Use of a Fluoroscopic Overlay to Guide Femoral Tunnel Placement During Posterior Cruciate Ligament Reconstruction

Paulo H. Araujo, Gele Moloney, Gustavo Rincon, Robert Carey, Xudong Zhang and Christopher Harner

Am J Sports Med 2014 42: 2673 originally published online September 15, 2014

DOI: 10.1177/0363546514549007

Use of a Fluoroscopic Overlay to Guide Femoral Tunnel Placement During Posterior Cruciate Ligament Reconstruction

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

Background: Intraoperative recognition of the local anatomy of the posterior cruciate ligament (PCL) is difficult for many surgeons, and correct positioning of the graft can be challenging.

Purpose: To investigate the efficacy of an overlay system based on fluoroscopic landmarks in guiding femoral tunnel placement during PCL reconstruction.

Study Design: Controlled laboratory study.

Methods: Twenty cadaveric knees were arthroscopically prepared, and their PCL femoral insertion sites were digitized. The digitized images were co-registered to computed tomography–acquired 3-dimensional bone models. Twenty surgeons with diverse backgrounds performed simulated arthroscopic reconstruction of the anterolateral (AL) and posteromedial (PM) bundles of the PCL, first without and then with the aid of a lateral fluoroscopic image on which the position of a target insertion site based on literature data was displayed as an overlay. The surgeons were allowed to adjust tunnel placement in accordance with the displayed target position. A 3-way comparison was made of the tunnel positions placed by the surgeons, the native insertion site positions, and the literature-based positions.

Results: The overlay system was effective in helping surgeons to improve femoral tunnel placement toward the target and toward the anatomic insertion site ($P < .05$). For femoral AL tunnel placement, surgeons needed 2.35 ± 2.21 extra attempts, which added an extra 80.00 ± 67.95 seconds to the procedure. For PM tunnel placement, surgeons needed 1.80 ± 1.88 extra attempts, adding 66.00 ± 70.82 seconds to the simulated surgery. In their first attempts, more than half of the surgeons positioned either the AL or PM femoral tunnel >5 mm from the native insertion site. With the use of the overlay, 70% of the surgeons were <5 mm away from the PM and 75% from the AL native insertion site.

Conclusion: The use of a fluoroscopic overlay to guide intraoperative placement of the femoral tunnel(s) during PCL reconstruction can result in more anatomic reconstructions and therefore assist in re-creating native knee kinematics after PCL reconstruction.

Clinical Relevance: Intraoperative fluoroscopy is an effective, easy, and safe method for improving femoral tunnel positioning during PCL reconstruction.

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

The posterior cruciate ligament (PCL) is the primary posterior stabilizer of the knee and a secondary restraint to external tibial rotation. It has about twice the maximum strength of the anterior cruciate ligament (ACL).[14,17,42] Injuries to the PCL are relatively infrequent compared with ACL injuries; yet, their incidence is reported to be 1% to 40% of acute knee injuries, and they remain a topic of investigative interest in the field of sports medicine.[23,29] In general, isolated grade I or II PCL injuries cause only minor disabilities[26,37,39] and are usually treated nonoperatively.[12,40] Grade III PCL injuries or PCL injuries combined with other ligament injuries require surgical repair.[10,15] Compared with ACL reconstruction, PCL reconstruction is a relatively uncommon procedure, with even the more experienced surgeons performing fewer than 10 reconstructions per year.[13]

||Address correspondence to Xudong Zhang, PhD, Department of Orthopaedic Surgery, University of Pittsburgh, 3820 South Water Street, Pittsburgh, PA 15230, USA (e-mail: xuz9@pitt.edu).

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

†Department of Biomechanics, Medicine and Rehabilitation of Locomotor System, Ribeirao Preto Medical School, São Paulo University, São Paulo, Brazil.

‡Department of Mechanical Engineering & Materials Science, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.

§Department of Bioengineering, University of Pittsburgh, Pittsburgh, Pennsylvania, USA.

One or more of the authors has declared the following potential conflict of interest or source of funding: This work was funded by research grants from the Smith & Nephew Corporate and The Pittsburgh Foundation.

The American Journal of Sports Medicine, Vol. 42, No. 11
DOI: 10.1177/0363546514549007

Anatomy and biomechanics studies have focused on the 2 functional bundles of the PCL: the anterolateral (AL) and the posteromedial (PM).[1,2,4,16,18,31] These 2 bundles have distinct insertions onto the tibia and femur and exhibit different tension patterns that are important for the mechanical functions that they serve.[18,37] The AL bundle is taut in flexion and is approximately twice the size of the PM bundle, which is taut in extension.[14,33]

Despite advances in knowledge of the knee anatomy and biomechanics as well as surgical techniques, PCL reconstruction remains a complex and technically demanding procedure. One challenging aspect is the intraoperative identification of PCL insertion sites. A PCL rupture is usually a late diagnosis, despite the known mechanisms of injury and symptoms.[36] As a chronic injury, when the PCL injury is surgically approached, soft tissue and bony landmarks are not easily visualized. In addition, because of relative unfamiliarity with the procedure, recognition of the local anatomy is difficult for many surgeons, and correct positioning of the graft can be challenging.

Many methods have been developed to aid in femoral tunnel placement, such as the clock-face reference,[1,11] the femoral chondral border,[2,14,31] the roof of the notch and the medial femoral condyle length,[43] the anterior cortex line of the femoral condyles,[20] and computer navigation.[35] The quadrant method derived from the Bernard et al[6] study for ACL tunnel placement has recently been proposed to aid in PCL tunnel placement by some authors.[27,32] The latest development has been a new image overlay, based on the Bernard et al[6] quadrant method and designed to assist with intraoperative placement of the femoral tunnel during PCL reconstruction. This overlay utilized the locations for AL and PM femoral insertion sites of the PCL as presented by Lorenz et al.[27]

The purpose of the current study was to investigate whether this imaging system based on fluoroscopic landmarks could guide surgeons toward a target location, thus evaluating its efficacy in improving anatomic femoral tunnel placement during PCL reconstruction. Our hypotheses were that femoral PCL tunnel placement would be facilitated by the use of an overlay based on fluoroscopic landmarks and that the overlay would also assist surgeons in performing more anatomic reconstructions.

MATERIALS AND METHODS

Specimen Preparation

This study, involving cadaveric specimens and human participants, was approved by our institution's Committee for Oversight of Research and Clinical Training Involving Decedents (CORID) and institutional review board. Twenty fresh-frozen cadaveric human knees (mean age, 60.6 years; range, 48-67 years) were used in this study. After a 24-hour thawing process, each specimen went through the following sequence of steps:

1. The skin and soft tissue were dissected from the tibia and femur, leaving intact the capsule and all tissues surrounding the knee joint. For image co-registration purposes, 6 spherical fiducial markers (precision nylon spheres; radius, 9.525 mm) were rigidly affixed to the tibia and femur, with 3 on each bone in a noncollinear manner and at least 6 cm away from the joint line. With the fiducial markers attached, high-resolution (slice spacing, 0.625 mm) computed tomography (CT) scans of the knee were taken in our institution's clinical radiology facility.
2. The knee underwent an arthroscopic procedure using a 3-portal technique performed by an experienced surgeon (P.H.A.).[3] The PCL was removed after identification of the AL and PM bundles based on fiber direction and tension during knee flexion and extension, leaving approximately 2 mm of stump to guide digitization of the insertion site (Figure 1). Twenty to 25 points outlining each PCL bundle attachment were digitized and recorded using a surgical navigation system (Polaris Spectra, NDI), which has a vendor-reported accuracy of ±0.3 mm. The fiducial markers were also "painted" using the digitization pointer of the navigation system to facilitate the subsequent co-registration of images. After the digitization process, the 2-mm stump of the PCL was completely removed arthroscopically using thermal ablation. The knee was then stored in a refrigerator ready for testing the next day.
3. A 3-dimensional (3D) bone model was reconstructed for each specimen from its CT scans using Mimics software (Materialise). Insertion morphological data collected by the digitization process were co-registered with corresponding 3D CT-based bone models by a procedure that best matched the fiducial markers measured from the CT and digitization modalities[25] (Figure 2). This procedure was performed to determine the native insertion sites of the AL and PM bundles of the PCL in each knee. The reported fiducial registration error of the procedure was 2%.

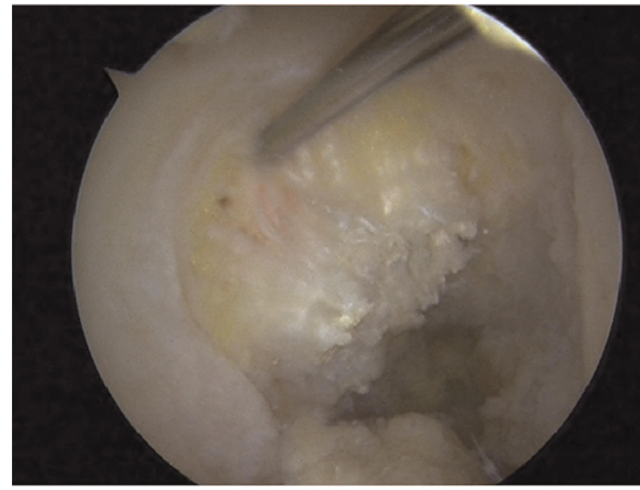

Figure 1. Femoral posterior cruciate ligament insertion site after ligament removal. A 2-mm stump was preserved to aid in the digitization process.

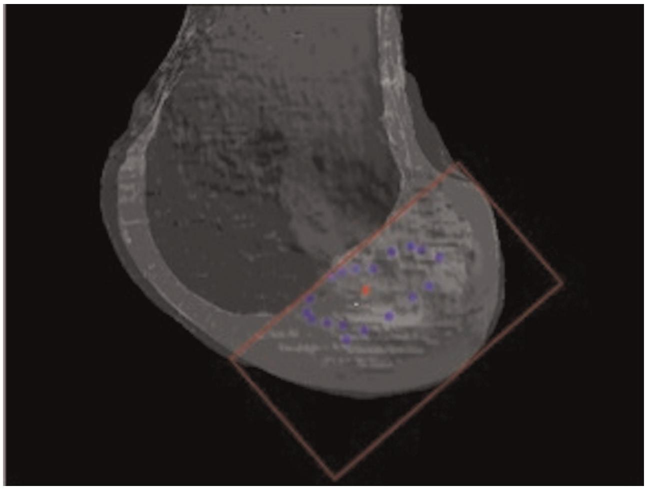

Figure 2. Three-dimensional computed tomography bone model with the digitized femoral posterior cruciate ligament insertion site co-registered.

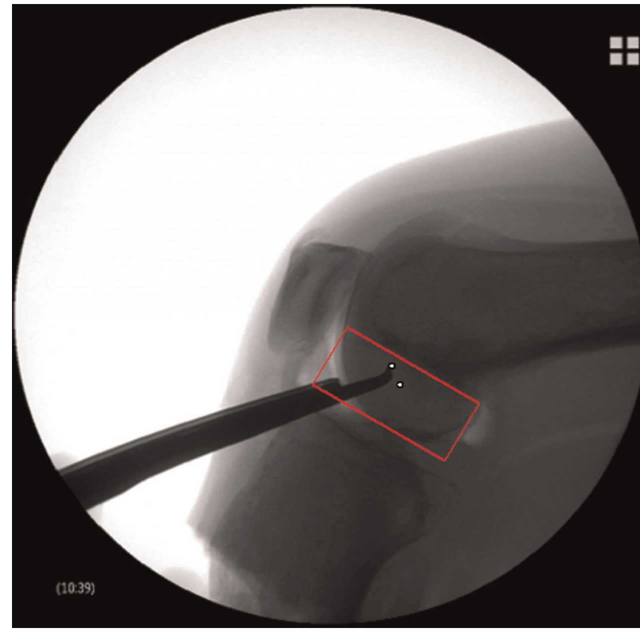

Figure 3. The overlay system placed on the fluoroscopic image.

Arthroscopic and Simulated Femoral PCL Tunnel Placement

A total of 20 orthopaedic surgeons were invited to each perform simulated arthroscopic surgery on a randomly selected prepared knee specimen. The group of surgeons was composed of 1 sports fellowship–trained orthopaedic surgeon, 10 orthopaedic sports surgeons participating in a visiting fellowship program at our institution, 3 sports medicine fellows, and 6 chief residents. The femur was positioned in a fixation device, reproducing the operating position in 90° of flexion. The tibia could be freely moved. Before the start of the simulated surgery, an initial lateral fluoroscopic image of the knee, aligned to maximize the overlap of the posterior femoral condyles, was obtained.

Using arthroscopic visualization, each surgeon was asked to touch, with a pointed awl, the femoral locations for the AL and PM tunnels for PCL reconstruction. The order in which these tunnels were identified was randomized across the surgeons. A lateral fluoroscopic image of the knee was taken after the surgeon was satisfied with the chosen arthroscopic position, with the surgeon's tunnel position indicated by the tip of the awl.

An overlay provided by a software program (Smith & Nephew) designed to show the "ideal" or target femoral tunnel positions for PCL reconstruction was then placed on the fluoroscopic image (Figure 3). The target tunnel positions for the AL and PM bundles were determined from existing literature data[27] and expressed as coordinates (in percentages) in a specimen-specific coordinate system. As a modification of the quadrant method described by Bernard et al[6] for ACL reconstruction, the coordinates were defined by the most anterior and posterior edges of the Blumensaat line and a perpendicular line extending to the distal edge of the femoral condyles. A specimen-specific frame was created by this software according to the bony landmarks selected by an experimenter. With both the selected point and target point in view, the surgeon decided whether to make an adjustment or keep the achieved position. The process was repeated as many times as needed until the surgeon felt the position was close enough to the given target point.

Imaging Analysis

The distance between the target point and the surgeon's chosen position, indicated respectively by the target point displayed by the overlay and the tip of the awl, was calculated from calibrated fluoroscopic images for each attempt. This was used as a measure of error in tunnel placement. The efficacy of the imaging system in guiding a surgeon to the target point was documented by registering the number of attempts and time to reach the final satisfactory position. The measurements were taken for femoral tunnel placement for both the AL and PM bundles.

The distance between the surgeon's position and the center of the native femoral insertion site was measured to evaluate whether the imaging system was leading surgeons to an improved anatomic tunnel position. The differences between a surgeon's chosen point and the overlay target and to the center of the native insertion site were categorized as <2.5 mm, 2.5 to 5 mm, and >5 mm. Five millimeters approximates the radius of a typical 10-mm drill used for PCL reconstruction.

Statistical Analysis

The mean ± SD of the distance from the surgeon's chosen position to the target position, as well as from the surgeon's position to the native insertion site position, were calculated. A Student *t* test was used to determine whether

TABLE 1
Extra Attempts and Time Added to Each PCL Femoral Tunnel Position[a]

	AL Bundle	PM Bundle
No. of extra attempts, mean ± SD	2.35 ± 2.21	1.80 ± 1.88
Median	1.5	2
Range	0-8	0-8
Extra time, s	80.00 ± 67.95	66.00 ± 70.82

[a]AL, anterolateral; PCL, posterior cruciate ligament; PM, posteromedial.

there was a significant difference between the positions after the first and last attempts across the 20 surgeons. The mean time to achieve a satisfactory tunnel position and the mean number of attempts were also calculated.

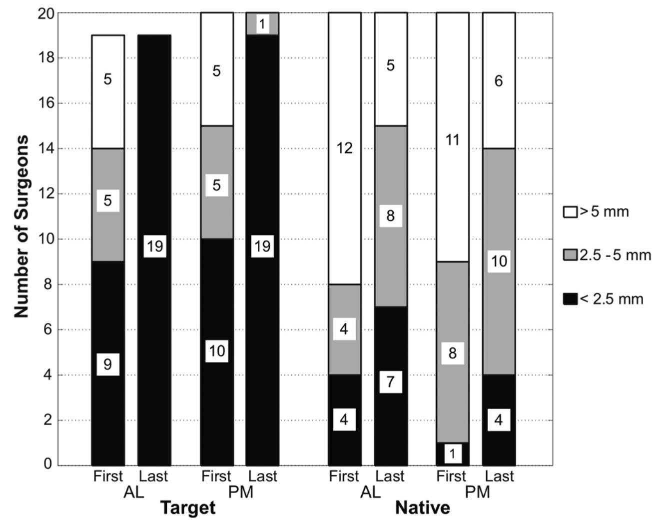

Figure 4. Number of surgeons who positioned the femoral tunnel >5 mm, 2.5 to 5 mm, and <2.5 mm from the overlay target or the native insertion site in their first and last attempts in simulated posterior cruciate ligament femoral tunnel positioning for the anterolateral (AL) and posteromedial (PM) bundles.

RESULTS

Table 1 and Figure 4 summarize the results from this study.

AL Tunnel Placement

The surgeons' first and last attempts were, on average, 3.64 ± 3.11 mm and 1.11 ± 0.71 mm, respectively, from the overlay target of the AL bundle ($P < .01$). The first and last attempts to place the femoral AL tunnel were a respective 5.67 ± 3.77 mm and 3.94 ± 2.23 mm from the native insertion site in the group of 20 surgeons ($P < .05$).

PM Tunnel Placement

The surgeons' first and last attempts were, on average, 3.19 ± 2.00 mm and 1.18 ± 0.62 mm, respectively, from the overlay point ($P < .01$). The first and last attempts to place the femoral PM tunnel were 6.05 ± 3.50 mm and 3.98 ± 1.91 mm, respectively, from the femoral native insertion site and were statistically different ($P = .01$).

For AL bundle reconstruction, the surgeons' placements were overall more anterior with respect to the native insertion; for PM bundle reconstruction, the placements were largely anterior and proximal during the first attempt but exhibited no obvious pattern nor bias in the last trial with respect to the insertion.

DISCUSSION

The results of this study demonstrate that the fluoroscopic overlay system could effectively guide surgeons toward a target point in placing a femoral PCL tunnel for anatomic reconstruction. To our knowledge, this was the first study that quantitatively evaluated the effectiveness of a fluoroscopic overlay system in guiding femoral PCL tunnel placement.

The clinical significance of this study lies in the fact that while surgeons are becoming increasingly aware of the importance of anatomic placement of the femoral tunnel during PCL reconstruction, they also need assistance in achieving such a placement in a relatively infrequent procedure. McGuire and Hendricks[28] reported superior clinical outcomes after 2-year follow-up comparing anatomic to nonanatomic double-bundle PCL reconstruction. Incorrect placement may lead to graft impingement, increased laxity, loss of motion, and functional deficits.[35] Around 85% of surgeons perform fewer than 10 ACL reconstructions per year,[13] which projects an even lower number for PCL reconstructions by surgeon per year. These numbers may explain the results shown in the current study in which more than half of the surgeons initially placed the PCL femoral tunnel more than 5 mm away from the anatomic insertion site. Therefore, reliable tools to aid surgeons in placing the femoral tunnel(s) to achieve anatomic positions are helpful.

Rosenberger et al[35] presented a 2-dimensional (2D) fluoroscopic navigation system for PCL reconstruction with an accuracy of 1.3 mm in femoral tunnel placement to aid in anatomic tunnel positioning. This method requires fluoroscopic images from 2 perpendicular views (anteroposterior and lateral) that are computer processed for later use by the navigation system. Therefore, in the best-case scenario, 2 fluoroscopic images are required to set the 2D navigation system, limiting the risk of radiation exposure. The fluoroscopic overlay system utilized in the current study, on the other hand, allows for accuracy of 1.11 ± 0.71 mm toward the target point for AL and 1.18 ± 0.62 mm for PM femoral tunnel placement. The radiation exposure using the overlay system is limited to less than 4 additional images for double tunnel positioning (2.35 ± 2.21 for the AL bundle and 1.80 ± 1.88 for the PM bundle). These extra attempts add 2 minutes and 26 seconds, on average, to the regular surgery for double tunnel placement (80.00 ± 67.95 seconds for AL bundle and 66.00 ± 70.82 seconds for PM bundle), which seems to be an insignificant increase in surgical time. The additional time, however, does not include the C-arm setup and draping, which certainly would not increase the surgical time up to significant levels that would preclude its use in the operating room. There is no report on additional time for the 2D navigation system to establish a comparison. The overlay system introduces other benefits compared with the Rosenberger et al[35] method: first, the infrastructure necessary for the overlay system is simpler, as only a C-arm and a user-friendly software program are needed to generate the overlay targets; second, it is more cost effective than a computer navigation system.

Johannsen et al[20] recently published a cadaveric study presenting radiographic landmarks to identify PCL bundle attachments. They concluded that a lateral view of the knee is the most appropriate view to guide femoral and tibial tunnel placement. Our study is in agreement regarding the most appropriate radiographic view to project the overlay system, but because Johannsen et al[20] did not evaluate the effectiveness of their method, a comparison in that regard is not feasible.

Lorenz et al[27] and Osti et al[32] also used cadaveric models to determine the anatomic position for the femoral PCL attachment. Both studies utilized a system derived from the Bernard et al[6] quadrant method, but the intraoperative effectiveness of their measurements was not evaluated.

Our study utilized an overlay system based on the measurement findings of Lorenz et al[27] and supported the efficacy of the overlay system in guiding surgeons toward a target location for arthroscopic PCL tunnel placement. For both AL and PM tunnel placement, the overlay system helped surgeons to position the femoral tunnel(s) closer to the software-displayed point ($P < .05$). The fluoroscopic overlay system, based on the quadrant method,[6] utilizes the Blumensaat line and a perpendicular line to the distal edge of the femoral condyles to create a frame where the different sides constitute the x- and y-axes. The target position is given by the confluence of certain percentage points within these axes. It is known that these percentages reflect the average population characteristics but may not always represent a specific knee's anatomy. Therefore, the overlay system was tested in this study for its capability of guiding surgeons toward a target point corresponding to an improvement in anatomic positioning for individual knees. In the tested scenarios, the overlay system was shown to help surgeons to place femoral tunnel(s) closer to the anatomic position ($P < .05$) when compared with the first attempt before fluoroscopy.

The ideal treatment for PCL injuries remains controversial. Nonoperative treatment for grade I and II PCL injuries has been historically advocated with good outcomes.[12,40] However, many other studies on the long-term outcome for PCL insufficiency point to the development of knee osteoarthritis of the medial and patellofemoral compartments and an overall decline in knee function.[8,10,21] Moreover, PCL reconstruction has been performed by either a single- or double-bundle technique. The single-bundle approach is the most performed technique of PCL reconstruction and aims to reconstruct the AL bundle of the PCL, which is the larger of the 2 bundles.[44] Despite good kinematics compared with the intact PCL from 0° to 60° of knee flexion, isolated AL reconstruction did not control knee laxity from 90° to 130° of knee flexion. On the other hand, according to the same study, only double-bundle reconstruction could restore normal knee laxity across the full range of motion.[34] Harner et al[16] showed in a cadaveric study that double-bundle PCL reconstruction could more closely reproduce the biomechanics of the intact knee compared with single-bundle reconstruction. However, another study on the same topic showed no differences in posterior-anterior translation comparing inlay single- and double-bundle PCL reconstructions.[5] Clinically, the same controversy exists, with some authors showing good outcomes for the single-bundle approach,[7,22,24,38] while others demonstrate good results for double-bundle reconstruction.[9,41] The current study showed that surgeons could be guided toward a target point provided by an overlay system. Moreover, the overlay system helped surgeons to place the femoral tunnels closer to the anatomic insertion site for double-bundle reconstruction. This study did not focus on single-bundle femoral tunnel placement. However, considering that the AL insertion site is chosen by most of the authors for single-bundle placement,[44] the results obtained for AL femoral tunnel placement in this study also confirm that the overlay system can help surgeons in single-bundle PCL reconstruction.

A recent study by Moloney et al[30] showed the results of the same overlay system applied to ACL reconstruction. In that study, the authors demonstrated that the overlay system could be used as an effective adjunct to arthroscopic visualization, allowing for more consistent tunnel placement during anatomic ACL reconstruction. For both the ACL and PCL, anatomic reconstruction has been shown to provide better outcomes compared with nonanatomic surgeries.[19,28] The results of these studies corroborate the efficacy of the overlay system in aiding PCL and ACL anatomic reconstructions.

A few limitations of this study are acknowledged. First, the 20 participating surgeons were from our own institution and overall were well versed in the anatomic reconstruction concept and technique. This may be a biased group not representative of orthopaedic surgeons at large. We, however, did pay attention to recruiting participants with diverse backgrounds and levels of surgical experience. Second, the quadrant method, on which the overlay target is based, requires a true lateral fluoroscopic incidence. In this laboratory study, ample time was allowed to ensure optimal lateral positioning for fluoroscopy, which may not be practical in a real intraoperative setting. In the operating room, many times, a mini C-arm is available, which is much easier to manipulate with lower radiation exposure as compared with regular fluoroscopy. Therefore, in a real-world setting with a mini C-arm, it is possible to obtain satisfactory lateral images within a manageable number of attempts and radiation safety limit. Third, the PCL, ACL, and synovial tissues were removed in this study from the intercondylar notch as the same knees were used to test a similar overlay system designed for ACL reconstruction, resulting in an empty notch with an unobstructed view of the lateral wall of the medial condyle. This could have benefited the surgeons in correctly placing the PCL tunnels. In other words, without this improved visibility of the notch, the overlay system might have demonstrated an even more salient positive effect on femoral tunnel anatomic placement.

In conclusion, a fluoroscopic overlay system based on PCL insertion morphological data could help surgeons improve femoral tunnel placement. The overlay assistance adds a modest manageable amount of time to the operation and a low, safe amount of radiation exposure but can result in a more anatomic placement for the femoral PCL tunnel(s).

REFERENCES

1. Amis AA, Gupte CM, Bull AMJ, Edwards A. Anatomy of the posterior cruciate ligament and the meniscofemoral ligaments. *Knee Surg Sports Traumatol Arthrosc*. 2006;14(3):257-263.
2. Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94(21):1936-1945.
3. Araujo PH, van Eck CF, Macalena JA, Fu FH. Advances in the three-portal technique for anatomical single- or double-bundle ACL reconstruction. *Knee Surg Sports Traumatol Arthrosc*. 2011;19(8):1239-1242.
4. Baek GH, Carlin GJ, Vogrin TM, Woo SL, Harner CD. Quantitative analysis of collagen fibrils of human cruciate and meniscofemoral ligaments. *Clin Orthop Relat Res*. 1998;357:205-211.
5. Bergfeld JA, Graham SM, Parker RD, Valdevit AD, Kambic HE. A biomechanical comparison of posterior cruciate ligament reconstructions using single- and double-bundle tibial inlay techniques. *Am J Sports Med*. 2005;33(7):976-981.
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. Boutefnouchet T, Bentayeb M, Qadri Q, Ali S. Long-term outcomes following single-bundle transtibial arthroscopic posterior cruciate ligament reconstruction. *Int Orthop*. 2013;37(2):337-343.
8. Boynton MD, Tietjens BR. Long-term followup of the untreated isolated posterior cruciate ligament-deficient knee. *Am J Sports Med*. 1996;24(3):306-310.
9. Chen CP, Lin YM, Chiu YC, et al. Outcomes of arthroscopic double-bundle PCL reconstruction using the LARS artificial ligament. *Orthopedics*. 2012;35(6):e800-e806.
10. Clancy WG Jr, Shelbourne KD, Zoellner GB, Keene JS, Reider B, Rosenberg TD. Treatment of knee joint instability secondary to rupture of the posterior cruciate ligament: report of a new procedure. *J Bone Joint Surg Am*. 1983;65(3):310-322.
11. Edwards A, Bull AM, Amis AA. The attachments of the fiber bundles of the posterior cruciate ligament: an anatomic study. *Arthroscopy*. 2007;23(3):284-290.
12. Fowler PJ, Messieh SS. Isolated posterior cruciate ligament injuries in athletes. *Am J Sports Med*. 1987;15(6):553-557.
13. Garrett WE, 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.
14. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint: anatomical, functional and experimental analysis. *Clin Orthop Relat Res*. 1975;106:216-231.
15. Harner CD, Höher J. Evaluation and treatment of posterior cruciate ligament injuries. *Am J Sports Med*. 1998;26(3):471-482.
16. Harner CD, Janaushek MA, Kanamori A, Yagi M, Vogrin TM, Woo SL. Biomechanical analysis of a double-bundle posterior cruciate ligament reconstruction. *Am J Sports Med*. 2000;28(2):144-151.
17. Harner CD, Livesay GA, Kashiwaguchi S, Fujie H, Choi NY, Woo SL. Comparative study of the size and shape of human anterior and posterior cruciate ligaments. *J Orthop Res*. 1995;13(3):429-434.
18. Harner CD, Xerogeanes JW, Livesay GA, et al. The human posterior cruciate ligament complex: an interdisciplinary study. Ligament morphology and biomechanical evaluation. *Am J Sports Med*. 1995;23(6):736-745.
19. Hussein M, van Eck CF, Cretnik A, Dinevski D, Fu FH. Prospective randomized clinical evaluation of conventional single-bundle, anatomic single-bundle, and anatomic double-bundle anterior cruciate ligament reconstruction: 281 cases with 3- to 5-year follow-up. *Am J Sports Med*. 2012;40(3):512-520.
20. Johannsen AM, Anderson CJ, Wijdicks CA, Engebretsen L, LaPrade RF. Radiographic landmarks for tunnel positioning in posterior cruciate ligament reconstructions. *Am J Sports Med*. 2013;41(1):35-42.
21. Keller PM, Shelbourne KD, McCarroll JR, Rettig AC. Nonoperatively treated isolated posterior cruciate ligament injuries. *Am J Sports Med*. 1993;21(1):132-136.
22. Kim SJ, Jung M, Moon HK, Kim SG, Chun YM. Anterolateral transtibial posterior cruciate ligament reconstruction combined with anatomical reconstruction of posterolateral corner insufficiency: comparison of single-bundle versus double-bundle posterior cruciate ligament reconstruction over a 2- to 6-year follow-up. *Am J Sports Med*. 2011;39(3):481-489.
23. Kim YM, Lee CA, Matava MJ. Clinical results of arthroscopic single-bundle transtibial posterior cruciate ligament reconstruction. *Am J Sports Med*. 2011;39(2):425-434.
24. Lahner M, Vogel T, Schulz MS, Strobel MJ. Outcome 4 years after isolated single-bundle posterior cruciate ligament reconstruction. *Orthopäde*. 2012;41(3):206-211.
25. 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.
26. Lipscomb AB, Anderson AF, Norwig ED, Hovis WD, Brown DL. Isolated posterior cruciate ligament reconstruction: long-term results. *Am J Sports Med*. 1993;21(4):490-496.
27. 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.
28. McGuire DA, Hendricks SD. Comparison of anatomic versus nonanatomic placement of femoral tunnels in Achilles double-bundle posterior cruciate ligament reconstruction. *Arthroscopy*. 2010;26(5):658-666.
29. Miyasaka K, Daniel D, Stone M, et al. The incidence of knee ligament injuries in general population. *Am J Knee Surg*. 1991;4(1):3-7.
30. Moloney G, Araujo P, Rabuck S, et al. Use of a fluoroscopic overlay to assist arthroscopic anterior cruciate ligament reconstruction. *Am J Sports Med*. 2013;41(8):1794-1800.
31. Morgan CD, Kalman VR, Grawl DM. The anatomic origin of the posterior cruciate ligament: where is it? Reference landmarks for PCL reconstruction. *Arthroscopy*. 1997;13(3):325-331.
32. Osti M, Tschann P, Kunzel KH, Benedetto KP. Anatomic characteristics and radiographic references of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *Am J Sports Med*. 2012;40(7):1558-1563.
33. Race A, Amis AA. Loading of the two bundles of the posterior cruciate ligament: an analysis of bundle function in AP drawer. *J Biomech*. 1996;29(7):873-879.

34. Race A, Amis AA. PCL reconstruction: in vitro biomechanical comparison of 'isometric' versus single and double-bundled ''anatomic'' grafts. *J Bone Joint Surg Br*. 1998;80(1):173-179.
35. Rosenberger RE, Bale RJ, Kneisl C, Krappinger D, Knoflach M, Attal R. Two-dimensional fluoroscopic navigation in posterior cruciate ligament reconstruction: a preclinical cadaver study. *Arch Orthop Trauma Surg*. 2010;130(8):971-976.
36. Schulz MS, Russe K, Weiler A, Eichhorn HJ, Strobel MJ. Epidemiology of posterior cruciate ligament injuries. *Arch Orthop Trauma Surg*. 2003;123(4):186-191.
37. Sekiya JK, Haemmerle MJ, Stabile KJ, Vogrin TM, Harner CD. Biomechanical analysis of a combined double-bundle posterior cruciate ligament and posterolateral corner reconstruction. *Am J Sports Med*. 2005;33(3):360-369.
38. Sekiya JK, West RV, Ong BC, Irrgang JJ, Fu FH, Harner CD. Clinical outcomes after isolated arthroscopic single-bundle posterior cruciate ligament reconstruction. *Arthroscopy*. 2005;21(9):1042-1050.
39. Shelbourne KD, Clark M, Gray T. Minimum 10-year follow-up of patients after an acute, isolated posterior cruciate ligament injury treated nonoperatively. *Am J Sports Med*. 2013;41(7):1526-1533.
40. Shelbourne KD, Davis TJ, Patel DV. The natural history of acute, isolated, nonoperatively treated posterior cruciate ligament injuries: a prospective study. *Am J Sports Med*. 1999;27(3):276-283.
41. Spiridonov SI, Slinkard NJ, LaPrade RF. Isolated and combined grade-III posterior cruciate ligament tears treated with double-bundle reconstruction with use of endoscopically placed femoral tunnels and grafts: operative technique and clinical outcomes. *J Bone Joint Surg Am*. 2011;93(19):1773-1780.
42. Trent PS, Walker PS, Wolf B. Ligament length patterns, strength, and rotational axes of the knee joint. *Clin Orthop Relat Res*. 1976;117:263-270.
43. Westermann RW, Sybrowsky C, Ramme AJ, Amendola A, Wolf BR. Three-dimensional characterization of the femoral footprint of the posterior cruciate ligament. *Arthroscopy*. 2013;29(11):1811-1816.
44. Wijdicks CA, Kennedy NI, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. *Am J Sports Med*. 2013;41(12):2839-2848.