanics and function suggests that anatomic placement of tunnels is imperative for more normal knee kinematics post-surgically.[5, 21, 24] Misplacement of femoral and tibial tunnels in single bundle ACL reconstruction (ACLR) has been reported to be a primary factor resulting in clinical failure.[25] The most limiting factor with a transtibial technique is the dependence of femoral tunnel positioning on tibial tunnel orientation and size. The primary results of this study suggest that limitations necessitated by a transtibial ACLR technique may result in nonanatomic femoral tunnel placement with tibial tunnel holes smaller than 8mm or 9mm.

With regard to restoring joint biomechanical stability, the modified transtibial ACLR technique has been shown to be equally efficacious to ACL reconstructions performed using other techniques. In a cadaveric laboratory study, Sims and colleagues used a robotic testing system to place uniform anteroposterior loads on knees with reconstructed ACLs using one of three endoscopic approaches.[23] The authors showed that the modified transtibial technique, the anteromedial portal technique, and the outside-in technique were all biomechanically comparable in their ability to restore normal knee joint laxity and in situ ACL forces.[23] Such results validate the utility of the modified transtibial approach, particularly for surgeons well-versed in its technique.

In this study, transtibial femoral reaming through 6 mm and 7 mm tibial tunnels produced errors in femoral tunnel positioning that were significantly superior to the native femoral ACL center with an average elevation distance of 4.42±1.76mm and 2.94±0.54mm, respectively ($p<0.0001$). Loh et al showed that grafts placed higher on the femoral wall in ACL reconstruction—a less coronally oblique orientation—less effectively resists rotatory loads as compared with grafts placed lower on the femoral wall.[18] More recently, decreased sagittal plane obliquity has also been implicated, predominantly because such an orientation less effectively and less efficiently opposes anterior translational loads as compared with the native ACL.[1, 3, 6, 17]

Based on the findings of this study, it appears that a 9mm tibial tunnel should be used in all transtibial ACL reconstructions in order to assure that anatomic femoral positioning can be reached in the "over-the-top" position. Although an 8mm tibial tunnel allowed anatomic femoral positioning to be reached in 2 specimens, it is difficult to predict what anatomic circumstances would be more forgiving to allow this. Depending on graft choice and fixation methods, a 9mm tibial tunnel may not be practical in certain situations. In these scenarios, a femoral independent ACL reconstruction technique may be a better choice to allow a lower, more anatomic femoral tunnel position to be achieved.

The primary strength of this study is the application of precise digitization technology—accurate to 0.5mm—for comparisons between ACL footprint and tunnel anatomy. This is the first time such technology has been applied in such a manner to identify the effect of tibial tunnel width on femoral tunnel positioning. Regarding limitations, the study's controlled laboratory study design using static cadaveric specimens inherently prevents any in vivo or biomechanical conclusions to be drawn regarding the effects of femoral tunnel positioning. Additionally, the study design was limited in that subtle anatomic differences between cadaveric specimens were not elucidated. Thus, it is unclear why some specimens allowed anatomic transtibial femoral tunnel positioning with an 8mm tunnel while most other specimens required a 9mm tibial tunnel to achieve the same result. Additional studies may be necessary to further delineate such findings.

Conclusions

Limitations necessitated by a transtibial ACLR technique may result in nonanatomic femoral tunnel placement with tibial tunnel holes smaller than 8mm or 9mm. However, tibial tunnels placed in the described proximal entry position with at least a 9 mm tunnel size allowed anatomic femoral placement. Depending on graft choice and fixation methods, a 9mm tibial tunnel may not be practical in certain situations. In these scenarios, a femoral independent ACL reconstruction technique may be a better choice to allow a lower, more anatomic femoral tunnel position to be achieved.

Tables

Table 1. Demographics of knee specimens. (n=8 specimens).

Demographic Category	*Characteristic*
Left/right	4 right 4 left
Age	47.2 ± 5.6 years Range (36-53 years)
Gender	Male - 6 (75%) Female - 2 (25%)
Cause of death	Renal failure - 1 (12.5%) Carcinomatosis – 2 (25%) Malignant lung neoplasm – 1 (12.5%) Metastatic colon cancer – 1 (12.5%) Retroperitoneal hemorrhage – 2 (25%) Acute myelogenous leukemia – 1 (12.5%)

Table 2. Tibial tunnel length.

Tibial Tunnel Length (mm)

Knee Specimen	6mm Full Reamer	11mm Full Reamer
K1	32.148	30.682
K2	31.684	26.543
K3	35.338	32.172
K4	29.530	35.662
K5	32.224	32.791
K6	31.238	32.668
K7	30.576	32.933
K8	30.248	33.082
Averages	31.62 (±1.77)	32.07 (±2.62)

Table 3. Tibial-articular ACL footprint area.

Tibial-Articular ACL Footprint Area (mm^2)

Knee Specimen	Native Landmark	6mm+	7mm+	8mm+	9mm+	10mm+	11mm+	10mm++
K1	151.16	39.84	52.90	61.24	73.26	97.21	104.41	192.79
K2	132.51	28.95	35.08	46.94	54.49	76.86	102.83	231.94
K3	187.64	41.77	50.93	66.69	85.82	98.10	105.48	160.44
K4	114.98	46.59	57.90	76.46	99.59	114.84	136.60	176.37
K5	120.54	35.02	56.63	65.35	78.76	90.34	83.96	173.74
K6	144.33	30.11	46.61	58.22	75.65	95.75	114.50	187.00
K7	189.74	36.94	38.03	52.88	87.17	100.01	129.25	188.41
K8	171.37	21.34	40.64	51.84	72.42	97.27	114.56	208.06
Averages	151.53 (±28.95)	35.07 (±8.06)	47.34 (±8.65)	59.95 (±9.54)	78.39 (±13.21)	96.30 (±10.53)	111.45 (±16.40)	189.84 (±22.13)

+Tunnels were reamed with guide centered on Tibial-Articular ACL Footprint with no subsequent Femoral reaming

++Tunnels were reamed with guide centered on Femoral-Articular ACL Footprint with subsequent Femoral reaming

Table 4. Elevation of guide pin tip in lowest possible over-the-top position to true center of femoral footprint. Negative value assigned distance if lowest possible tip position below true anatomic center of femoral footprint.

Elevation* (mm) of Guide Pin tip in Lowest Possible Over-the-top Position to True Center (TC) of Femoral Footprint

Knee Specimen	6mm+	7mm+	8mm†	9mm§	10mm§	11mm§
K1	3.80	3.73	1.80	BELOW TC	BELOW TC	BELOW TC
K2	4.17	3.18	3.12	BELOW TC	BELOW TC	BELOW TC
K3	2.78	2.21	-2.64	BELOW TC	BELOW TC	BELOW TC
K4	6.04	2.77	1.20	BELOW TC	BELOW TC	BELOW TC
K5	2.65	2.63	2.33	BELOW TC	BELOW TC	BELOW TC
K6	3.10	2.81	1.82	BELOW TC	BELOW TC	BELOW TC
K7	7.66	3.67	1.58	BELOW TC	BELOW TC	BELOW TC
K8	5.19	2.52	-1.24	BELOW TC	BELOW TC	BELOW TC
Averages	4.42 (±1.76)	2.94 (±0.54)	0.99 (±1.93)	-2.33 (±0.59)	-2.74 (±0.86)	-2.77 (±1.04)
P-value in comparison with 8mm tunnel elevation	--	--	--	0.0006	0.0002	0.0016
P-value in comparison with 7mm tunnel elevation	--	--	--	<0.0001	<0.0001	<0.0001
P-value in comparison with 6mm tunnel elevation	--	--	--	<0.0001	<0.0001	<0.0001

*Negative value assigned to distance if lowest possible tip position below true anatomic center of femoral footprint
+Guide pin position was superior to TC of femoral footprint in all specimens
†Guide pin was able to be positioned inferior TC of femoral footprint in some specimens (denoted with negative value)
§Guide pin was able to be positioned inferior to TC of femoral footprint in all specimens

Table 5. Comparisons of native ACL femoral footprint with femoral ACL intra-articular aperture after 10mm reaming.

ACL Femoral Footprint Comparisons (mm)

Footprint Center	**PCL† (Notch Distance)**	**Femoral Back Wall**	**Intra-articular Inferior femoral cartilage surface**	**Anterior Notch Edge**
Native	18.54 (±1.66)	9.83 (±2.30)	7.59 (±1.93)	11.70 (±3.36)
10mm⁺	18.85 (±2.62)	9.69 (±2.24)	7.68 (±1.32)	12.29 (±2.68)
Footprint Periphery	**Superior to PCL† (Notch Distance)**	**Posterior to Femoral Back Wall**	**Inferior to Intra-articular cartilage surface**	**Anterior to Anterior Notch Edge**
Native	14.69 (±1.94)	3.63 (±1.75)	2.86 (±1.52)	3.77 (±2.94)
10mm⁺	13.98 (±2.48)	3.02 (±1.61)	2.77 (±0.80)	4.65 (±3.39)
		Footprint Area (mm^2)		
Native		107.79 (±37.30)		
10mm⁺		115.27 (±8.56)		

⁺Tunnels were reamed with guide centered on Femoral-Articular ACL Footprint with subsequent Femoral reaming
†Notch Distance is distance from anterolateral corner of PCL footprint to center of ACL footprint

Figures.

Figure 1. Specimens were mounted in 90° flexion on a custom designed mount stationary on a laboratory table stabilized to floor. In order to ensure that the necessary exposures of the ACL insertions did not destabilize the knee and result in aberrant motion of the tibia and femur, a three-point coordinate system was arbitrarily defined on each specimen by choosing and marking a point on the femur, tibia, and laboratory table. The *x, y,* z coordinates of each of these points were measured and repeatedly referenced throughout the study to assure a static relationship between the femur, tibia, and digitizer (MicroScribe™; CNC Services, Amherst, Virginia) accurate to 0.05 mm.

Figure 2. **A**) Anterior view of right knee after capsule, patella, patellar tendon, and ligamentum mucosum have been removed. **B**) Using an oscillating saw, the medial femoral condyle was then carefully removed with great caution taken to avoid damage to the femoral ACL insertion. Anterior cruciate ligament being probed here.

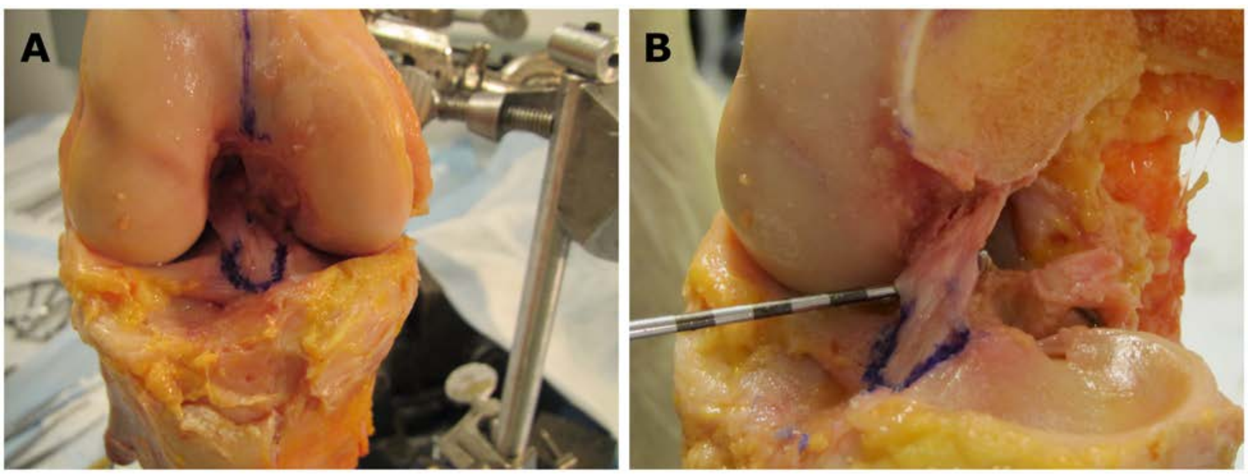


Figure 3. As shown by Piasecki and colleagues, there is an optimal tibial tunnel starting point (15.9 mm below the medial plateau, 9.8 mm posteromedial to the medial margin of the tibial tubercle) which best allows for anatomic femoral tunnel drilling using a transtibial technique.[20] Using this idealized tibial tunnel starting point, a guide pin was drilled using a standard ACL tibial aimer (Smith & Nephew Endoscopy, Andover, MA) to the center of the marked tibial footprint. Guide pin intersection with the intercondylar notch wall was observed and verified.

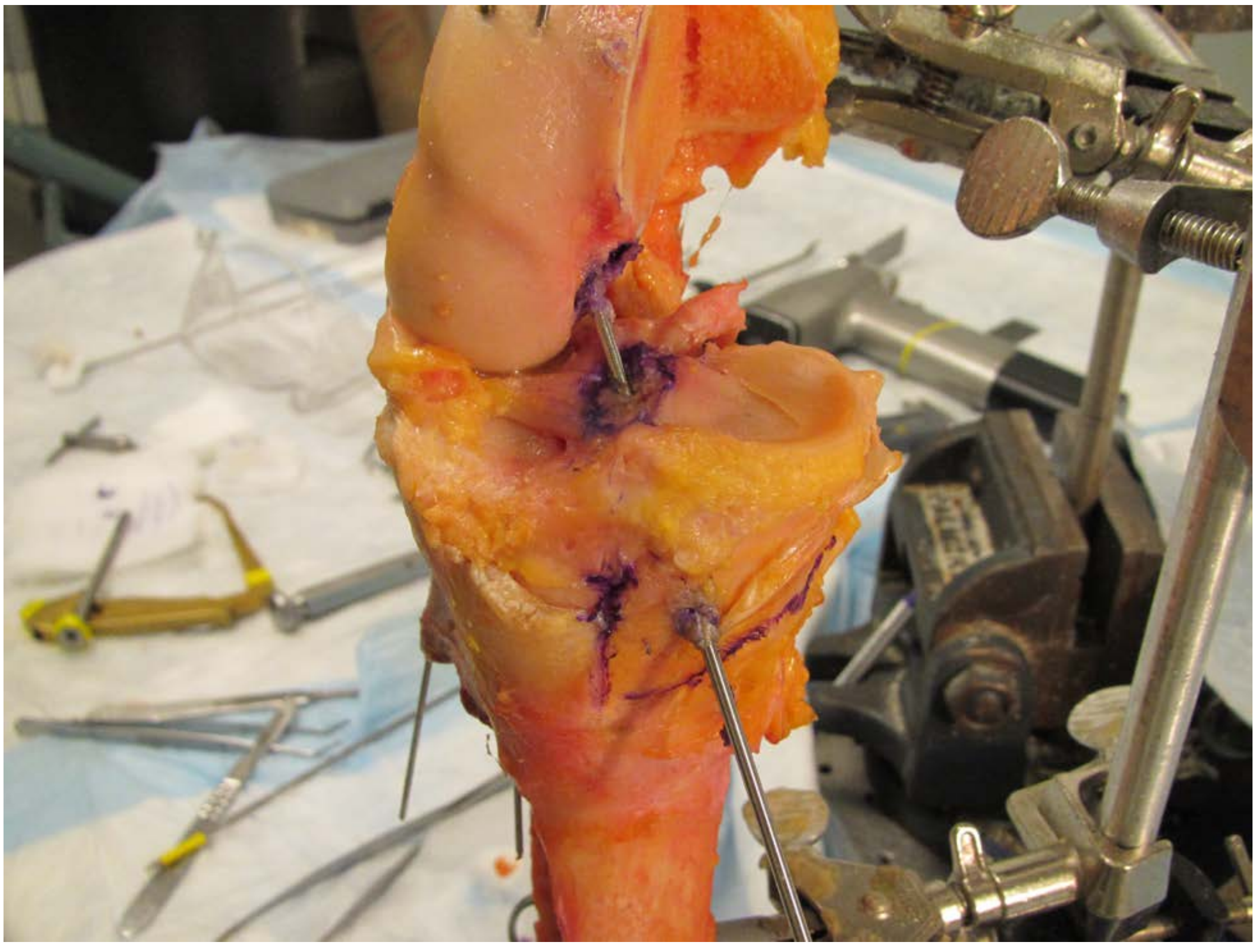


Figure 4. Native femoral ACL footprint (blue) with locations of over-the-top positions achieved with various tibial tunnel sizes. Rhino software (McNeel, Seattle WA) was used to geometrically determine the center of the native femoral footprint and measure in millimeters the relationship of this point with the over-the-top femoral position achieved with each tibial tunnel size. Note that there is a threshold for tibial tunnel size, under which, the surgeon will be unable to obtain anatomic femoral tunnel placement using a transtibial technique. As shown in this specimen, a tibial tunnel smaller than 9mm does not allow for reaming of an anatomic femoral tunnel (brown).

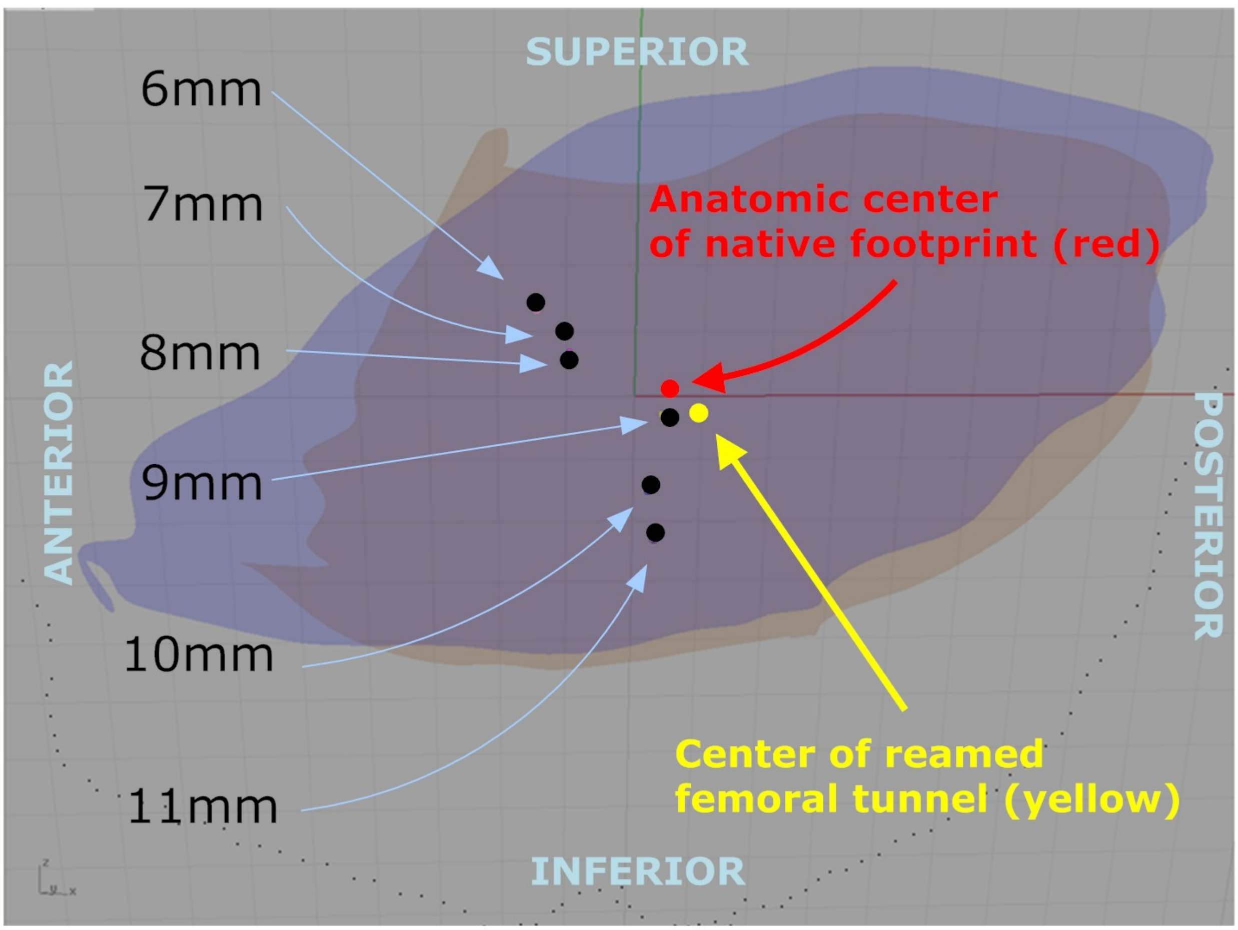
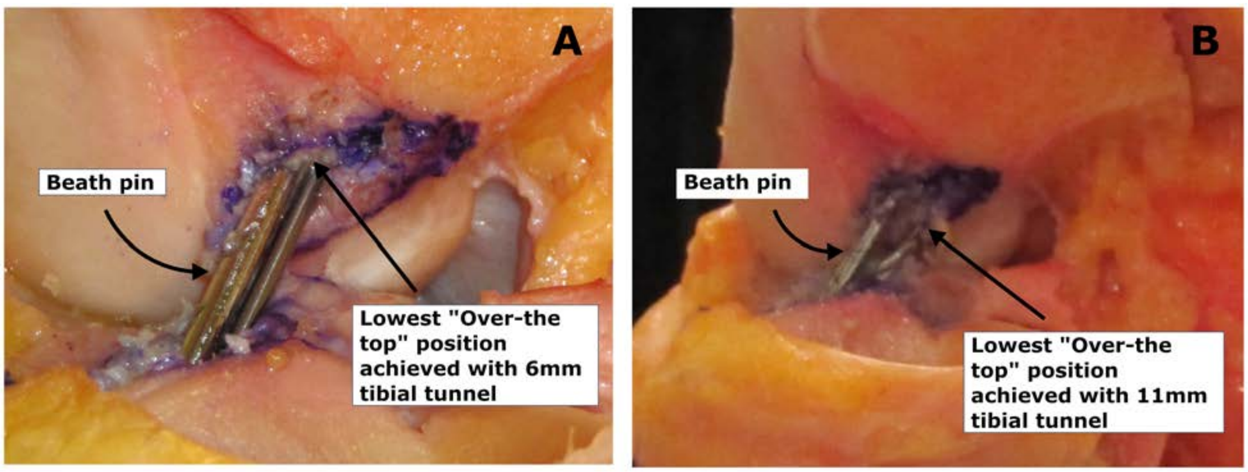


Figure 5. Close-up view of cadaver native femoral ACL footprint (blue outline) with locations of over-the-top positions (beath pin without guide used for demonstration purposes) achieved. As shown here, the tibial tunnel represents a potentially unforgiving linear constraint to instrumenting the femur. (**A**) With a 6mm tibial tunnel, placement of a femoral tunnel will be too high and anterior relative to the native femoral footprint center. (**B**) On the other hand, an 11mm tibial tunnel in the same specimen affords great flexibility, easily allowing the anatomic femoral position to be achieved.



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