Kinematics of the Posterior Cruciate Ligament/Posterolateral Corner–Injured Knee After Reconstruction by Single- and Double-Bundle Intra-articular Grafts

William B. Wiley, MD, Michael J. Askew,* PhD, Arne Melby III, MD, and Donald A. Noe
From the Walter A. Hoyt, Jr, Musculoskeletal Research Laboratory, Department of Orthopaedic Surgery, Summa Health System, Akron, Ohio

Background: Single- and double-bundle reconstructions have been proposed for the knee after combined posterior cruciate ligament/posterolateral corner injuries.

Hypothesis: The double-bundle posterior cruciate ligament reconstruction is superior to the single-bundle posterior cruciate ligament reconstruction with regard to restoration of normal knee kinematics to the posterior cruciate ligament/posterolateral corner–sectioned knee.

Study Design: Controlled laboratory study.

Methods: Kinematics of 8 fresh-frozen, cadaveric human knees were determined in the following conditions: intact, sectioned posterior cruciate ligament/posterolateral corner, single anterolateral bundle posterior cruciate reconstruction, and double-bundle posterior cruciate reconstruction.

Results: The sectioned knee demonstrated a posterior shift of the tibial neutral position and the abnormal posterior, varus, and external rotation laxities used clinically to define a combined posterior cruciate ligament/posterolateral corner injury. Both reconstructions restored the posterior laxity to levels that were not statistically different from those seen in the intact knee, but the double-bundle reconstruction more closely mimicked the posterior laxity profile of the intact knee, having statistically lower posterior laxities than did the single-bundle reconstruction at 30°, 60°, and 90° of flexion ($P < .05$, analysis of variance, HSD test). The resting position of the tibia after double-bundle reconstruction trended to be anteriorly subluxated relative to its position for the intact knee at flexion angles of 30° and greater ($P < .05$, paired t test). Neither technique corrected the abnormal varus or external rotation laxities.

Conclusion: With either single- or double-bundle reconstructions, additional posterolateral reconstruction is recommended to correct the external rotation laxity.

Clinical Relevance: Knowledge of the kinematics of the combined posterior cruciate ligament/posterolateral corner–injured knee is important in the proper diagnosis of the injury and in the selection of the appropriate surgical reconstruction.

Keywords: knee; posterior cruciate ligament (PCL); reconstruction; in vitro; laxity; subluxation

The surgical treatment of posterior instability of the knee is evolving rapidly; however, there are as yet no prospective randomized studies of operative versus nonoperative treatment of the knee when the posterior structures have been injured to guide surgeons as to indications for surgical treatment or selection of reconstruction technique. The purpose of this study was to establish, using an in vitro cadaveric model, the kinematic laxity pattern of the knee after an anatomically defined PCL/posterolateral corner (PLC) injury, for which most authorities advocate surgical treatment. Furthermore, we tested the hypothesis that a double-bundle PCL repair is preferable to a single-bundle PCL repair with regard to restoration of normal joint positioning and laxity of a combined PCL/PLC–injured knee.

Posterior cruciate ligament injuries make up from 4% to 20% of all knee ligament injuries and up to 38% of ligamentous injuries seen in trauma patients.[7,23] Although the

*Address correspondence to Michael J. Askew, PhD, Hoyt Musculoskeletal Research Laboratory, Summa Health System, PO Box 2090, 444 North Main Street, Akron, OH 44309-2090 (e-mail: askewm@summa-health.org).

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PCL is recognized as providing primary restraint to posterior tibial translation,[10-12] isolated PCL injuries usually result in low levels of instability because of the presence of effective secondary restraints. Isolated PCL injuries are, therefore, commonly treated nonoperatively, although there is evidence suggesting that such treatment may lead to progressive knee pain and chronic instability.[3,17,27,30,32] However, after a combined injury involving the PCL and the PLC, when abnormal posterior laxity usually exceeds 10 mm, medial femoral condyle cartilage degeneration rapidly appears.[32] It has been shown, in cadaveric studies, that posterior tibial translation, varus deformity, and increased quadriceps force needed to extend the PCL/PLC–deficient knee lead to increased medial compartment and patellofemoral joint forces.[31] Surgical intervention is the treatment of choice for the PCL/PLC–deficient knee that demonstrates more than 10 mm of abnormal posterior laxity and at least 15° of abnormal external rotation laxity (a grade 2+ posterior drawer indicative of a grade 3 PCL sprain and additional grade 3 injury to the posterolateral structures).[25]

The operative treatment of a combined PCL/PLC injury remains controversial in that there is no consensus as yet on the optimum reconstruction procedure. Controversy exists regarding graft selection, tunnel position, flexion angles for joint reduction, graft tensioning, and fixation. The PCL is a complex soft tissue structure made up of 2 bands or bundles: a larger anterolateral (AL) bundle and a smaller posteromedial (PM) bundle. The customary PCL reconstruction involves a single-bundle graft positioned to mimic the AL band and tensioned and fixed at 90° of flexion with the tibia anteriorly displaced to restore normal femoral-tibial positioning at that flexion angle. Several studies have reported that such single-bundle reconstructions restore posterior laxity but only at low knee flexion angles.[4,9,15,28] The question has arisen as to whether a single-bundle reconstruction of the PCL is sufficient or if a double-bundle reconstruction, mimicking the natural PCL anatomy, is necessary. Several authors have reported on double-bundle techniques and described different landmarks for the tunnels as well as different knee positions for tensioning and fixation of the grafts.[†] It has been the common belief that the AL bundle tightens in knee flexion and the PM bundle tightens in extension,[10] but recent studies have shown that both bundles elongate during knee flexion.[19,29] In the various reports of double-bundle reconstructions, the AL bundle has been tensioned and fixed at flexion angles from 60° to 90°, and the PM bundle has been tensioned and fixed at knee flexion angles from 0° to 120°.[1,5,6,9,14,21,25,26,29] The issue is confused and complicated by conflicting results. Data from Bergfeld et al[1] and Race and Amis[29] suggest that little is gained by the additionally complex double-bundle surgical procedure. Harner et al[14] found that the double-bundle reconstruction was better able to restore posterior laxity but also found that the ability of a single-bundle reconstruction to do so depended greatly on the joint angle and graft tension at the time of graft fixation.[15] However, these studies were all conducted on knees with simulated isolated PCL injuries. There is clearly a need for further investigation to develop consensus on an optimum procedure for the treatment of the combined PCL/PLC injury.

[†]References 1, 2, 5, 6, 9, 14, 21, 25, 26, 29.

MATERIALS AND METHODS

Eight fresh-frozen, cadaveric lower extremities from 5 male donors, whose mean age at death was 73 ± 6 years (range, 66-82 years), were tested. This sample size was chosen based on published reports of similar testing in which 5, 8, or 10 cadaveric specimens had been used.[14,16,21,29] Two studies published recently also used 8 specimens.[1,13] The knee specimens were prepared for laxity testing using a protocol that has been described in previous studies.[18,22] After the specimen was thawed to room temperature, the Achilles and posterior tibial tendons were harvested. Grafts were prepared by tubularizing these tendons with 2-0 synthetic absorbable suture (Vicryl, Ethicon Inc, Johnson & Johnson, Somerville, NJ) and a modified Bunnell stitch of No. 5 braided, nonabsorbable polyester suture (Mersilene, Ethicon Inc) for fixation. The Achilles tendon, to be used as a graft for the AL bundle, was sized to 10 mm, and the posterior tibial tendon, to be used as a graft for the PM bundle, was sized to 8 mm. The knee specimen was then stripped of all soft tissue beyond the joint capsule proximally and the tibial tubercle distally. The tibia and femur were then each transected approximately 20 cm from the joint. The distal end of the tibia and proximal end of the femur were potted in PVC pipe with polymethyl methacrylate. The femur, via its PVC extension, was rigidly attached to a 3-axis load-torque cell (FARO Medical Technologies, Lake Mary, Fla) mounted on an in vitro knee kinematics test stand. A 6 degrees of freedom instrumented spatial linkage (FARO Medical Technologies) was connected between the tibia and the test stand. The load cell provided measurement of 3-dimensional forces and torques applied to the knee specimen, and the instrumented spatial linkage measured the 6 degrees of freedom motion of the tibia relative to the femur. The accuracies of these instruments in this application have been shown to be <1 mm, <1°, <3 N, and <1 N·m at the 95% confidence limits[18,22] for the translations, rotations, forces, and torques, respectively.

During preparation for testing, each specimen was examined physically and radiographically for evidence of previous surgery or clinically evident cruciate ligament abnormalities. When the joint capsule was opened during testing, the specimen was also inspected to verify initially intact cruciate ligaments and the lack of frank articular degeneration. Two specimens available for these tests were excluded based on these inspections.

Each knee specimen in its intact condition, with sham medial parapatellar and posteromedial arthrotomies, was put through a passive flexion-extension cycle to determine the neutral or resting positions of the tibia with respect to the femur, in terms of anterior/posterior, medial/lateral, proximal/distal, varus/valgus, and internal/external tibial

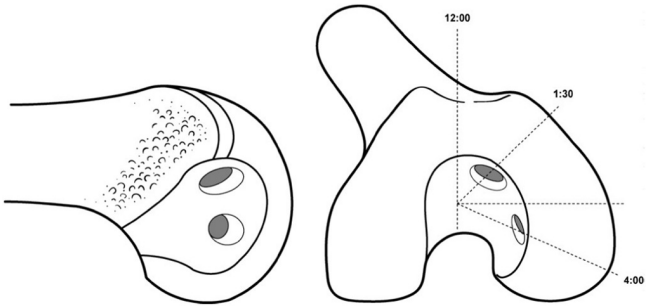

Figure 1. Femoral tunnel locations for the single- and double-bundle reconstructions.

displacements at 0°, 30°, 60°, and 90° of flexion. Displacements from the neutral positions were then determined after the application of 100-N anterior and posterior forces, 10-N·m varus and valgus rotation torques, and 3-N·m internal and external rotation torques. The PCL and the PLC were then sectioned. Sectioned PLC structures were the fibular collateral ligament, the popliteus tendon, the posterolateral capsule, and the arcuate complex. The passive flexion-extension cycle was repeated to determine any changes in the neutral position of the tibia from that seen in the intact knee due to the sectioning of the PCL/PLC. The anterior-posterior stress tests (100 N), varus-valgus stress tests (10 N·m), and internal-external rotation tests (3 N·m) were repeated for the PCL/PLC–sectioned specimen. The displacements of the PCL/PLC–sectioned knee in these stress tests were measured from the initial neutral positions of the intact knee. This testing protocol was then repeated after each of the following 2 reconstruction techniques.

Single AL Bundle Graft (Achilles Tendon) PCL Reconstruction

The drill holes were made following the recommendations of Bisson and Clancy.[2,6] For the femoral tunnel in a right knee, the AL bundle guide wire was placed at the 1:30 clock position, 6 mm posterior to the articular surface (Figure 1). The wire was then overdrilled to 10 mm. The placement of the tibial tunnel was performed with the tibia jig set at 55°, and the exit point was slightly lateral to the interspine line and in the distal third of the tibial PCL insertion. After the satisfactory positioning of a guide wire, the tibial tunnel was overdrilled to 10 mm. A GORE-TEX Crucial Smoother (W L Gore and Associates Inc, Flagstaff, Ariz) was used to prepare the tunnel and to pass the graft. The graft was secured proximally to a screw post on the femur (Figure 2). The graft was passed through the femoral drill hole, across the joint, and through the tibial drill hole. After 20 flexion-extension cycles with tension on the graft to seat and precondition the graft, the joint was put into 90° of flexion, and the graft was tensioned until the anterior surface of the tibia had translated, without rotational constraint, 1 cm anterior to the femoral condyles. The tensioned graft was then fixed to a screw post on the tibia.

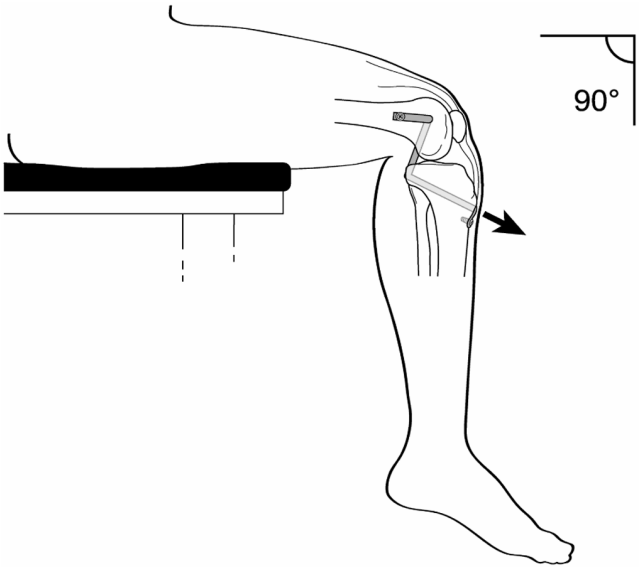

Figure 2. Posterior cruciate ligament reconstruction technique with tensioning and fixation of the graft on the tibia with the knee at 90° of flexion and the tibia displaced anteriorly.

Double-Bundle PCL Reconstruction

The Achilles tendon graft used in the single-bundle reconstruction described above was released before the installation of the double-bundle reconstruction was begun and was reinstalled during the double-bundle procedure. To position the femoral tunnel for the PM bundle graft, the guide wire was placed at the 4-o'clock position approximately 5 mm posterior and distal to the tunnel for the AL bundle (Figure 1). The wire was then overdrilled to 8 mm, creating a "shallow-shallow" double-tunnel placement as described by Noyes et al.[25] The existing tibial tunnel was then overdrilled to 12 mm to accommodate the double graft. The GORE-TEX Crucial Smoother was used to prepare the tunnels and to pass the grafts. The grafts were fixed proximally to femoral screw posts and passed through the drill holes. The joint was again put through 20 flexion-extension cycles with tension on the grafts to seat and precondition the grafts. Tensioning and fixation of the AL bundle graft proceeded as described above for the single-bundle reconstruction. A preliminary trial, presented in the Appendix, had indicated that superior restoration of normal motion and stability was achieved when both the AL and the PM bundles were fixed at 90° of flexion. Thus, with the joint still at 90° of flexion, the PM bundle graft was tensioned to remove slack without changing the anteriorly translated position of the tibia relative to the femur. The tensioned PM graft was then fixed to the screw post on the tibia.

Analysis of variance (ANOVA), followed when necessary by post priori Tukey HSD tests ($P < .05$), was used to statistically assess differences in the mean changes in neutral positions and laxities between the knee conditions. Paired t tests ($P < .05$) were used to identify trends in the tibial resting position data where statistical significance was not found by the ANOVA-HSD tests.

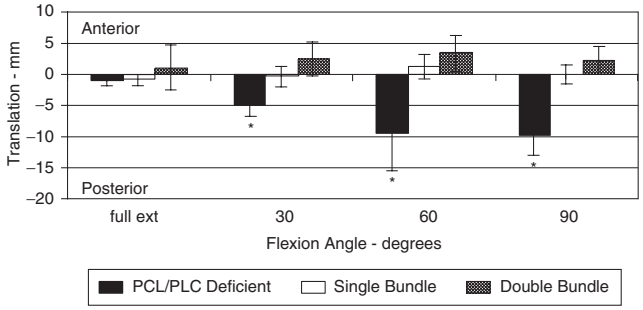

Figure 3. Anterior and posterior changes in tibial neutral position (mean ± SD). *Statistical significance ($P < .05$) from intact knee condition. PLC, posterolateral corner; ext, extension.

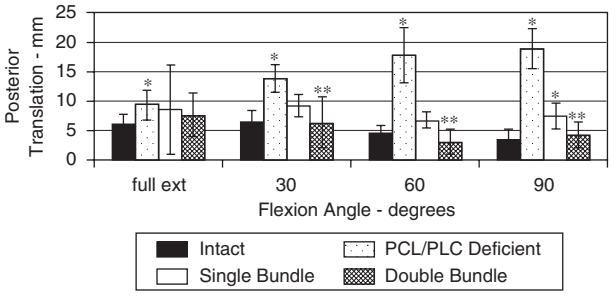

Figure 4. Posterior tibial translation with 100 N of posterior force (mean ± SD). *Statistical significance ($P < .05$) from intact knee condition. **Statistical significance ($P < .05$) from single-bundle reconstruction. PLC, posterolateral corner; ext, extension.

TABLE 1
Tibial Resting Position: Varus/Valgus Deviation (deg) of Neutral Tibial Position Relative to the Intact Knee Condition[a]

	Full Extension	30°	60°	90°
PCL/posterolateral corner deficient	–0.1 ± 1.8	–0.2 ± 5.2	–2.1 ± 3.9	–2.2 ± 3.6
Single bundle	–0.4 ± 1.2	–1.8 ± 1.8	–1.1 ± 2.0	–1.3 ± 3.6
Double bundle	–1.2 ± 2.0	–1.0 ± 4.7	–0.4 ± 2.4	–2.0 ± 2.1[b]

[a]Positive value is valgus, and negative value is varus (mean ± SD).
[b]Statistical significance ($P < .05$) from intact knee condition.

TABLE 2
Tibial Resting Position: Internal/External Deviation (deg) of Neutral Tibial Position Relative to the Intact Knee Condition[a]

	Full Extension	30°	60°	90°
PCL/posterolateral corner deficient	–0.7 ± 1.1	1.6 ± 4.1	4.3 ± 6.0	1.1 ± 1.5
Single bundle	0.8 ± 2.6	2.9 ± 2.5[b]	2.6 ± 3.9	–4.7 ± 7.2
Double bundle	2.1 ± 1.6[b]	2.4 ± 3.8	4.1 ± 5.7	4.1 ± 6.4

[a]Positive value is external, and negative value is internal (mean ± SD).
[b]Statistical significance ($P < .05$) from intact knee condition.

RESULTS

Kinematic Analysis of the PCL/PLC–Injured Knee

Neutral Tibial Positions. When the PCL and PLC were cut, the neutral position of the tibia was significantly ($P < .05$) posteriorly displaced, except at full extension (Figure 3). The mean posterior translation of the tibial neutral position increased with increasing flexion, reaching 9.8 mm at 90° of flexion. Varus angulation occurred when the PCL and PLC were cut, but the changes were not significant (Table 1). The resting position of the tibia tended to be externally rotated when the PCL and PLC were sectioned, but again, the changes were not statistically significant (Table 2).

Tibial Laxities. Posterior tibial translations in the intact knee due to 100-N posterior loads were greatest at 30° of flexion and trended to decrease with flexion (Figure 4). Sectioning of the PCL and PLC significantly increased ($P < .05$) the posterior translation with 100 N of posterior load. The mean posterior translation reached 18.9 mm at 90° of flexion, demonstrating a 15-mm increase over the mean value seen for the intact knee. Varus laxity also significantly increased after cutting of the PCL/PLC, reaching 13.6° at 90° of flexion (Figure 5). The external rotation laxity also increased with the simulated injury, reaching 20.9° at 90° of flexion (Figure 6). It should be noted that although the external rotation of the injured knee increased, on average, it exceeded that of the intact knee by only 10°.

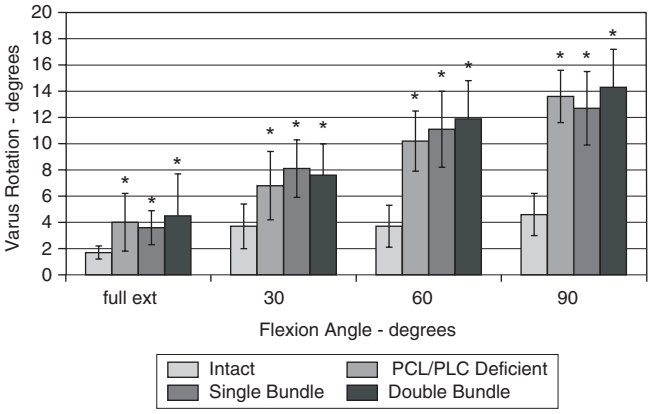

Figure 5. Varus tibial rotation laxity at 10 N·m varus torque (mean ± SD). *Statistical significance ($P < .05$) from intact knee condition. PLC, posterolateral corner; ext, extension.

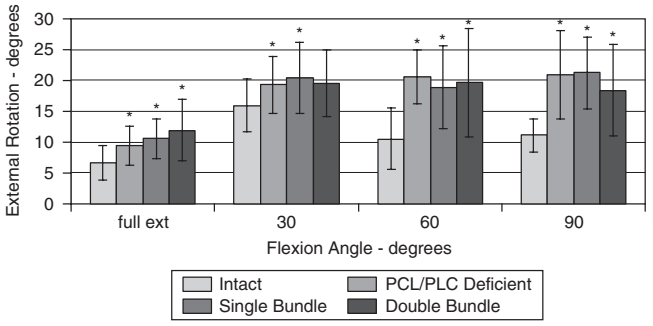

Figure 6. External tibial rotation at 3 N·m external torque (mean ± SD). *Statistical significance ($P < .05$) from intact knee condition. PLC, posterolateral corner; ext, extension.

Kinematics of the Single- and Double-Bundle PCL Reconstructions

Neutral Tibial Positions. Both tested reconstruction techniques reduced the posterior displacement of the tibial neutral position (Figure 3). The single-bundle reconstruction more closely mimicked the intact knee in neutral position across all angles of flexion, and there was a trend for the double-bundle reconstruction to subluxate the knee anteriorly at flexion angles of 30° and more ($P < .05$, paired t tests). The reconstructions had no effect on the varus shift or the axial rotation of the neutral position of the tibia (Tables 1 and 2).

Tibial Laxities. Except for the single-bundle reconstruction at 90°, the posterior laxity results of both reconstructions did not differ statistically from those of the intact knee (Figure 4). However, the double-bundle technique trended to more closely mimic the intact condition with regard to posterior tibial laxity, and its results were statistically different from those of the single-bundle reconstruction at 30°, 60°, and 90° of flexion. The abnormal varus laxity (Figure 5) and the abnormal external rotations (Figure 6) of the PCL/PLC–sectioned knee were not statistically changed by the reconstructions.

We evaluated the coupled posterior translation that occurred when the 3-N·m external torque was applied to the tibia to further assess the posterolateral rotatory instability that was created with the PCL/PLC injury. Relative to the intact knee, the PCL/PLC–deficient knees showed increased coupled posterior displacement, which was statistically significant at 60° and 90° of flexion (Figure 7). The double-bundle reconstruction provided translations closer to those of the intact knee than did the single-bundle reconstruction, but both reconstructions reduced the coupled posterior displacement to levels not significantly different from those of the intact knee with the exception of the single-bundle reconstruction at 90° of flexion.

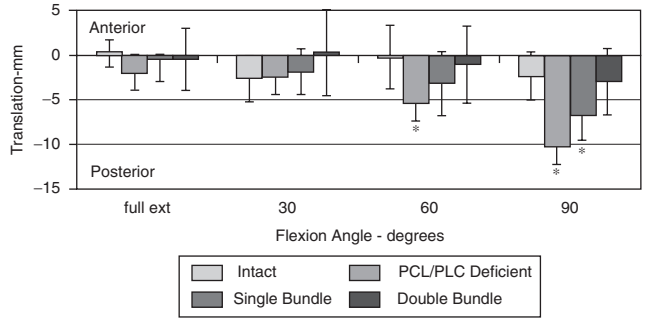

Figure 7. Coupled anterior-posterior translation with external rotation torque of 3 N·m (mean ± SD). *Statistical significance ($P < .05$) from intact knee condition. PLC, posterolateral corner; ext, extension.

DISCUSSION

The PCL/PLC injury model was selected for study because clinical indications for surgical treatment are not usually achieved in an isolated PCL-injured knee. Surgical indications are usually taken as more than a 10-mm side-to-side increase in posterior laxity, increased varus laxity, and a 15° side-to-side increase in external rotation laxity, all at 90° of flexion.[25] These indications are usually achieved in the combined grade 3 PCL/PLC injury. For the specimens tested in this study, the anatomically defined PCL/PLC injury created a mean increase of 15 mm in posterior laxity and an increase of 10° of external rotation laxity at 90° of flexion, increased varus laxity at all flexion angles, and, most important, an increase of 8 mm in the coupled posterior translation with external rotation at 90° of flexion. All these abnormalities objectively demonstrate posterolateral rotatory instability after the sectioning of the PCL/PLC and foretell the rapid medial condylar degeneration seen clinically after PCL/PLC injuries.[32]

This article has reported on single- and double-bundle reconstructions for a knee in which both the PCL and the PLC were sectioned to simulate a combined injury. Previously published reports have discussed single- and double-bundle PCL reconstructions for only isolated PCL injuries.[1,14,15,21,29] Harner et al[16] did investigate the effects of injury to the posterolateral structures but only in the context of how sectioning of the posterolateral structures affected the stability of a knee that had already undergone a single-bundle reconstruction of an insolated PCL injury.

The posterior laxity results after the single- and double-bundle reconstructions of the combined PCL/PLC–sectioned knee were similar to those reported for similar reconstructions of isolated PCL injuries. The posterior laxity after the single-bundle reconstruction was significantly greater than that of the intact knee only at 90° of flexion, although there were no statistical differences in posterior laxity between the double-bundle reconstruction and the intact knee, in agreement with the findings of Bergfeld et al[1] and Race and Amis.[29] Although not different from those of the intact knee, the posterior laxities after the double-bundle reconstruction were significantly less than those for the single-bundle reconstruction for 30°, 60°, and 90° of flexion. These findings are similar to those of Harner et al[14] for single- and double-bundle reconstructions of an isolated PCL injury, although they found statistical differences between the single- and double-bundle reconstructions and between the single-bundle reconstruction and the intact knee at all flexion angles from full extension to 120°. However, in testing of a separate set of knees using the same testing protocol, Harner et al[15] found no difference in posterior laxity between the single-bundle reconstruction and the intact knee. Direct comparisons between these studies are made difficult by the differences in tested knee conditions (isolated or combined injuries) and reconstruction techniques (flexion angles at graft fixation, etc) that exist between them.

Although not statistically significant, results of the ANOVA-HSD analysis and paired *t* tests ($P < .05$) identified a trend for the double-bundle reconstruction to abnormally anteriorly subluxate the neutral resting tibial position at flexion angles of 30° and greater (Figure 3). This trend may reveal an overconstraint of the reconstructed knee, possibly resulting from the surgical technique variables of PM tunnel placement, graft tensioning, and fixation after the AL bundle graft had reduced the joint by anterior tibial translation. The neutral resting position of the tibia after reconstruction of the PCL/PLC–deficient knee has not been examined in previous biomechanical studies of single- or double-bundle reconstructions,[1,14,25,28,29] but it is a very important factor in the postreconstruction course of the knee and warrants further study. Subluxation of the tibiofemoral joint into an abnormal neutral position could lead to rapid cartilage degeneration. We know from clinical studies that single-bundle AL reconstructions stretch out with time.[6,8,20,24] Although undesirable in the single-bundle reconstruction, such stretching after the double-bundle technique tested in this study might reduce or eliminate the joint subluxation caused by the overconstraint associated with the double-bundle reconstruction.

The anteriorly displaced tibial resting position seen after the double-bundle reconstruction tested in this study may possibly have resulted from the chosen femoral tunnel placement and/or the flexion angle at which the grafts were tensioned and fixed.[25] There is no consensus as to where or how to tension and fix the PM bundle of a double-bundle PCL reconstruction. Past studies have tensioned and fixed the PM bundle at flexion angles ranging from 0° to 120°.[1,5,6,9,14,21,25,26,29] Noyes et al[25] cautioned that shallow PM tunnel placement, as used in this study, may cause overconstraint of the knee in flexion, but deep tunnel positions may not control posterior laxity in flexion. We based our decision to tension and fix the PM grafts at 90° of flexion on the results of a preliminary trial (see the Appendix) in which the posterior laxity most closely mimicked that of the intact knee when the PM graft was tensioned at 90°. Tensioning of the PM bundle at 90° of flexion has been used in other studies.[21,29] The tunnel location and other aspects of the reconstruction procedure may also affect the in situ loads carried by the graft. The measurement or calculation of such in situ forces was beyond the scope of this study but has been done in other studies.[14-16,21,29]

Neither reconstruction adequately addressed the instability created by the PLC injury. Significantly increased varus and external rotation laxity remained after both reconstructions (Figures 5 and 6). The increased coupled posterior translation with external rotation at 90° (Figure 7) was best addressed by the double-bundle reconstruction but, again, at a cost of overconstraint and joint subluxation.

We found only a 10° increase in external rotation laxity at 90° of flexion after cutting of the PCL and the PLC. This observed increase in external rotation laxity is less than the standard clinical diagnostic criterion, a finding that suggests that injuries to the PLC may be underdiagnosed. Noyes et al[25] recommended using the final position of the posteriorly subluxated lateral tibial plateau as part of the criteria and not just the increased external rotation laxity. We found that coupled posterior translation with external rotation at 90° was 10.2 mm for the PCL/PLC–injured knee but was only 2.3 mm for the intact knee. This difference is possibly a more easily recognizable clinical laxity abnormality than is the external rotational abnormality.

Past biomechanical studies have addressed the increased stress placed on the graft and the persistent posterolateral rotatory instability that remains after a single-bundle PCL reconstruction for a knee that also has a PLC injury.[16,25,33] This study has now further demonstrated that the external rotatory instability of the PCL/PLC–injured knee is not corrected by either a single- or a double-bundle PCL reconstruction. We recommend addressing the PLC injury separately.

CONCLUSION

The laxity profile of the reconstructed combined PCL/PLC–sectioned knee was better with the tested double-bundle reconstruction technique than with the tested single-bundle reconstruction technique. The PLC deficiency was not adequately addressed by either of the reconstruction techniques tested.

ACKNOWLEDGMENT

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APPENDIX
Preliminary Double-Bundle Trial

Because of the wide range of flexion angles reported in the literature for the tensioning and fixing of a posteromedial (PM) bundle graft,[1,5,6,9,14,22,26,27,30] we conducted a preliminary trial on a single knee specimen to establish the PM bundle reconstruction protocol for the double-bundle reconstruction technique to be tested in this study. A single, fresh-frozen, cadaveric, lower extremity specimen was thawed to room temperature and was prepared, along with its Achilles and posterior tibial tendons, for testing as described in the Materials and Methods section. Once mounted on the test stand, the specimen was evaluated for the tibial neutral position at 60° and 90° of flexion, and the anterior/posterior tibial laxities as a result of 85-N forces were measured at these 2 flexion angles. The knee was again tested after sectioning of the PCL and posterolateral corner and then after a double-bundle PCL reconstruction. The bony tunnel positions and the reconstruction techniques were as described in the Materials and Methods section. With the knee in

90° of flexion, the anterolateral bundle graft tensioned until the anterior surface of the tibia had translated 1 cm anterior to the femoral condyles. The tensioned graft was then fixed to a screw post on the medial tibia. The PM bundle posterior tibial tendon graft was tensioned and fixed separately on the tibia with the knee at 0°, 60°, 90°, and 120° of flexion.

From the results of the 1 specimen trial in which the flexion angle at which the PM graft was tensioned and fixed was varied (Tables A1 and A2), it was judged that the double-bundle reconstructions with the AL and PM grafts both tensioned and fixed at 90° of flexion provided knee positions and laxities that most closely mimicked normal. This protocol was used in the double-bundle reconstruction in the subsequent tests in this study.

TABLE A1
Posterior Tibial Translation (mm)
With 85-N Posterior Force

	Flexion	
	60°	90°
Intact	6.3	3.1
Double posteromedial bundle		
Tensioned at 0°	9.2	8.9
Tensioned at 60°	4.8	6.1
Tensioned at 90°	3.9	2.5
Tensioned at 120°	3.3	0.3

TABLE A2
Total Tibial Translation (mm)
With 85-N Anterior-Posterior Forces

	Flexion	
	60°	90°
Intact	18.9	8.3
Double posteromedial bundle		
Tensioned at 0°	23.2	18.5
Tensioned at 60°	20.1	15.1
Tensioned at 90°	15.3	8.7
Tensioned at 120°	14.9	8.5