

A Validation Study of a Novel 3-Dimensional MRI Modeling Technique to Identify the Anatomic Insertions of the Anterior Cruciate Ligament

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Background: Anatomic single bundle anterior cruciate ligament (ACL) reconstruction is the current gold standard in ACL reconstructive surgery. However, placement of femoral and tibial tunnels at the anatomic center of the ACL insertion sites can be difficult intraoperatively. We developed a “virtual arthroscopy” program that allows users to identify ACL insertions on preoperative knee magnetic resonance images (MRIs) and generates a 3-dimensional (3D) bone model that matches the arthroscopic view to help guide intraoperative tunnel placement.

Purpose: To test the validity of the ACL insertion sites identified using our 3D modeling program and to determine the accuracy of arthroscopic ACL reconstruction guided by our “virtual arthroscopic” model.

Study Design: Descriptive laboratory study.

Methods: Sixteen cadaveric knees were prescanned using routine MRI sequences. A trained, blinded observer then identified the center of the ACL insertions using our program. Eight knees were dissected, and the centers of the ACL footprints were marked with a screw. In the remaining 8 knees, arthroscopic ACL tunnels were drilled into the center of the ACL footprints based on landmarks identified using our virtual arthroscopic model. Postprocedural MRI was performed on all 16 knees. The 3D distance between pre- and postoperative 3D centers of the ACL were calculated by 2 trained, blinded observers and a musculoskeletal radiologist.

Results: With 2 outliers removed, the postoperative femoral and tibial tunnel placements in the open specimens differed by 2.5 ± 0.9 mm and 2.9 ± 0.7 mm from preoperative centers identified on MRI. Postoperative femoral and tibial tunnel centers in the arthroscopic specimens differed by 3.2 ± 0.9 mm and 2.9 ± 0.7 mm, respectively.

Conclusion: Our results show that MRI-based 3D localization of the ACL and our virtual arthroscopic modeling program is feasible and does not show a statistically significant difference to an open arthrotomy approach. However, additional refinements will be required to improve the accuracy and consistency of our model to make this an effective tool for surgeons performing anatomic single-bundle ACL reconstructions.

Clinical Relevance: Arthroscopic anatomic single-bundle ACL reconstruction is the current gold standard for ACL reconstruction; however, the center of the ACL footprint can be difficult to identify arthroscopically. Our novel modeling can improve the identification of this important landmark intraoperatively and decrease the risk of graft malposition and subsequent graft failure.

Keywords: anterior cruciate ligament; reconstruction; footprints; arthroscopy

Anterior cruciate ligament (ACL) tears are extremely common injuries in active persons participating in running, jumping, and pivoting sports, with an annual incidence estimated at up to 36.9 per 100,000 person-years based on population data.¹⁶ These injuries can be complicated by primary and secondary injuries to the meniscus and articular cartilage,^{12,29} which increases the risk of early-onset knee osteoarthritis (OA).^{13,28,37} Radiographic OA is up to

105 times more likely to occur in adults who had childhood ACL tears.⁶ With pain leading to functional impairment, OA is one of the most common and cost-intensive causes of chronic disability in the United States.²⁵

Studies have shown that stabilizing the knee can help prevent secondary injuries in the knee.^{3,8,13} Arthroscopic anatomic single-bundle ACL reconstruction with the graft centered in the ACL footprint is the current preferred technique for surgical reconstruction.^{21,32} However, ACL footprints vary in location between patients and can also be difficult to identify arthroscopically. Graft malposition, secondary to improper tunnel positioning, is the most common

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cause of graft failure^{27,34} and can be associated with ongoing knee pain, instability, effusion, limited knee range of motion, and poor function.^{10,15,19,33}

We developed a computer-based “virtual arthroscopy” tool allowing users to identify the ACL insertions on routine clinical magnetic resonance imaging (MRI). Using this tool, the center of the ACL footprint was identified and a 3-dimensional (3D) model was generated. We have previously demonstrated and published the inter- and intraobserver reliability of using this tool to identify the ACL center.³⁵ We further developed this tool to allow the 3D model to be rotated to match the arthroscopic view seen by surgeons.

The purposes of this study were to test the validity of the ACL insertion sites identified using our 3D modeling program and to determine the accuracy of arthroscopic ACL reconstruction guided by our “virtual arthroscopic” model. We hypothesized that the ACL insertion centers identified on MRI would be within 4 mm of insertion points identified surgically on cadaveric dissection. The 4-mm threshold represents the radius of an average 4-strand hamstring tendon ACL graft and is similar to the established reliability of our MRI model.³⁵

METHODS

Based on our previous work,³⁵ we determined the minimum statistically significant difference between pre- and postoperative MRI insertions to be 4 mm and the MRI standard deviation was 1.5 mm.³⁵ Our sample size was calculated with an alpha of 5% and beta of 10% (ie, 90% power), with which we determined that we would need 6 knees. To account for potential data loss, we added an additional 2 (33%) specimens, resulting in 8 knees in each arm of our study (16 knees total) (Figure 1).

Eight pairs of fresh-frozen cadaveric knees were pre-scanned using the same five 2-dimensional (2D) MRI sequences used in our routine clinical protocol using a knee coil on a Siemens Symphony 1.5-T magnet: coronal and sagittal proton density (PD) (repetition time [TR]/echo time [TE], 1800/13 ms; matrix, 512 × 278; field of view [FOV], 160 × 160 mm; slice thickness, 3 mm), coronal and sagittal PD fat-saturated (FS) (TR/TE, 2500/39 ms; matrix, 384 × 269; FOV, 180 × 180 mm; slice thickness, 3 mm) and axial PD FS (TR/TE, 2440/38 ms; matrix, 384 × 230; FOV, 160 × 160 mm; slice thickness, 4 mm).

Each knee was randomly assigned to the arthroscopic or open group. Prior to any procedure, a trained, blinded observer (V.S.) whose accuracy has been previously confirmed against a musculoskeletal radiologist (J.L.J.)³⁵ carefully traced the bony contours of the distal femur and

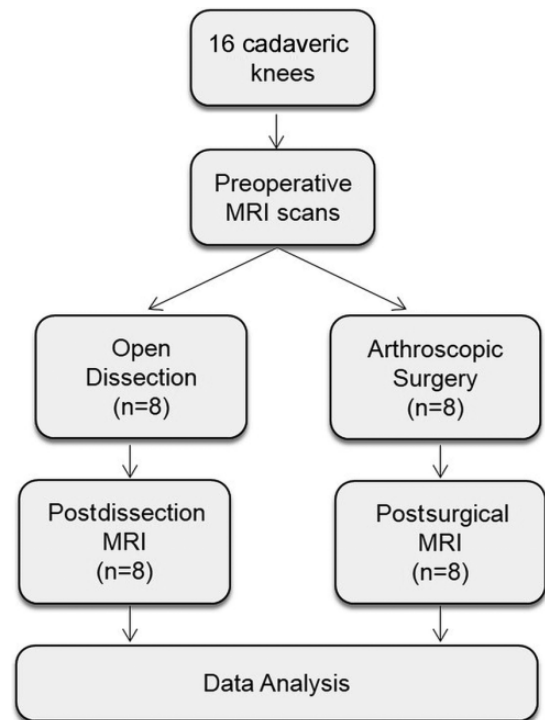


Figure 1. Study design and flow.

proximal tibia of each specimen on 2D coronal images using our program. Each ACL insertion was also identified on multiple planes along the visible ligament-bone interface on preoperative MRI. Our program then applied a cubic spline interpolation in both the axial and sagittal planes, creating a virtual 3D bone model, marked with the series of user-identified points corresponding to the ligament insertion sites. Each model was qualitatively reviewed to confirm the appropriateness of ligament locations (Figure 2).

Open Procedure

Through a midline incision and a medial parapatellar arthrotomy, the 8 knees selected for this group were opened and the ACL identified. The anterior cruciate ligament (ACL), posterior cruciate ligament (PCL), and medial collateral ligament (MCL) were transected to allow for adequate exposure of the entire ACL femoral and tibial footprints. The ACL was then dissected off of each footprint as closely to the bone as possible, with particular care used to preserve the actual ligament insertion site on the bone (Figure 3). The ACL footprint on both the

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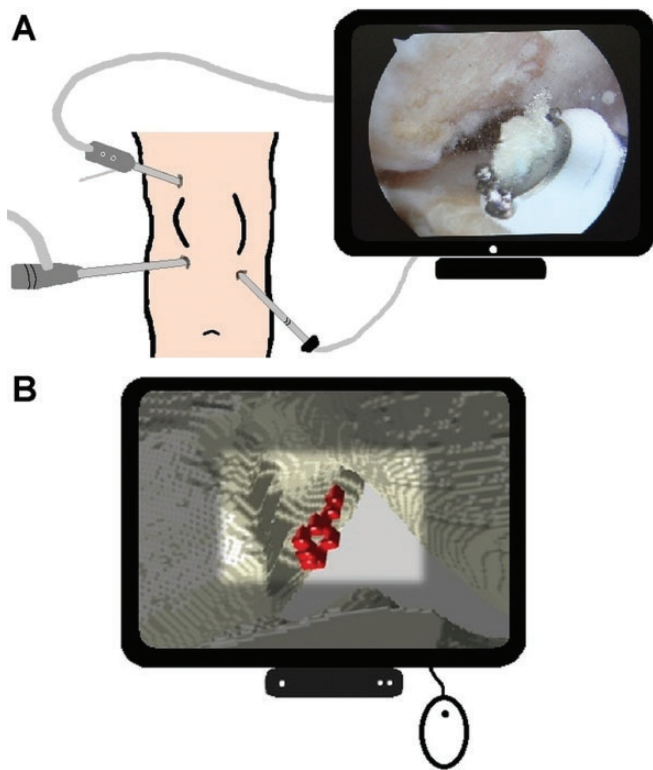


Figure 2. Arthroscopic model with associated 3-dimensional (3D) bone model of the anterior cruciate ligament footprints. (A) A radiofrequency wand was used to identify the femoral footprint arthroscopically on the lateral wall of the femur. (B) The associated femoral footprint (in red) as identified on the 3D model. Each dot represents a portion of the ligament identified on axial, coronal, or sagittal magnetic resonance imaging using our program.

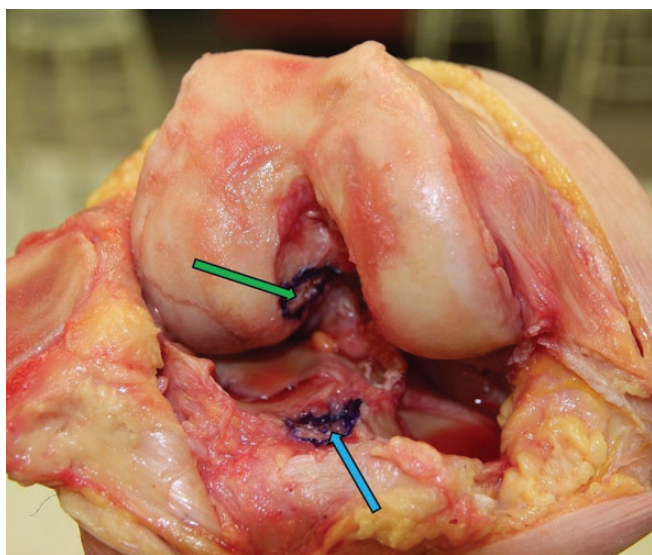


Figure 3. Open knee dissection showing the femoral (green arrow) and tibial (blue arrow) anterior cruciate ligament footprint.

femoral and tibial sides was carefully marked with a surgical pen. A ruler was then used to measure the length and width of each footprint. From these measurements, the center of the footprints was identified. A drill was placed into the center of each footprint, followed by a guide wire, and a 7 × 25-mm BioSure HA interference screw (Smith & Nephew) was inserted over the top of the wire and into the center of the footprint.

Arthroscopic Procedure

In each of the remaining 8 knees, the femoral and tibial ACL tunnels were positioned using the preferred surgical technique at our institution. A high anterolateral viewing portal and a low anteromedial working portal were first established followed by a third central portal, which was established for the use of an arthroscopic ruler. The ACL was identified and carefully resected using a combination of a shaver and radiofrequency wand to identify the femoral and tibial footprints in each knee. In 8 knees, arthroscopic anatomic single-bundle ACL tunnels were drilled on both the femoral and tibial sides using an anteromedial portal technique. A 7.5-mm reamer was used as it is one of the most common tunnel diameters in hamstring ACL reconstruction.³⁰ The centers of the ACL footprints were identified using our virtual arthroscopic model. The distance from the center to 2 landmarks on each of the femoral and tibial sides was measured based on structures easily visible both arthroscopically and on MRI. On the femoral side, the landmarks were the posterior capsular insertion and the inferior articular margin of the lateral femoral condyle with the knee at 70° of flexion, which represents the position of the knee intraoperatively during ACL footprint identification. On the tibial side, the landmarks were the posterior aspect of the anterior horn of the lateral meniscus and the central anterior margin of the PCL (Figure 4). The centers of the ACL femoral and tibial footprints were then identified arthroscopically using the aforementioned landmarks and an arthroscopic ruler through the central portal. Once the centers were identified, they were marked using a Steadman awl on the femoral side and electrocautery on the tibial side. The surgeon was also asked to verify the center point with clinical correlation. Where the surgeon's clinical assessment differed from the point suggested by the computer model, the surgeon's clinical expertise was utilized. A Beath pin was then inserted into the center of the femoral ACL footprint followed by the 7.5-mm femoral reamer. On the tibial side, the direct tip aimer was used to place the Beath pin into the mark in the center of the tibial ACL footprint followed by the 7.5-mm tibial reamer. In 1 knee, the hamstring tendons were harvested and an ACL reconstruction was performed using 7 × 25-mm BioSure HA interference screws for fixation on both the femoral and tibial sides.

Postprocedural MRI was performed on all 16 knees. Manual bone segmentation and ligament identification was again completed on these postprocedural images within our program (Figure 5). The distance between the pre- and postoperative 3D centers of the ACL footprints were calculated by a trained, blinded observer (Y.P.) and a musculoskeletal-trained radiologist (J.L.J.) using the formula

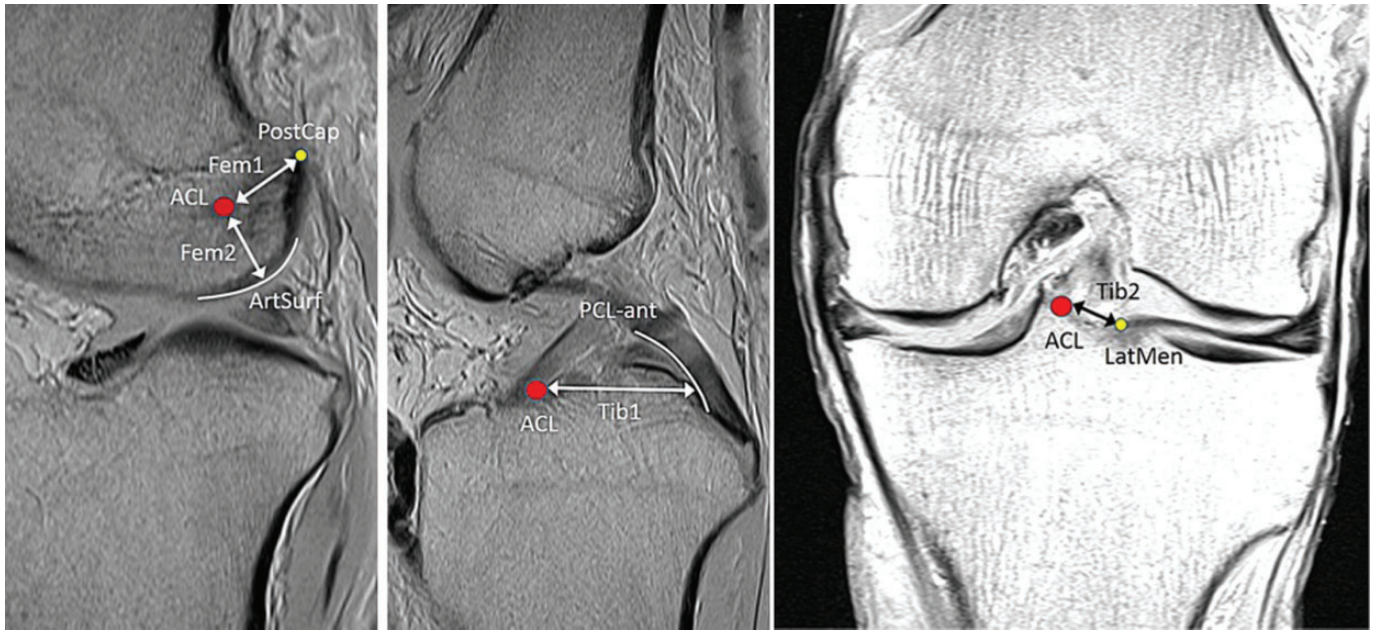


Figure 4. Sagittal and coronal proton density–weighted magnetic resonance images showing distances used to place the anterior cruciate ligament (ACL) tunnels at arthroscopy. Fem1, distance from center of the ACL insertion to the upper edge of posterior capsular insertion (PostCap); Fem2, distance to the articular surface (ArtSurf) at 70° of knee flexion; Tib1, distance from ACL insertion to the anterior border of the posterior cruciate ligament (PCL-ant); Tib2, left-right distance from the ACL to the medial edge of the anterior lateral meniscal tibial insertion (LatMen).

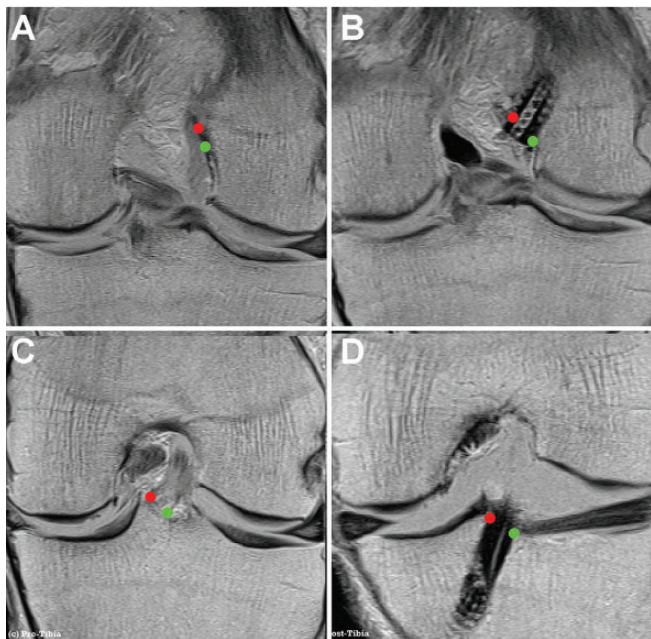


Figure 5. Coronal proton density images demonstrating the (A and C) preprocedural anterior cruciate ligament (ACL) footprints and (B and D) postprocedural ACL tunnels. The red and green points represent (A and C) the ACL insertions on the preoperative magnetic resonance images (MRIs) and (B and D) the edges of the graft tunnels on the postprocedural MRIs.

$$d = \sqrt{(L1 - L2)^2 + (P1 - P2)^2 + (S1 - S2)^2}$$

where $L1$, $P1$, and $S1$ are the coordinates for the preprocedural 3D center and $L2$, $P2$, and $S2$ are the coordinates for the postprocedural 3D center, both in the lateral, posterior, superior (LPS) coordinate system. The mean lengths of the anteromedial and posterolateral bundles in the sagittal plane and width of the anteromedial and posterolateral bundles in the sagittal and coronal planes were calculated automatically by our program for each examiner and for both examiners combined.

Data Analysis

Data were analyzed using SPSS version 20 software (IBM Corp). Descriptive statistics were reported as mean \pm SD. Paired Student t tests were performed to assess whether error of tunnel position at arthroscopy was significantly greater ($P < .05$) than that found with open surgery and MRI.

RESULTS

Open Procedure

The mean length and width of the femoral footprint were 13.8 ± 1.4 mm and 10.3 ± 1.4 mm, respectively. The mean length and width of the tibial footprint were 13.4 ± 1.5 mm and 10.4 ± 1.4 mm, respectively. The range was 11 to 16 mm for length and 8 to 12 mm for width. The postoperative

TABLE 1
Consensus Meeting for Cases With a >4-mm
Difference Between the MRI-Identified ACL Footprint
Centers and Surgical Tunnel Centers^a

Specimen		Pre- to Postprocedural Distance, mm		Potential Source of Error
		Open	Arthroscopic	
1	Femur	3.7	3.2	Anatomic variant
	Tibia	6.1	3.1	
2	Femur	3.5	5.9	Combined imaging + surgical
	Tibia	2.2	4.0	
3	Femur	3.0	1.3	Surgical
	Tibia	3.8	3.0	
4	Femur	1.4	3.5	Surgical
	Tibia	3.0	3.5	
5	Femur	2.5	9.2	Surgical
	Tibia	3.2	3.0	
6	Femur	1.0	3.7	Surgical
	Tibia	2.1	3.3	
7	Femur	2.3	3.4	Surgical
	Tibia	3.4	1.5	
8	Femur	2.8	3.8	Surgical
	Tibia	3.8	3.2	

^aACL, anterior cruciate ligament; MRI, magnetic resonance imaging.

femoral and tibial tunnel centers differed by 2.5 ± 0.9 mm and 3.4 ± 1.2 mm, respectively, from preoperative centers identified on MRI.

Arthroscopic Procedure

The postoperative femoral and tibial tunnel centers differed by 4.2 ± 2.4 mm and 3.1 ± 0.7 mm, respectively, from preoperative centers identified on MRI. There was no significant difference between the open and arthroscopic knees (femur, $P = .08$; tibia, $P = .47$).

There were several outliers in both the open and arthroscopic specimens. In cases where the difference in centers was >4 mm, a consensus meeting for second review was performed (Table 1).

DISCUSSION

MRI has been shown to detect ACL tears with high accuracy.⁵ It is also commonly used to assess graft position and integrity after ACL reconstruction.^{1,2,22} We have developed a novel tool using routine knee MRI sequences that can identify the centers of the ACL femoral and tibial footprints accurately and reliably, thereby allowing for the creation of a 3D model that can be digitally rotated into a “virtual arthroscopic” view, simulating the arthroscopic views observed in the operating room. Multiple previous studies have shown that the ACL footprint is not the same in every patient, and therefore the centers of the ACL footprints also differ.^{11,22,26} Using this model, we are able to locate intra-

articular landmarks on MRI that are also reliably found arthroscopically, allowing surgeons to individualize ACL reconstructive surgery. Guided individualized placement of the ACL tunnels to improve the accuracy and consistency of graft placement may decrease the rate of graft failure secondary to graft malpositioning and ultimately decrease the rate of early-onset OA in these young, active patients with ACL tears.

The open-surgery portion of the current study directly validated the accuracy of MRI localization of ligament footprint locations against their actual locations, as identified surgically. The ACL footprint size measured in our open specimens was consistent with previous studies.^{22,36} In the open specimens, the ACL femoral footprint tended to be qualitatively easier to identify than the tibial footprint, which may account for the greater accuracy (MRI vs surgery) of the femoral footprint (2.5 ± 0.9 mm) compared with the tibial footprint (3.4 ± 1.2 mm). This is not surprising given that the entire femoral ACL footprint is easily seen when the knee is dissected by sectioning 3 of the 4 main ligaments while the center of the ACL tibial footprint can be difficult to identify, even at open surgery, due to its broad fan-shaped insertion. On consensus review, we believe that the outlier specimen had a particularly broad and fan-shaped native tibial footprint. This allows a variety of possible tunnel locations all lying within the anatomic footprint of the ACL. Consistent with this, Frank et al¹⁴ and McConkey et al²⁶ both identified that there are circumstances where the ACL tunnel is drilled within the native footprint and therefore technically “anatomic” but that the footprint is much larger than the tunnel.

The arthroscopic portion of the study tested how accurately tunnels could be arthroscopically placed using the “virtual arthroscopy” imaging tool as a guide. Accuracy of placement on postoperative MRI, compared with the planned locations on preoperative MRI, was only slightly lower than the accuracy of ligament localization on open dissection specimens, and this difference was not statistically significant. As in previous studies, we found that the ACL femoral tunnel was difficult to identify arthroscopically,²⁶ with tunnels placed arthroscopically a mean 4.2 ± 2.4 mm from the location planned on preoperative MRI. When we removed 2 outliers, the mean was only 3.2 ± 0.9 mm. In these 2 outlier specimens, the arthroscopic femoral tunnel was posterior to the MRI-identified ACL femoral footprint, but the arthroscopic tunnel placement was in the so-called “usual” position based on commonly used intra-articular landmarks. On consensus review of the scans, we believed that the differences in these specimens could be attributed to a combination of anatomic variation of the femoral insertion and a surgical bias to position the tunnel more posteriorly in an effort to avoid the historical vertical and anterior femoral tunnel malpositioning.²⁶ The center of the ACL tibial footprint was easier to identify arthroscopically, with the difference between planned and actual tunnel locations 3.1 ± 0.7 mm. This is consistent with previous studies.³¹ The tibial footprint is generally easy to visualize arthroscopically, and as previously reported, the landmarks to identify the ACL tibial footprint center are reproducible and relatively easy to locate.¹¹

A key concern with anatomic single-bundle ACL reconstruction is that the ideal tunnel position has not yet been established.²⁶ It is believed that the ideal tunnel position would be the center of the native ACL footprints. McConkey et al²⁶ performed a study where surgeons performed their standard single-bundle ACL reconstruction in cadaveric knees and rated their own tunnel positions. Then, tunnel positions were assessed arthroscopically by an independent surgeon and also via a 3D computed tomography (CT) scan based on previously accepted radiographic criteria.^{4,7,9,23,24} McConkey et al²⁶ found that surgeons were more likely to determine that their own tunnels were drilled in the so-called ideal position than another independent surgeon was to agree with this. The authors noted that current challenges in ACL reconstructive surgery include this lack of agreement between surgeons on the ideal tunnel position in single-bundle ACL reconstruction and as well as a lack of techniques available for arthroscopic assessment of tunnel position.

The strength of our approach is that it is the first to assist ACL reconstruction using imaging to help individualize tunnel placement prior to and during the procedure. In prior studies, the surgeon placed the tunnels for ACL reconstruction surgically first and only used imaging (radiographs, 3D CT, MRI) postoperatively to evaluate tunnel placement.^{17,20} Our technique is applicable to intrasubstance tears where the ligament attachment to the bone is intact and therefore identifiable rather than for avulsion type injuries. We determined the anatomic location for tunnel placement preoperatively and had interactive 3D imaging available intraoperatively to help guide the surgeon. After removing the outliers, we were able to identify all tunnel centers within our 4-mm target level of accuracy. We set 4 mm as the acceptable margin for error as this equals the radius of the average 4-strand hamstring tendon autograft and is near the expected interobserver reliability of our MRI model.³⁵ Of course, a lower margin of error near 2 mm would be even more desirable and would require further refinement of our methods. Some errors are unavoidable, including parallax during knee arthroscopy,¹⁸ but we feel many of the errors found in this study could be improved by user training.

This study had limitations. The sample size, although substantial for a cadaveric study and justified by power analysis, was still small and, due to the novelty of the technique, there was a steep learning curve for all involved. The sources of error in the outliers with >4-mm variation between MRI and surgical or arthroscopic insertion sites were related to reader inexperience on imaging and surgical bias. In addition, there was surgeon bias in the 2 specimens with significant anatomic variability to the ACL femoral footprint visualized on MRI. Based on experience, the senior surgeon (C.H.) believed that the footprint identified on MRI was notably more anterior than what would normally be seen and therefore placed the tunnel in a more traditional position when viewing the knee arthroscopically rather than in the MRI-identified position. No additional external gold standard was available for independent validation given that this is a new and novel technique. We also had only a single consultant surgeon involved. We also recognize that not all surgeons use 70° as their operative knee

flexion angle. With this being our first model, we decided to program it to 70° of flexion as it is the most commonly used technique at our institution. We are planning to be able to adjust the knee flexion angle in future models. Further work is needed to test the real-world utility of our technique in the hands of multiple surgeons and trainees.

This study presents a novel MRI-based 3D localization tool and a virtual arthroscopic modeling program that addresses a clinical need for imaging assistance to improve surgical outcomes in a common injury that affects many young, active patients. We have shown in cadavers that using “virtual arthroscopy” to assist in ACL reconstruction is feasible with a tunnel placement error of approximately 3 mm. Additional refinement of MRI-reading and arthroscopic techniques are needed to improve the accuracy and consistency of this tool to effectively aid surgeons performing anatomic single-bundle ACL reconstructions.

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