AJSM PreView, published on June 6, 2013 as doi:10.1177/0363546513490657

Use of a Fluoroscopic Overlay to Assist Arthroscopic Anterior Cruciate Ligament Reconstruction

Gele Moloney,* MD, Paulo Araujo,* MD, Stephen Rabuck,* MD, Robert Carey,† BS, Gustavo Rincon,‡ MD, Xudong Zhang,*†§ PhD, and Christopher Harner,* MD
Investigation performed at the University of Pittsburgh, Pittsburgh, Pennsylvania

Background: A growing body of evidence supports the importance of anatomic tunnel positioning in the success of anterior cruciate ligament (ACL) reconstruction, which stimulates the need for technologies to aid surgeons in achieving accurate anatomic tunnel placement. Intraoperative fluoroscopy is potentially one such technology, while its efficacy and usability have yet to be established.

Purpose: To investigate the performance of an intraoperative fluoroscopic overlay in guiding tunnel placement during ACL reconstruction.

Study Design: Controlled laboratory study.

Methods: Twenty cadaveric knees underwent computed tomography (CT) scans and arthroscopic digitization of ACL insertion sites. The outlines of the digitized insertion sites were mapped to the corresponding CT-acquired bone models through a coregistration procedure. Twenty orthopaedic surgeons performed simulated ACL reconstructions, each on a randomly assigned cadaveric knee, first without and then with the aid of a fluoroscopic overlay system. The overlay system displayed on a lateral fluoroscopic image targets points representing the locations of the ACL insertion sites estimated from the literature data. Surgeons were allowed to adjust their tunnel positions under the guidance of the fluoroscopic image. Their initial, intermediate, and final positions were documented and compared with the target points as well as the native insertion sites.

Results: Surgeons demonstrated significant ($P < .01$) improvements in femoral and tibial tunnel placements relative to the target points from an average distance of 3.9 mm to 1.6 mm on the femur and 2.1 mm to 0.9 mm on the tibia. The improvements toward the knee-specific actual insertion sites were significant on the tibial side but not on the femoral side.

Conclusion: Surgeons can be successfully guided with fluoroscopy to create more consistent femoral and tibial tunnels during ACL reconstruction. More research is warranted to develop better population representations of the locations of natural insertion sites.

Clinical Relevance: Intraoperative fluoroscopy can be an effective, easy, and safe method for improving tunnel positioning during ACL reconstruction.

Keywords: ACL reconstruction; fluoroscopy; computer-assisted surgery; ACL insertion sites

Anterior cruciate ligament (ACL) reconstruction is performed at a rate of 175,000 per year,[16] with 85% by surgeons who perform fewer than 10 per year.[10] The percentage that fail, defined as a reconstruction that eventually requires revision or one that results in persistent episodes of instability, has been recently reported to be as high as 16.5%.[4]

There are many reported causes of a failed ACL reconstruction, including technical errors, failure of graft incorporation, and recurrent trauma. Technical errors include tunnel malposition, inadequate graft fixation, and inappropriate graft tensioning. Femoral or tibial tunnel malposition is commonly found to account for failed ACL reconstructions, with rates quoted from 36% to 88%.[12,18,26,27] In a multicenter retrospective evaluation of 293 failed ACL reconstructions, a malpositioned femoral tunnel, generally anterior, was responsible for 108 cases or 36%, while tibial tunnel malposition was responsible for 32 cases or 11%.[26] Marchant and colleagues[18] found a malpositioned tunnel in 107 of 122 knees (88%) undergoing revision ACL reconstruction. Malpositioned or nonanatomic tunnels can cause graft failure by a variety of mechanisms such as graft impingement and graft stretching, resulting in the failed restoration of knee kinematics and persistent instability.

§Address correspondence to Xudong Zhang, PhD, Orthopaedic Research Laboratories, 3820 South Water Street, Pittsburgh, PA 15203 (e-mail: xuz9@pitt.edu).

*Department of Orthopaedic Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania.

†Department of Mechanical Engineering and Materials Science, University of Pittsburgh, Pittsburgh, Pennsylvania.

‡Department of Orthopaedics, San Jose Hospital, University of the Health Science Foundation, Bogota, Colombia.

One or more of the authors has declared the following potential conflict of interest or source of funding: Research funding provided by The Pittsburgh Foundation and Smith & Nephew.

The American Journal of Sports Medicine, Vol. XX, No. X
DOI: 10.1177/0363546513490657

TABLE 1
Literature Data on Center Locations of ACL Insertion Sites[a]

		Femur						Tibia		
	n	AM, x-Axis	AM, y-Axis	PL, x-Axis	PL, y-Axis	SB, x-Axis	SB, y-Axis	AM	PL	SB
Colombet et al (2006)[8]	7	26.4 ± 2.6	25.3 ± 4.2	32.3 ± 3.9	47.6 ± 6.5			36 ± 3.8	53 ± 3.4	
Forsythe et al (2010)[9]	8	21.7 ± 2.5	33.2 ± 5.6	35.1 ± 3.5	55.3 ± 5.3					
Zantop et al (2008)[29]	20	18.5	22.3	29.3	53.6					
Lorenz et al (2009)[15]	12	21 ± 3	22 ± 2	27 ± 3	45 ± 3			41 ± 3	52 ± 3	
Pietrini et al (2010)[21]	12	21.6 ± 5.6	14.6 ± 7.7	28.9 ± 4.6	42.3 ± 6.0			36.3 ± 3.8	51.0 ± 4.0	
Yamamoto et al (2004)[28]	10	25 ± 6	16 ± 5	29 ± 6	42 ± 3	27 ± 6	38 ± 4			
Guo et al (2009)[11]	16					43.1 ± 4.6	38.3 ± 2.7			
Musahl et al (2003)[20]	8					27 ± 4	28 ± 3			43 ± 3

[a]Values are mean ± standard deviation percentages along the axes of the coordinate systems proposed by Bernard et al[6] for the femur and by Amis and Jakob[2] for the tibia. ACL, anterior cruciate ligament; AM x-axis and AM y-axis, location of the anteromedial bundle along the x- and y-axes, respectively; PL x-axis and PL y-axis, location of the posterolateral bundle along the x- and y-axes, respectively; SB, single bundle.

A growing body of literature supports the efficacy of anatomic ACL reconstruction in better restoring knee kinematics. Sadoghi and colleagues[23] compared anatomic and nonanatomic single- and double-bundle ACL reconstructions in 53 patients and found that anatomic reconstructions, whether single or double bundle, had superior clinical scores, better anterior-posterior stability, and less pivot shift than nonanatomic reconstructions. An in vivo biomechanics study comparing transtibial nonanatomic ACL reconstructions with anatomic ACL reconstructions suggested that nonanatomic reconstructions resulted in knees that were more internally rotated and anteriorly and medially translated compared with contralateral control knees. Anatomic reconstructions, on the other hand, were found to result in knee kinematics that were not significantly different from the contralateral control knee kinematics.[1] In vitro studies evaluating the effects of varied tunnel positions on knee laxity also demonstrated the advantage of anatomic reconstruction in restoring joint kinematics.[5,19]

The importance of native insertion sites in defining anatomic ACL reconstruction has motivated several morphometric studies of insertion sites of the ACL.[§] These insertion sites, while 3-dimensional (3D), are often reported in 2 dimensions using the system described by Bernard and Hertel[6] for the femur and by Amis and Jakob[2] for the tibia. Table 1 provides a summary of the position data of ACL insertion sites obtained from these studies.

To translate the knowledge of insertion site anatomy or morphometry into improved intraoperative positioning of tunnels, many methods for intraoperative identification of the correct tunnel position have been proposed, including use of the clock face, direct visualization of the ligament footprints, and use of other bony and soft tissue landmarks as references.[30] The reliability of the clock-face method has been questioned,[3] whereas intra-articular landmarks can be difficult to identify intraoperatively. Variability in knee structure, changes associated with chronic ACL injuries, cases of revision ACL reconstruction, and surgeons' preferences to preserve as much of the native ligament as possible can all make identification of the insertion site challenging.

Several adjuncts to arthroscopic visualization have been proposed to assist in performing anatomic ACL reconstructions, including computer-aided navigation and intraoperative fluoroscopic systems. A system combining navigation and fluoroscopy demonstrated the increased precision of tunnel placement.[24] While there is some preliminary evidence to support the use of computer-aided surgical navigation technology for more accurate ACL tunnel placement,[13,20] it is often criticized for being expensive, invasive, and time consuming.[22] Fluoroscopy offers a practical alternative to improve the tunnel position during ACL reconstruction, especially in the setting where arthroscopic landmarks may be difficult to identify. Its efficacy of assisting surgeons in anatomic ACL reconstructions, however, has yet to be rigorously investigated. A prospective evaluation of 73 patients undergoing ACL reconstruction with or without the use of noninvasive fluoroscopic guidance found that the use of fluoroscopic assistance led to more consistent femoral tunnel positions but no improvement in clinical outcomes as measured by International Knee Documentation Committee scores, KT-1000 arthrometer measurements, and stress radiographs.[7]

The purpose of this study was 2-fold: (1) to evaluate the role of intraoperative fluoroscopy in guiding surgeons during ACL reconstructions and (2) to investigate the performance errors associated with using an average value to represent a range of insertion sites seen in a population. Our hypotheses were that the use of an overlay based on fluoroscopic landmarks would assist surgeons in performing more anatomic ACL reconstructions and that the literature-based average insertion site center would be an adequate representation not jeopardizing anatomic tunnel placement.

[§]References 8, 9, 11, 15, 20, 21, 29.

MATERIALS AND METHODS

Knee Specimen Preparation and Morphometry of ACL Insertion Sites

Our institution's Committee for Oversight of Research and Clinical Training Involving Decedents (CORID) and Institutional Review Board approved this study, which involved cadaveric specimens and human participants. Twenty cadaveric specimens from the midfemur to midtibia were obtained. The specimens were examined radiographically and excluded if there was evidence of previous surgery, osteoarthritis, or osteophytes. There were 11 male and 9 female donors, with an average age of 61.1 ± 5.2 years at the time of death. Specimens were stored in a freezer at $-20°$ and thawed at room temperature 24 hours before use.

The specimens were dissected of skin and soft tissue proximal to the proximal aspect of the knee joint capsule and distal to the tibial tuberosity. Care was taken to preserve the capsule. Six fiducial markers (precision nylon spheres; radius, 9.525 mm) were affixed to the femur and tibia (3 on each) in a noncollinear fashion. The specimens then underwent high-resolution computed tomography (CT) scans ($0.5 \times 0.5 \times 0.625$ mm). The bones and fiducial markers in each CT slice were segmented using thresholding and manual segmentation with Mimics software (Materialise, Leuven, Belgium); individual slices were then combined to create 3D models using a regularized marching tetrahedral algorithm.

Three arthroscopic portals, anteromedial, anterolateral, and central, were created in each knee. The fat pad and any synovium surrounding the cruciate ligaments were debrided arthroscopically. The ACL was transected, leaving approximately a 2-mm stump at the femoral and tibial insertion sites. With use of an optical motion capture system (Polaris Spectra, NDI, Waterloo, Ontario, Canada) with a vendor-reported accuracy of ± 0.3 mm, the ACL insertion site was defined: depending on its size, 10 to 25 individual points at the periphery of the insertion site were digitized with arthroscopic visualization. Surfaces of the fiducial markers were also digitized such that spherical point clouds were created to enable a co-registration procedure, which will be described later. After digitization of the insertion sites, the remnant stumps were debrided to bone using thermal ablation.

A simulated ACL reconstruction was then performed as described in the following section before each knee was disarticulated to facilitate direct visualization of the femoral and tibial insertion sites. The ACL insertions as well as the fiducial markers on the disarticulated knee were digitized again using the same procedure described above.

A co-registration procedure developed by our laboratory[14] was used to map the digitized ACL insertion sites onto the corresponding CT-based 3D bone models. The fiducial registration error, defined as the difference in intermarker distances between the two modalities, was less than 2%. The resulting 3D models were used to generate digitally reconstructed lateral radiographs of the knee along with the insertion sites. The positions of projected insertion site points were quantitatively expressed in the lateral plane based on the method proposed by Bernard et al[6] for the femur and by Amis and Jakob[2] for the tibia. The geometric centers of the projected insertion site points were computed for each specimen and then statistically summarized across all specimens.

Use of a Fluoroscopic Overlay in Simulated ACL Reconstructive Surgery

The fluoroscopic overlay was created on a lateral fluoroscopic image of the knee. Before the start of a simulated surgical procedure, the fluoroscopy unit was positioned by an experimenter to obtain an "ideal" lateral image of the knee with maximum overlap of the posterior femoral condyle.

The femoral overlay, based on the method originally described by Bernard et al,[6] was defined by drawing a line along the Blumensaat line followed by a perpendicular line extended to the edge of the femoral condyles. A rectangular coordinate system was then established with the origin as the most posterior and proximal point and the Blumensaat line as the x-axis (Figure 1). The target points displayed by the overlay to guide surgeons were based on data obtained by Colombet and colleagues.[8] Reported as a percentage along each axis, the center of the anteromedial (AM) bundle was located at 26% and 25% on the x- and y-axis, respectively, and the posterolateral (PL) bundle was at 33% and 48%, respectively. The center of the entire footprint was estimated to be the average of the AM and PL bundle centers at 29% on the x-axis and 37% on the y-axis. These percentage values were predetermined during development of the software tested in this study.

The tibial overlay was defined along the Amis-Jakob line,[2] which runs parallel to the medial tibial plateau from the anterior cortex of the tibia to the posterior corner of the posterior cruciate ligament (PCL) fossa posteriorly. Target points on the overlay were based on the work done by Pietrini and colleagues,[21] which found the insertion center of the AM bundle at 36% and the insertion center of the PL bundle at 51% from the anterior cortex along this line. The center of the entire footprint was estimated to be at the midpoint of the centers of the two bundles at 44%.

A group of 20 orthopaedic surgeons performed parts of the arthroscopic ACL reconstructions each on a randomly assigned knee specimen. The group of surgeons consisted of 1 sports fellowship–trained orthopaedic surgeon, 10 orthopaedic sports surgeons participating in a visiting fellowship at our institution to study ACL reconstruction, 3 sports medicine fellows, and 6 chief residents.

With arthroscopic visualization, each surgeon was asked to mark with an awl the location where he or she would start the femoral tunnel for a single-bundle ACL reconstruction, and a lateral radiograph of the knee was obtained. The appropriate overlay was then created and a target point presented. The surgeon was then asked to adjust the tunnel starting position to match the point presented by the overlay, making as many adjustments as needed, until he or she felt satisfied with the position, and another lateral radiograph was obtained (Figure 2).

Attention was then turned to the tibia. The surgeon placed a drill guide in the location where he or she would

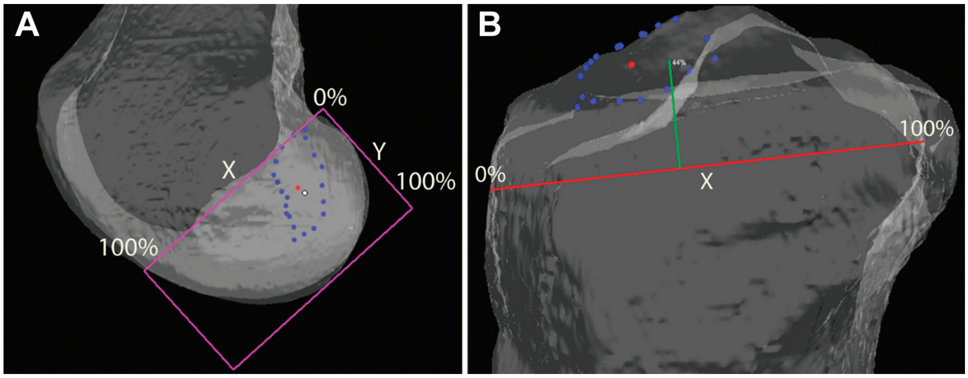

Figure 1. A sagittal plane projection of a computed tomography–based 3-dimensional bone model containing the digitized outline of the ACL insertion site (blue) and the geometric center of the insertion site (red) on both the femur (A) and the tibia (B). On the femur (A), the white dot indicates the 2-dimensional position of the geometric center of the literature-based target insertion site[8] in reference to the rectangular frame (purple rectangle). On the tibia (B), the green line indicates the 1-dimensional position of the geometric center of the literature-based target insertion site[21] in reference to the Amis-Jakob line[2] (red line).

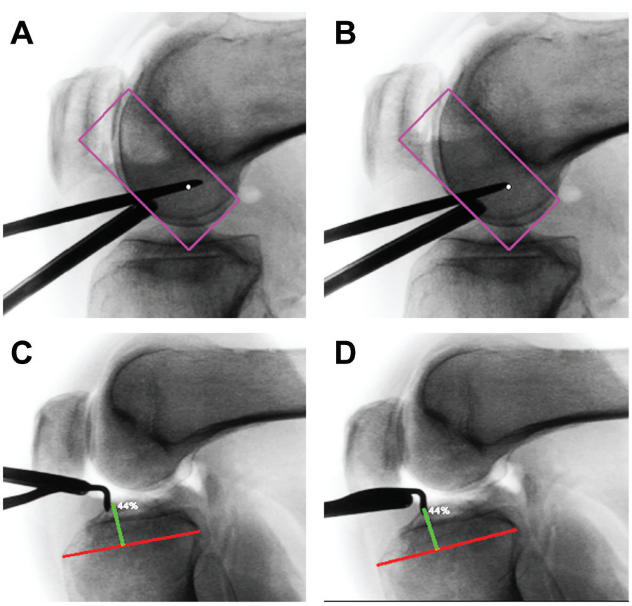

Figure 2. A surgeon's anterior cruciate ligament single-bundle tunnel placement on the femur (A, B) and tibia (C, D) before (A, C) and after (B, D) adjustments were made under the visual guidance of the intraoperative imaging system.

aim the tibial tunnels for single- or double-bundle ACL reconstruction, again in randomized order. Once satisfied, a lateral fluoroscopic image was obtained and the tibial overlay presented. Using a parallel pin guide, the surgeon then adjusted his or her position to match that given by the overlay (Figure 2). Sixteen surgeons successfully completed the tibial portion of the experiment, following a protocol change in the use of the tibial overlay that was made after the first 4 surgeons were tested.

For each tunnel placement trial, the duration between the first and last fluoroscopic images was recorded as a measure of the time added intraoperatively because of the use of the fluoroscopic overlay. The interobserver and intraobserver reliability in establishing the femoral and tibial coordinate systems used to express the insertion site locations were also empirically evaluated. Two experimenters created the coordinate systems on 2 separate occasions at least 3 weeks apart. The interobserver and intraobserver reliability were evaluated using the intraclass correlation coefficient (ICC).

Data Analysis

The distance between the point chosen by the surgeon, indicated by the tip of the awl or the drill guide, and the target point displayed by the overlay was calculated from calibrated fluoroscopic images. This distance was measured before and after the use of the fluoroscopic overlay. To assess the adequacy of using an average point to represent a population, the points chosen by the surgeon before and after the use of the fluoroscopic overlay were compared with the native ACL insertion sites of the knee that the surgeon was operating on, and the distances between them were measured. Statistical comparisons were made using paired t tests with a significance level of $\alpha = .05$.

RESULTS

Table 2 presents the locations of the ACL native insertion centers identified in this study, using the same form and same coordinate systems as the literature data presented in Table 1. The interobserver and intraobserver reliability in establishing the coordinate systems, as measured by the ICC, were found to be 0.99 for the femoral axes and 0.81 and 0.85, respectively, for the tibial axes. The centroid locations of the native insertion sites identified after disarticulation were the same as those identified before disarticulation.

TABLE 2
Center Locations of Native ACL Insertion Sites From the Current Study[a]

	Femur, x-Axis	Femur, y-Axis	Tibia
Mean ± SD (n = 20)	33.7 ± 4.3	32.0 ± 8.6	41.5 ± 4.0

[a]Locations are reported as percentages along each axis. ACL, anterior cruciate ligament; SD, standard deviation.

TABLE 3
Distance to Target Point and Native Insertion Site Before and After the Use of Fluoroscopic Overlay[a]

	Before Fluoroscopy	After Fluoroscopy	*P* Value[b]
Distance to target point displayed by the overlay system, mm			
Femur (n = 20)	3.9 ± 2.2	1.6 ± 1.6	<.01
Tibia (n = 16)	2.1 ± 1.3	0.9 ± 0.6	<.01
Distance to native insertion site, mm			
Femur (n = 20)	4.3 ± 2.5	3.7 ± 1.7	NS
Tibia (n = 16)	2.8 ± 1.3	1.7 ± 1.2	<.01

[a]Values are presented as mean ± standard deviation. NS, not significant.
[b]Paired *t* test.

With the target points displayed by the fluoroscopic overlay system as references, surgeons demonstrated significant improvements in femoral and tibial tunnel positioning. The average distances from the target points before and after the use of fluoroscopy for all tunnels are summarized in Table 3, where the before and after difference was statistically significant ($P < .01$) for both the femoral and tibial sides.

The improvements toward the target points, however, did not directly correspond to improvements towards the native insertion sites. The average distances between the points chosen by the surgeons and the knee-specific native insertion sites before and after the use of fluoroscopy are also listed in Table 3. The before and after difference was statistically significant on the tibial side but not the femoral side.

When the distances to the target points displayed by the overlay system were stratified into <2.5 mm, 2.5 to 5 mm, and >5 mm (Figure 3), the improvements appeared more salient categorically. For example, the number of surgeons who achieved a placement <2.5 mm away from the target increased from 5 to 15 on the femoral side and from 10 to 16 on the tibial side, with the assistance of fluoroscopy. The improvements with respect to the native insertion centers were more moderate categorically (Figure 4).

On the femoral side, surgeons made an average of 1.8 ± 0.4 adjustments per tunnel placement trial, which added an average of 60 ± 74 seconds (range, 0-440 seconds). On the tibial side, surgeons made an average of 1.6 ± 1.9 adjustments per tunnel placement trial, which added an average of 81 ± 82 seconds (range, 0-985 seconds). When surgeons were divided by level of training into subgroups

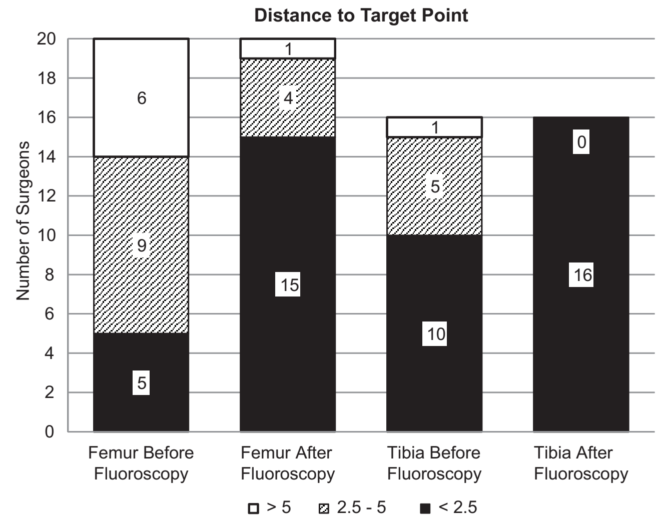

Figure 3. The distribution of tunnel placement measured by distance (mm) to the literature-based target points for the femur and tibia before and after adjustments were made with guidance from the intraoperative fluoroscopy imaging system.

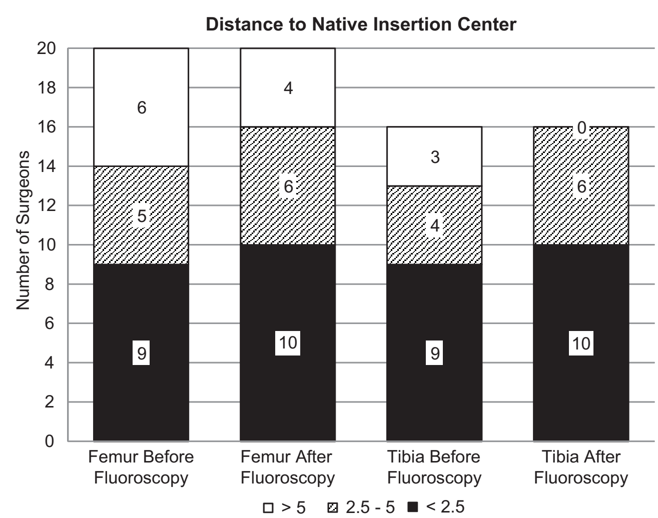

Figure 4. The distribution of tunnel placement measured by distance (mm) to the native anterior cruciate ligament insertion centers for the femur and tibia before and after adjustments were made with guidance from the intraoperative fluoroscopy imaging system.

as residents, fellows, and attending physicians, we did not find any significant between-group difference or trend in any of the performance measures described above.

DISCUSSION

While the importance of anatomic ACL reconstruction is being increasingly appreciated, even experienced surgeons familiar with this concept may find it difficult to reliably identify the ACL insertions with arthroscopic techniques alone. As demonstrated in this study, more than half of the surgeons had an initial tunnel position >2.5 mm away from the center of the native femoral insertion site before the use of the overlay system (Figure 4). With a significant portion of ACL reconstructions performed by low-volume surgeons, tools to aid in anatomic tunnel placement are much needed. Previous studies have shown computer-aided surgical navigation to be effective in guiding tunnel positioning, but studies examining the performance of a fluoroscopic overlay system, as a more cost-effective and readily accessible alternative to improve tunnel positioning, have been lacking.[7,13,20] This study was intended to provide the first set of performance data to support the efficacy of the fluoroscopic overlay.

Surgeons were effectively guided by the overlay system but were not necessarily led to a more anatomic tunnel position: the improvement in terms of the reduction of distance to the native insertion site was significant on the tibial side but not the femoral side. This finding is a reflection of the difference in variability between femoral and tibial locations of ACL insertion sites and the suitability of using the mean to characterize a distribution. The femoral insertion sites, when expressed in the 2D coordinate system proposed by Bernard et al[6] (Table 1), vary in a considerable range not only across different studies in the literature but also across specimens within each study, especially along the y-axis; the tibial insertion sites, when projected onto a lateral radiograph and along the Amis-Jakob line,[2] appear to be less variable (Table 1). Our data (Table 2), when examined along with the literature data, confirmed the same variability difference between femoral and tibial ACL insertions. Clearly, with less radiographic variability of the tibial insertion, it is more likely that the target point could adequately approximate the native insertion site, whereas the more variable femoral insertion is less likely to be well represented by a single target point.

In addition to the effectiveness in providing surgical guidance, other aspects of the fluoroscopic overlay system are also noteworthy. First, the time required to employ this technology was minimal: 60 seconds of additional time for femoral tunnel adjustment and 81 seconds for tibial tunnel adjustment, which means less than 2.5 minutes of additional operative time. While this does not include the time to set up and drape the C-arm or position the leg for imaging, it demonstrates the potential for using this technology efficiently in the operating room. Second, fluoroscopy poses minimal risks to the patient, with an estimated radiation exposure of 0.2 mSv,[25] which is a fraction of the average 3-mSv annual radiation experienced by the general population from natural cosmic radiation.[17] Third, mini-fluoroscopy is cost-effective as compared with, for instance, intraoperative surgical navigation systems and is commonly present at most surgical centers and readily accessible to surgeons. These usability aspects make the fluoroscopic overlay system a favorable choice for improving anatomic ACL reconstruction.

A few limitations of this study should be recognized, particularly with regard to the difference between a laboratory setting and real ACL reconstructive surgery. First, to quantitatively describe the anatomy of the cruciate ligaments, the ACL, PCL, and surrounding synovial tissue were removed from the knees, resulting in an empty notch. This allowed the surgeon unobstructed visualization of the entire notch and wall of the lateral femoral condyle. In reality, many surgeons prefer to retain as much residual ligamentous tissue as possible rather than clear the entire wall to visualize the insertion site. Second, the concept of a fluoroscopic overlay is predicated on a perfect lateral radiograph of the knee. In the laboratory, additional time was spent to ensure maximal overlap of the femoral condyles. There is likely more variability in the lateral radiograph obtained intraoperatively, and the effect of this variability on the effectiveness of the overlay is not known. In addition, there was likely a selection bias associated with our surgeon group. The participating surgeons are members of or in training with a high-volume sports medicine practice that focuses on ACL reconstruction. Compared with the general orthopaedic surgeon population with more diverse backgrounds, the participants in this study likely had more exposure to anatomic ACL reconstruction. A follow-up study conducted with surgeons of more heterogeneous backgrounds, preferably at a different institution, would complement the current study in providing a more objective and robust evidence base.

In conclusion, the use of a fluoroscopic overlay to guide intraoperative tunnel placement during ACL reconstruction has the potential to be a fast, easy, and safe intraoperative tool. It is an effective adjunct to arthroscopic visualization that enables the creation of more consistent and potentially more anatomic tunnels during ACL reconstruction. More extensive evaluations of the application of fluoroscopy are necessary for further advancement of this technology. Studies with a greater sample size to better characterize the ACL insertion position and its variability may provide a statistically more robust target for the femoral side. Alternatively, patient-specific target points based on preoperative imaging may hold potential to produce a more effective overlay system. Empirical investigations of using fluoroscopic overlay systems by low-volume surgeons to improve tunnel placement and clinical outcomes ultimately will be necessary to assess the broad clinical impact.

REFERENCES

1. Abebe ES, Utturkar GM, Taylor DC, et al. The effects of femoral graft placement on in vivo knee kinematics after anterior cruciate ligament reconstruction. *J Biomech*. 2011;44(5):924-929.
2. Amis AA, Jakob RP. Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc*. 1998;6 Suppl 1:S2-S12.
3. Azzam MG, Lenarz CJ, Farrow LD, Israel HA, Kieffer DA, Kaar SG. Inter- and intraobserver reliability of the clock face representation as used to describe the femoral intercondylar notch. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(8):1265-1270.
4. Barrett AM, Craft JA, Replogle WH, Hydrick JM, Barrett GR. Anterior cruciate ligament graft failure: a comparison of graft type based on age and Tegner activity level. *Am J Sports Med*. 2011;39(10):2194-2198.

5. Bedi A, Maak T, Musahl V, et al. Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important. *Am J Sports Med*. 2011;39:366-373.
6. Bernard M, Hertel P, Hornung H, Cierpinski T. Femoral insertion of the ACL: radiographic quadrant method. *Am J Knee Surg*. 1997;10(1):14-21, discussion 21-22.
7. Chouteau J, Benareau I, Testa R, Fessy MH, Lerat JL, Moyen B. Comparative study of knee anterior cruciate ligament reconstruction with or without fluoroscopic assistance: a prospective study of 73 cases. *Arch Orthop Trauma Surg*. 2008;128(9):945-950.
8. Colombet P, Robinson J, Christel P, et al. Morphology of anterior cruciate ligament attachments for anatomic reconstruction: a cadaveric dissection and radiographic study. *Arthroscopy*. 2006;22(9):984-992.
9. Forsythe B, Kopf S, Wong AK, et al. The location of femoral and tibial tunnels in anatomic double-bundle anterior cruciate ligament reconstruction analyzed by three-dimensional computed tomography models. *J Bone Joint Surg Am*. 2010;92(6):1418-1426.
10. Garrett WE Jr, Swiontkowski MF, Weinstein JN, et al. American Board of Orthopaedic Surgery Practice of the Orthopaedic Surgeon, part-II: certification examination case mix. *J Bone Joint Surg Am*. 2006;88(3):660-667.
11. Guo L, Yang L, Wang AM, Wang XY, Dai G. Roentgenographic measurement study for locating femoral insertion site of anterior cruciate ligament: a cadaveric study with X-Caliper. *Int Orthop*. 2009; 33(1):133-137.
12. Johnson DL, Swenson TM, Irrgang JJ, Fu FH, Harner CD. Revision anterior cruciate ligament surgery: experience from Pittsburgh. *Clin Orthop Relat Res*. 1996;325:100-109.
13. Kodali P, Yang S, Koh J. Computer-assisted surgery for anterior cruciate ligament reconstruction. *Sports Med Arthrosc*. 2008;16(2):67-76.
14. Li K, O'Farrell M, Martin D, Kopf S, Harner C, Zhang X. Mapping ligament insertion sites onto bone surfaces in knee by co-registration of CT and digitization data. *J Biomech*. 2009;42(15):2624-2626.
15. Lorenz S, Elser F, Brucker PU, Obst T, Imhoff AB. Radiological evaluation of the anterolateral and posteromedial bundle insertion sites of the posterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(6):683-690.
16. Lyman S, Koulouvaris P, Sherman S, Do H, Mandl LA, Marx RG. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am*. 2009;91(10):2321-2328.
17. Ma CB, Steinbach L. Musculoskeletal imaging. In: Lieberman JR, ed. *AAOS Comprehensive Review*. Rosemont, Illinois: American Academy of Orthopaedic Surgeons; 2009:137-142.
18. Marchant BG, Noyes F, Barber-Westin S, Flekenstein C. Prevalence of nonanatomical graft placement in a series of failed anterior cruciate ligament reconstructions. *Am J Sports Med*. 2010;38: 1987-1996.
19. Markolf KL, Hame SL, Hunter DM, Oakes D, Gause P. Biomechanical effects of femoral notchplasty in anterior cruciate ligament reconstruction. *Am J Sports Med*. 2002;30(1):83-89.
20. Musahl V, Burkart A, Debski RE, Van Scyoc A, Fu FH, Woo SL. Anterior cruciate ligament tunnel placement: comparison of insertion site anatomy with the guidelines of a computer-assisted surgical system. *Arthroscopy*. 2003;19(2):154-160.
21. Pietrini SD, Ziegler CG, Anderson CJ, et al. Radiographic landmarks for tunnel positioning in double-bundle ACL reconstructions. *Knee Surg Sports Traumatol Arthrosc*. 2010;19(5):792-800.
22. Rivkin G, Liebergall M. Challenges of technology integration and computer-assisted surgery. *J Bone Joint Surg Am*. 2009;91 Suppl 1:13-16.
23. Sadoghi P, Kropfl A, Jansson V, Muller PE, Pietschmann MF, Fischmeister MF. Impact of tibial and femoral tunnel position on clinical results after anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27(3):355-364.
24. Shafizadeh S, Balke M, Wegener S, et al. Precision of tunnel positioning in navigated anterior cruciate ligament reconstruction. *Arthroscopy*. 2011;27(9):1268-1274.
25. Singer G. Radiation exposure to the hands from mini C-arm fluoroscopy. *J Hand Surg Am*. 2005;30(4):795-797.
26. Trojani C, Sbihi A, Djian P, et al. Causes for failure of ACL reconstruction and influence of meniscectomies after revision. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(2):196-201.
27. Uribe JW, Hechtman KS, Zvijac JE, Tjin-A-Tsoi EW. Revision anterior cruciate ligament surgery: experience from Miami. *Clin Orthop Relat Res*. 1996;325:91-99.
28. Yamamoto Y, Hsu WH, Woo SL, Van Scyoc AH, Takakura Y, Debski RE. Knee stability and graft function after anterior cruciate ligament reconstruction: a comparison of a lateral and an anatomical femoral tunnel placement. *Am J Sports Med*. 2004;32(8):1825-1832.
29. Zantop T, Wellmann M, Fu FH, Petersen W. Tunnel positioning of anteromedial and posterolateral bundles in anatomic anterior cruciate ligament reconstruction: anatomic and radiographic findings. *Am J Sports Med*. 2008;36(1):65-72.
30. Ziegler CG, Pietrini SD, Westerhaus BD, et al. Arthroscopically pertinent landmarks for tunnel positioning in single-bundle and double-bundle anterior cruciate ligament reconstructions. *Am J Sports Med*. 2011;39(4):743-752.