Comparison of Posterolateral Corner Reconstructions Using Computer-Assisted Navigation

Brian T. Feeley, M.D., Mark S. Muller, M.D., Seth Sherman, M.D., Answorth A. Allen, M.D., and Andrew D. Pearle, M.D.

Purpose: This study evaluated different fibular-based reconstruction techniques for grade III posterolateral corner (PLC) injuries. Methods: Seven fresh-frozen cadaveric knees were used in this study. A surgical navigation system was used to determine varus opening and external rotation at 0°, 30°, and 60° with a 9.8-Nm varus stress and 5-Nm external rotation stress applied to the tibia. Intact and disrupted PLC knees were used as controls. Four different fibular-based reconstruction techniques were evaluated. The femoral attachments consisted of a single- or double-tunnel technique, and the fibula attachment consisted of an anteroposterior or oblique tunnel technique. Results: Sectioning of the PLC resulted in an increase in varus and external rotation at all flexion angles. All reconstruction techniques restored varus and external rotation stability compared with the PLC-deficient state, but the single–femoral tunnel reconstruction with an anteroposterior fibular tunnel did not restore varus or external rotation stability at 30° and 60°. No reconstruction technique overconstrained the knee at any flexion angle. Conclusions: A double femoral tunnel with an oblique fibular tunnel best restored native knee kinematics to the lateral side of the knee. Clinical Relevance: Although there are many different techniques to reconstruct the PLC-deficient knee, this study suggests that a single-graft, fibular-based reconstruction that replicates the femoral insertions of the lateral collateral ligament and popliteus will be able to restore varus and external rotation stability to the knee.

The posterolateral corner (PLC) of the knee is a complex structure that provides both static and dynamic stabilization to resist varus and external rotation forces on the knee. The primary anatomic contributors to the PLC include the fibular (lateral) collateral ligament (LCL), popliteus tendon, and popliteofibular ligament (PFL). The LCL is the primary static restraint to varus opening of the knee. It originates just proximal and posterior to the lateral epicondyle and inserts on the posterior aspect of the femoral head. The popliteus originates from the posteromedial aspect of the tibia and inserts anteriorly and distally compared with the LCL origin on the distal femur, with a mean distance of 18.5 mm between them. The popliteus functions as both a static and dynamic stabilizer to resist varus forces. The PFL arises from the myotendinous junction of the popliteus and runs distally and laterally to insert on the fibular styloid process.

Acute injuries to the PLC are often due to a multiligamentous traumatic knee dislocation. In the acute setting, PLC injuries can be treated with direct repair or repair with augmentation. Chronic injuries to the PLC are better managed with PLC reconstruction techniques rather than direct repair. Because of the complex anatomy and biomechanics of the PLC,
many techniques have been described to restore native knee anatomy and kinematics to the lateral side of the knee. These reconstruction techniques can be broadly classified into nonanatomic reconstructions, anatomic fibular-based reconstructions, and anatomic tibial- and fibular-based reconstructions. Nonanatomic reconstructions include biceps femoris tenodesis, osteotomy, and single-femoral tunnel reconstruction. More recently, there has been an emphasis on restoring native knee anatomy with more anatomic reconstructions. Noyes and Barber-Westin described a technique that uses 2 femoral tunnels to restore the anatomy of the PLC on the distal femur with a transfibular tunnel, and Arciero described a similar fixation of the femur with an oblique femoral tunnel. LaPrade et al. proposed a reconstruction technique that attaches ligaments to both the fibula and tibia to better restore anatomy of the popliteus tendon. There is concern, however, that this technique is more technically demanding and may overconstrain the knee.

Despite the many techniques available to reconstruct the PLC-deficient knee, there have been few biomechanical studies that have evaluated the different fibular-based reconstruction techniques regarding their ability to restore native laxity to the lateral side of the knee. The purpose of this study was to evaluate 4 different fibular-based reconstruction techniques regarding their ability to restore native knee kinematics. We specifically sought to determine whether there was a difference in a single- versus double-tunnel femoral reconstruction and whether there was a difference with an anteroposterior (AP) versus oblique fibular tunnel. We used computer-assisted navigation to assess knee kinematics, because we have previously shown the accuracy of this technique in biomechanical studies. We hypothesized that there would be no difference between PLC reconstruction techniques in their ability to restore native knee kinematics to the lateral side of the knee.

**METHODS**

Seven fresh-frozen cadaveric knees with a mean age of 48.4 years (range, 38 to 62 years) were used for this study. There were 4 male knees and 3 female knees. Pilot data in this model as well as previous studies showed that a total of 7 knees were required to adequately power the study. The tibia and femur were sectioned at the mid part of the shaft and scraped clean of soft tissue to within 15 cm of the joint line. The specimens were stored at −20°C and were thawed overnight before use. They were mounted and secured with a vise attached to the proximal femur, allowing free motion from 0° to 110° of flexion. Knees were excluded if there was ligamentous laxity, significant arthritis, gross malalignment, or evidence of previous surgery.

To acquire the kinematic data, we used the Praxim Surgetics surgical navigation system (PraximMedivision, Grenoble, France). Surgetics ACL Logics Universal Software (PraximMedivision) was used for data acquisition as previously described. The Surgetics ACL Logics software acquires reference points directly on the bone surfaces to determine the articular anatomy of the knee. The reference points included for this study were the center of the femoral notch, the middle of the transverse meniscal ligament on the anterior tibia, and the center of the medial and lateral tibial plateaus. This system has been shown to be very precise, within 1° or 1 mm compared with an industrial robotic sensor. Reflective markers were mounted in the proximal femur and distal tibia. Once the markers were placed, surface landmarks on the tibial plateau and distal femur were recorded, intra-articular surface geometry was mapped, and the 3-dimensional model was created. The knee was manually cycled from 0° to 110° of flexion.

The intact knee was tested at 0°, 30°, and 60° of knee flexion with an applied varus load of 9.8 Nm. The degree of knee flexion was obtained by the surgical navigation system. The load was manually applied with a tensiometer parallel to the joint line 10 cm from the joint. The varus and rotational displacement was recorded by the surgical navigation system in degrees. An axial load was applied, and the knee was placed at neutral rotation on the knee at the start of testing. An external load was also applied by placement of a 5-Nm load with a tensiometer perpendicular to the joint line to externally rotate the knee. Rotational displacement was recorded by the navigation system in degrees. Each testing condition was repeated in duplicate. Once the data from the intact knee were obtained, the lateral side of the knee was exposed to isolate the structures of the PLC. The dissection was taken down through the subcutaneous tissues to the iliotibial (IT) band. The IT band was divided in line with its fibers to expose the attachments of the LCL and popliteus. Care was taken to maintain the distal attachment of the IT band during the dissection. The attachments of the LCL and the popliteus were identified, and these structures were removed from the cadaveric specimens. The origins and insertions of these structures were carefully marked on the cadaveric specimens. Care was taken to preserve the poste-
rior cruciate ligament (PCL) and the posterior capsule. Testing was then repeated in the PLC-deficient state at all 3 flexion angles.

All reconstructions were performed with a semitendinosus tendon tensioned to 30 N, as described by Markolf et al.\textsuperscript{17} in a recent biomechanical study of the PLC. The tendon was harvested from the insertion of the pes, with care being taken to preserve the entire length of the tendon. The mean tendon width was 7.5 mm (range, 6 to 8 mm). There were 4 reconstructions tested to determine differences between the number of femoral tunnels and the obliquity of the fibular tunnels (Table 1). The technique described by Larsen et al.\textsuperscript{13} consists of a single femoral tunnel placed posterior to the lateral epicondyle and an AP fibular tunnel. We termed this reconstruction technique AP-Fi-SF for an AP fibular tunnel (Fi) and a single femoral tunnel (SF). The proximal fibula was exposed, and a guide-wire was placed 2 cm distal to the proximal tip of the fibula and positioned parallel to the joint line. The guide-wire was fired directly posteriorly to exit the fibula parallel to the joint line. The guide-wire was then over-reamed with a 7- or 8-mm reamer. Both ends of the graft were sutured with No. 2 FiberWire (Arthrex, Naples, FL) and pulled through the proximal fibular tunnel. An 8-mm tunnel was placed in the femoral attachment of the LCL, and both graft ends were pulled through the tunnel. The graft was tensioned to 30 N with the knee flexed to 30° as measured by the surgical navigation software and fixed with a bioabsorbable interference screw (Arthrex). The single-femoral tunnel reconstruction was also tested with an oblique fibular tunnel as described by Bicos and Arciero\textsuperscript{24} (Ob-Fi-SF). This reconstruction was performed in a similar fashion on the femoral side, but the fibular tunnel was drilled with a 6-mm drill through an oblique fibular tunnel after the previous AP tunnel had been filled with methylmethacrylate. The oblique tunnel was drilled over a guidewire that was rotated 45° from the AP tunnel, 2 cm distal to the proximal fibula. The angle was measured with a goniometer so that the angle between the 2 tunnels measured 45° on each specimen. As with the AP tunnel, the oblique tunnel was oriented parallel to the joint line. The oblique tunnel ran from anteromedial to posterolateral on the fibula. The double–femoral tunnel reconstructions were performed with both the AP (AP-Fi-DF) and oblique (Ob-Fi-DF) fibular tunnels. The 2 femoral tunnels were placed at the anatomic landmarks that corresponded to the femoral attachments of the LCL and popliteus\textsuperscript{25} and drilled with a 6-mm drill to accept the graft. The graft was tensioned as previously described and fixed with a bioabsorbable interference screw. The reconstructions were performed in the order shown in Table 1. Both AP fibular-based configurations were tested, methylmethacrylate was placed in the AP tunnel, and the oblique tunnel was drilled as described. The methylmethacrylate was allowed to completely dry and harden before any drilling of the oblique tunnel. There was no cortical disruption of the proximal fibula with either drilling or testing of the reconstructions.

Repeated-measures analysis of variance and Student\textit{t} tests were used to compare the reconstruction techniques used in this study. A power analysis was performed based on our previous studies with the assumption of \(\alpha = 0.05\) and \(\beta = 0.80\). An intraclass correlation coefficient (ICC) was used to determine variability within each knee at each testing condition. Significance was set at \(P < .05\). Data are presented as the mean with a 95% confidence interval (CI).

### RESULTS

The computer navigation system showed excellent reproducibility in this study. The ICC with varus opening was 0.91 (\(P = .003\)). With external rotation, the ICC was 0.87 (\(P = .02\)). Within each group of knees, the ICC with varus opening was 0.84 (\(P = .02\)), and with external rotation, the ICC was 0.85 (\(P = .01\)). All knees showed coupled external rotation and varus opening with the varus-directed force.

Application of a 9.8-Nm varus force to the intact knee at 0° resulted in a mean varus opening of 3.5° (95% CI, 2.6° to 4.4°). At 30°, the varus opening increased to 4.8° (95% CI, 4.6° to 5.1°), and at 60°, the varus opening increased to 4.0° (95% CI, 3.3° to 4.7°). Application of a 9.8-Nm external rotation force to the intact knee resulted in external rotation of 12.0° (95% CI, 10.7° to 13.3°) at 0°, 13.3° (95% CI, 11.7° to 15.0°) at 30°, and 12.5° (95% CI, 11.1° to 13.9°) at 60°.

Sectioning of the PLC structures led to a significant increase in varus displacement at all flexion angles with a varus applied force. At 0°, varus opening in the

### Table 1. Testing Conditions

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<th>Condition</th>
<th>Fibular Tunnel</th>
<th>Femoral Tunnel</th>
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<tr>
<td>AP-Fi-SF</td>
<td>AP</td>
<td>Single</td>
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<tr>
<td>AP-Fi-DF</td>
<td>AP</td>
<td>Double</td>
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PLC-deficient state increased to 7.5° (95% CI, 6.0° to 9.0°) ($P < .001$ v PLC intact) (Fig 1). At 30°, varus opening increased to 10.7° (95% CI, 9.0° to 12.4°) ($P < .01$ v PLC intact). At 60°, varus opening increased to 7.7° (95% CI, 5.4° to 9.9°) ($P < .05$ v PLC intact) (Fig 1). Similar results were seen with an external rotation force, with significantly increased external rotation at all flexion angles compared with the PLC-intact knee ($P < .01$ at 0°, 30°, and 60°) (Fig 2).

All reconstructions were able to significantly decrease varus and external rotation laxity compared with the PLC-deficient state. Reconstruction with the AP fibular tunnel and single femoral tunnel (AP-Fi-SF) was able to restore native knee laxity at 0° with a varus applied force (Table 2 and Fig 1). At 30° and 60°, however, the AP-Fi-SF reconstruction was unable to restore varus laxity back to the native knee state. When an external rotation force was applied, the AP-Fi-SF reconstruction resulted in significantly decreased external rotation compared with the PLC-deficient state at all flexion angles (Table 3 and Fig 2). However, this reconstruction was unable to restore external rotation laxity compared with the intact knee at any flexion angle.

Reconstruction with the AP fibular tunnel and a double femoral tunnel (AP-Fi-DF) also was able to restore native knee laxity at 0° with a varus applied force (Table 2 and Fig 1). Unlike the single–femoral tunnel reconstruction, at 30° and 60°, this reconstruction was able to restore varus laxity to the knee. With an external rotation force, the AP-Fi-DF reconstruction significantly reduced external rotation compared with the PLC-deficient state. It was unable to restore native knee laxity with regard to external rotation at 0° and 30° (Table 3 and Fig 2). It was able to restore native knee external rotation laxity at 60°. In addition, use of the double femoral tunnel did decrease external rotation significantly at 30° and 60° compared with the single–femoral tunnel configuration (AP-Fi-SF).

The oblique fibular reconstruction with a single femoral tunnel (Ob-Fi-SF) was able to restore varus laxity at all flexion angles to the intact knee state. With external rotation, the Ob-Fi-SF reconstruction...
was able to restore the knee to its native state at 0° and 30°. At 60°, however, the Ob-Fi-SF reconstruction had significantly greater external rotation compared with the intact knee ($P < .05$) (Table 3 and Fig 2).

The oblique fibular reconstruction with a double femoral tunnel (Ob-Fi-DF) resulted in the best overall reconstruction in terms of its ability to restore varus and external rotation laxity. At all flexion angles, there was no significant difference between the Ob-Fi-DF reconstruction and the intact PLC state with regard to varus or external rotation. In addition, the Ob-Fi-DF reconstruction resulted in significantly less external rotation when an external rotation load was applied compared with the AP-Fi reconstructions. Finally, at 60° and with an external rotation force, the Ob-Fi-DF reconstruction resulted in significantly less external rotation compared with the Ob-Fi-SF reconstruction (Table 3 and Fig 3).

**DISCUSSION**

The aim of this study was to determine the optimal fibular-based reconstruction techniques for the PLC-injured knee. The study investigated 4 different reconstruction techniques to test the influence of a single– versus double–femoral tunnel reconstruction and the influence of the orientation of the fibular tunnel. Although all the reconstructions performed better than the PLC-deficient state, the oblique reconstructions were better able to restore native knee laxity when an external rotation force was applied to the knee. From this study, we conclude that a double–femoral tunnel configuration that restores the anatomy to the femoral attachments of the PLC, with an oblique fibular tunnel, is the best reconstruction technique to restore knee laxity to the PLC-deficient knee.

The contributions of each structure on the lateral side of the knee have been well described previously in the literature. Nielsen and Helmig showed that the LCL and popliteus can resist varus and external rotation forces, with the LCL having a greater role against varus and the popliteus tendon having a greater role against external rotation. Similarly, Gollehon et al. found that selective sectioning of the posterolateral structures did not increase posterior translation but complete transection increased posterior translation considerably. Our study found that disruption of the PLC resulted in an increase in varus rotation at all flexion angles, with a peak varus rotation at 30°. This finding was comparable to that of Gollehon et al., who found that combined sectioning of the PLC resulted in a peak varus rotation at 30°. Our study found that an external rotation torque of 5 Nm resulted in increased external rotation at all flexion angles, which has been found in previous sectioning studies as well.

Many reconstruction techniques have been described for the treatment of chronic posterolateral knee instability. Many early techniques are

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<td>0°</td>
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Data are presented as mean (95% CI). All reconstructions resulted in significant decreases in varus compared with the PLC-intact state. *$P < .05$ compared with PLC-intact state.

<table>
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Data are presented as mean (95% CI). All reconstructions resulted in significant decreases in external rotation compared with the PLC-deficient state. *$P < .05$ compared with PLC-intact state. †$P < .05$ v AP fibular reconstructions. ‡$P < .05$ v AP-Fi-SF. §$P < .05$ v Ob-Fi-SF.
nonanatomic and involve an osteotomy and tightening of the lax PLC ligament complex or tenodesis of the biceps femoris. As our understanding of the biomechanics of knee reconstruction has evolved, we have become increasingly aware that anatomic reconstructions of the knee better restore knee kinematics and improve patient function. This has been shown consistently with both anterior cruciate ligament and PCL reconstruction techniques. Recent efforts to restore rotatory stability to the PLC after a grade III injury have focused on restoring the anatomy to this side of the knee. However, there are few in vitro biomechanical studies that have evaluated different anatomic reconstruction techniques. LaPrade et al. proposed a 2-graft technique that reconstructs the popliteus, PFL, and LCL by reconstructing the path of the popliteus with one graft and the LCL with another graft. In a biomechanical study this reconstruction was able to restore varus stability and eliminate the external rotation laxity produced by a grade III PLC injury. This reconstruction is based on a popliteal graft that is fixed to the tibia, not the fibula as described in this study. However, Markolf et al. recently found that a tibial-based reconstruction configuration with the grafts tensioned to 30 N at 30° resulted in overconstraint of varus rotation of the knee when compared with an intact LCL. On the basis of these results, we chose to focus on single-graft reconstructions that did not require fixation to the tibia.

The primary finding of this study was that all reconstruction techniques were able to decrease varus and external rotation instability compared with the PLC-deficient knee. However, the combination of the double femoral tunnel and oblique fibular tunnel performed better in terms of restoring varus stability and external rotation stability. The single-femoral tunnel reconstruction is based on the original description of Larsen et al. This reconstruction aims to restore the function of both the LCL and the PFL but does not restore the popliteus tendon anatomy. In addition, the original description of Larsen et al. places the femoral tunnel at the lateral epicondyle. We chose to place the single femoral tunnel at the origin of the LCL because this was shown to be more isometric in a recent study. In our study the single femoral tunnel with the AP fibular tunnel did not restore varus laxity to the PLC-intact state at 30° and 60° and did not restore external rotation laxity at 30° and 60°. Contrary to our results, a recent study by Apsingi et al. found that the single-femoral tunnel technique was able to restore varus and external rotation. In this study the limbs of the graft were tensioned differently, with the anterior limb tensioned at 20° of knee flexion and the posterior limb tensioned at 90°. In addition, a smaller varus force was applied during their testing compared with our testing conditions (5 Nm vs. 9.8 Nm). The small but significant increase in laxity seen in our study with the single-tunnel techniques could be eliminated by a different tensioning technique before testing, and further testing may be warranted to determine whether this alternative tensioning technique restores laxity to varus stress at the higher forces used in our study.

The double-femoral tunnel reconstruction technique is based on the goal of a fibular-based, single-graft reconstruction that replicates the LCL and popliteus anatomy as it relates to the distal femur. This technique had previously been tested in a biomechanical setting by Nau et al., who found that the technique in conjunction with an AP fibular tunnel was able to restore varus and external rotation laxity at 30° and 90°. Our study found similar results. The double-femoral tunnel reconstructions were able to restore the PLC varus stability to the intact state at all flexion angles, whereas the single femoral tunnel did not restore external rotation laxity at 30° and 60° with an AP fibular tunnel. Interestingly, when this reconstruction technique was augmented with a tibial graft as well in a recent study, there was abnormal internal tibial rotation with dynamic testing. Markolf et al. found that a tibial graft to replicate the anatomy of the popliteus overconstrained varus rotation. These data suggest that the double-femoral tunnel configuration with a fibular tunnel may be the most appropriate technique to provide an anatomic reconstruction of the PLC-deficient knee without overconstraining the knee.

The use of an oblique fibular tunnel to better control
rotational stability has been suggested by Bicos and Arciero. To our knowledge, however, this technique has not been evaluated in a biomechanical study. In our study there was no statistical difference between the AP and oblique fibular tunnels in controlling varus force at any flexion angle. However, the oblique fibular tunnel did control external rotation better at 30° and 60° compared with the AP fibular tunnel. Thus the oblique tunnel may help improve rotational stability after PLC reconstruction with a fibular-based technique. The creation of an oblique tunnel is not more difficult than an AP tunnel and is technically easier to perform than a tibial tunnel with harvesting and placement of 2 grafts. This technique in combination with the double femoral tunnel may be the best method to perform a single-graft, fibular-based anatomic reconstruction of the PLC.

The use of computer-assisted navigation in the field of biomechanics allows for precise measurements of rotational and translational changes to specimens. In our study the computer-assisted navigation was highly precise, with ICCs that suggested reproducibility both within each knee and across each testing group. Previous studies in our laboratory as well as others have validated the use of computer-assisted navigation in the study of knee kinematics. We have previously used a similar model to evaluate reconstruction techniques on the medial side of the knee and found the computer navigation system to be reliable and precise in determining rotational stability of the knee. Pearle et al. compared the Surgetics image-free navigation system with a traditional robotic testing system. The ICC for all tests was greater than 0.99 (P < .001), suggesting that surgical navigation is a precise tool to quantify knee stability examination. Computer-assisted navigation is an appealing alternative to traditional biomechanical testing. This study suggests that computer navigation is quite accurate and can provide a real-time multiplanar arthrometer as well as kinematic data to the surgeon. However, future studies that use either fluoroscopic analysis and/or a robotic sensor to confirm external validity of the testing apparatus would be quite beneficial.

There are several weaknesses to this study. We chose to test reconstruction techniques that compare the use of 1 or 2 tunnels in the femur and the orientation of the fibular tunnel. However, there are other reconstruction techniques, including ones that attempt to restore anatomy to the PLC by attaching a graft to the proximal lateral tibia. LaPrade et al. showed that this reconstruction technique restored static stability as measured by joint translation in response to varus loading and external rotation torque. However, this technique is technically demanding, requires the use of 2 separate grafts, and may overconstrain the knee. For these reasons, we chose to focus on single-graft reconstruction techniques. The next step in our evaluation may be to compare this technique with the Ob-Fi-DF reconstruction to determine what differences there are, if any, between these reconstruction techniques in our model. A second weakness is that no cyclic loading study was performed in this set of experiments. With the different isometries of the double femoral fixation points, a cyclic loading study to determine changes in graft strength and length over time would be beneficial in deciding which graft is clinically best to restore PLC function, as would clinical outcomes with each type of graft. Finally, this study focused on reconstruction of the PLC in a PCL-intact state. Because many injuries that involve the PLC also result in a PCL injury, it would be beneficial to perform this set of experiments in PCL-deficient knees and after a PCL reconstruction to determine how these reconstruction techniques affect the kinematics of a multiligament knee injury reconstruction.

**CONCLUSIONS**

A double femoral tunnel with an oblique fibular tunnel best restored native knee kinematics to the lateral side of the knee. Although there are many different techniques to reconstruct the PLC-deficient knee, this study suggests that a single-graft, fibular-based reconstruction that replicates the femoral insertions of the LCL and popliteus will be able to restore varus and external rotation stability to the knee.

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