Biomechanical Analysis of Posterior Cruciate Ligament Reconstruction With Aperture Femoral Fixation

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abstract

The goal of this study was to determine whether single-tunnel–double-bundle-equivalent posterior cruciate ligament (PCL) reconstruction using an aperture femoral fixation device better replicated normal knee kinematics than single-bundle reconstruction. Eight fresh-frozen human cadaver knees underwent arthroscopically assisted PCL reconstruction and were examined with a robotic testing system to assess knee joint kinematics under combinations of applied internal, neutral, and external rotational tibial torque and anteroposterior translational forces at 0°, 30°, 60°, 90°, and 120° flexion. Three conditions were tested: (1) intact PCL; (2) single-tunnel PCL reconstruction with anterolateral and posteromedial bundle fixation at 90°/90° (single bundle); and (3) 90°/0° (double-bundle equivalent), respectively. Posterior tibial translation was the primary outcome measure. Compared with the intact knee, double-bundle-equivalent reconstruction under external tibial torque allowed greater posterior translation across the flexion arc as a whole (P=.025) and at 30° flexion (P=.027) when results were stratified by flexion angle. No other kinematic differences were found with single-bundle or double-bundle-equivalent fixation, including mediolateral translation and both coupled and isolated tibial rotation (P>.05). Single-bundle PCL reconstruction closely approximated native knee rotational and translational kinematics, whereas double-bundle-equivalent reconstruction permitted increased posterior translation with applied external tibial torque, particularly at lower flexion angles. Single-bundle PCL reconstruction provides knee stability similar to the intact condition, making it a practical alternative to conventional double-bundle PCL reconstruction. The authors found that double-bundle-equivalent reconstruction provided no advantage to justify its clinical use. [Orthopedics. 2015; 38(1):9-16.]
The primary goal in posterior cruciate ligament (PCL) reconstruction is to restore normal knee stability by recreating the native knee anatomy. Various studies have shown the native PCL to have a larger anterolateral bundle that resists posterior tibial translation, primarily at higher flexion angles, and a posterior-medial bundle that exerts its greatest contribution at lower flexion angles. Some biomechanical studies have shown that independently reconstructing and tensioning both anterolateral and posterior-medial bundles better reproduces normal knee biomechanics than single-bundle reconstruction that addresses only the anterolateral bundle. A recent retrospective comparative study suggested that double-bundle reconstruction offers clinical superiority; however, many clinical and biomechanical studies found no significant advantages of double-bundle over single-bundle constructs. Currently, no prospective randomized controlled trials clearly support 1 method over the other. Further, it is difficult to draw accurate conclusions from the available literature on PCL reconstruction because of myriad technical considerations that preclude isolation of a single independent variable. These factors include tunnel position, tibial fixation method (transtibial vs inlay), femoral fixation method, number of femoral and tibial tunnels, graft tensioning parameters, graft size, angle of graft fixation, complexity of injury, chronicity of injury, and method for clinical and/or biomechanical evaluation.

Early-onset knee osteoarthritis is associated with PCL injury, although the relative contributions from the initial osteochondral insult and subsequent alteration of normal joint kinematics have not been delineated. With increasingly sophisticated testing models, the ability to detect kinematic abnormalities has improved. However, the clinical relevance of these differences and the extent to which normal anatomy and biomechanics must be restored to prevent or delay joint degeneration are unknown.

The single-bundle and double-bundle-equivalent PCL reconstruction methods investigated in this study used a unique all-inside femoral fixation device. Short-term clinical results with the single-bundle construct have been favorable; however, neither construct has been studied biomechanically. Improved stability may be realized from both anatomic bundle positioning and independent bundle tensioning that better matches the native PCL. The goal of this study was to compare the kinematics of the intact knee with those after single-bundle and double-bundle-equivalent PCL reconstruction; the authors hypothesized that the latter construct would more closely restore intact knee kinematics.

**Materials and Methods**

In this study, 8 fresh-frozen human cadaveric knee specimens, 3 male and 5 female, were used. Average donor age was 59 years (range, 33-76). Each specimen was thawed at room temperature 24 hours before testing. Specimens were not used if manual examination or diagnostic arthroscopy showed ligamentous injury or significant osteoarthritis. The femur and the tibia were truncated approximately 25 cm from the joint line, and the peripheral 7 cm of each bone was exposed to allow for rigid potting into Wood’s metal. The capsule and soft tissue stabilizers around the knee joint were preserved. The tibiae were mounted vertically to a custom-designed fixator with 3 bicortical cannulated screws and then fixed to a 6-degrees-of-freedom force/torque sensor (SI-1500-240; ATI Industrial Automation, Apex, North Carolina) that was mounted rigidly to a cross-beam. Femurs were similarly placed in a custom mount on a robotic manipulator (Rotopod R2000; Parallel Robotics System, Hampton, New Hampshire). A knee joint coordinate system was established with a MicroScribe coordinate measuring machine (Immersion Corporation, San Jose, California). The memory lock function of the testing system allowed the specimen to be removed from the robot after surgery and precisely returned for further testing. This robotic musculoskeletal simulation testing system was previously validated (Figure 1).

After a neutral position (position of the knee with a 20 N compressive load and zero translational or rotational force) was established at each of 5 flexion angles (0°, 30°, 60°, 90°, and 120°), loading conditions were applied. These included internal-external rotation (0±1.5 Nm) and anteroposterior drawer (0±150 N) in all combinations. Mediolateral and varus-valgus loads were held at 0 N. Coupled tibial rotation was permitted. The robot manipulated the knee joint in 6 degrees of freedom until the applied load was balanced by the knee at the given flexion angle. This position represented the kinematic response of the knee to the applied load. Joint loads and kinematics were recorded throughout testing. Specimens were taken through an initial run of the protocol before data collection to allow for tissue creep.

Anteroposterior knee laxity was defined as anteroposterior displacement of the tibia relative to the femur between ±150 N loads. The anterior endpoint was used for reference because this convention has been shown to provide greater accuracy for assessing anteroposterior translation. Medial-lateral translation was measured as the corresponding mediolateral tibial displacement at a posterior load of 0 to 150 N. Referenced from the neutral position, angular displacement after ±1.5 Nm Tibial torque was recorded as well as coupled tibial rotation across a 0 to 150 N posterior load. A reference of 0 N was used to avoid confounding measurements with the coupled internal rotation seen with anterior tibial translation. The intact knee was tested first to establish baseline parameters. Next, each specimen underwent diagnostic arthroscopy followed by PCL reconstruction, randomized to the single-bundle or double-bundle technique, and was returned for robotic testing. This
process was repeated with the reconstruction method not yet performed.

Surgical Technique
A PCL reconstruction was performed as described by Uribe et al,16 with slight modifications for the double-bundle-equivalent protocol. Cryopreserved half-split tibialis anterior tendons were used for grafting (>240 mm long), 1 per knee. No. 5 Ticron sutures (Sherwood Medical, St Louis, Missouri) were whipstitched along each graft end, using the intact and split ends as the anterolateral and posteromedial bundles, respectively. The split ends were individually passed through the AperFix femoral implant (Cayenne Medical, Scottsdale, Arizona) according to the manufacturer’s protocol, designed to facilitate bundle separation, and looped to double graft diameter.

Standard diagnostic arthroscopy was performed on each specimen to confirm cruciate ligament integrity and assess intra-articular pathology. The PCL was then debrided arthroscopically. A 70° arthroscope was also used through an accessory posteromedial portal to debride the posterior knee and PCL insertion on the tibia. Femoral tunnel preparation was performed by passing a guide wire freehand from the lateral portal into the anterolateral half of the PCL footprint, 8 mm from the articular margin, and drilled 11 mm in diameter to a depth of 40 mm.

With the knee at 45° flexion, a trans-tibial PCL guide set to 50° was placed through the medial portal to rest at the tibial PCL insertion site on the posterior tibia, 1.5 cm distal to the articular surface and slightly lateral to the midline. A 1.5-cm incision was made over the anteromedial tibia. The guide wire was then passed through to the posterior tibial cortex, and an 11-mm tibial tunnel was created under arthroscopic visualization.

The femoral device loaded with the graft was guided through the lateral portal into the femoral tunnel to a marked depth of 35 mm (Figures 2A-B). Before deployment, the designated anterolateral and posteromedial graft tails were positioned corresponding to native PCL bundle orientation. The device was then deployed, and the construct was secured within the femur by aperture tendon-bone compression (Figure 2C). The graft tails were then passed through the tibial tunnel independently from posterior to anterior, using previously placed shuttle sutures (Figure 2D). The anterolateral bundle was delivered through the tibia first and held taut in a lateral direction, followed by passage of the posteromedial bundle, which was directed medially (Figure 2E). This maneuver helped to approximate the native anatomy of the tibial PCL insertion site (Figure 2F). The graft tails were then secured with either the single-bundle or double-bundle-equivalent protocol (Figure 2F).

Single-Bundle PCL Reconstruction. With tension applied to the graft suture ends of both the anterolateral and posteromedial bundles, the knee was cycled to ensure that there was no osseous or ligamentous impingement. While equal tension, bundle position, and anterior drawer force were maintained, an 11-mm AperFix tibial interference screw was inserted, fixing both bundles at 90° knee flexion. After biomechanical testing, specimens were returned to the wet laboratory and the tibial interference screw was removed and discarded before the alternative (single-bundle or single-tunnel–double-bundle method) reconstruction was performed. Femoral fixation and graft integrity were ensured before and after each procedure (Figure 3).

Figure 1: Schematic drawing of the 6-degrees-of-freedom musculoskeletal simulator. Shown are the Tibiofemoral (inset) and other various coordinate systems required for kinematic testing of the knee. Abbreviations: FEM, femur; FIX, knee flexion fixture; LOD, 6-axis load cell; MIC, MicroScribe (Immersion Corporation, San Jose, California); PLA, Rotopod platform (Rotopod R2000; Parallel Robotics System, Hampton, New Hampshire); ROB, Rotopod base; Tib, tibia. (Reprinted with permission, Cleveland Clinic Center for Medical Art & Photography © 2009-2014. All rights reserved.)
tained. After the knee was brought to 0° flexion, the posteromedial bundle was tensioned and an 11-mm AperFix tibial interference screw was inserted. Provisional fixation was removed, and the construct was probed for final assessment of tension and integrity.

Data Analysis
For each flexion angle and rotational torque parameter tested, anteroposterior translation (millimeters), mediolateral translation (millimeters), and angular displacement (degrees) from the final loading cycle of each specimen were extracted 6-degrees-of-freedom kinematic measurements from the same knee for 3 different conditions (intact, single-bundle, and double-bundle equivalent). All combinations of 3 rotational torques and 5 flexion angles were statistically compared.

A priori power analysis suggested a sample size of 8 knees to detect the mean differences of 2.3±1.8 mm between intact and surgically modified knees (alpha<.05, beta=0.10). Repeated measures mixed model analyses were used for overall comparisons between groups (considering flexion arc as a whole), and pairwise comparisons between least squares means of different conditions were assessed with Tukey-Kramer adjustments for multiple comparisons. Differences were considered statistically significant at P<.05.

RESULTS
Anteroposterior Stability
With applied internal tibial rotational torque, no significant differences in overall mean anteroposterior translation were seen between native knee and either the single-bundle or double-bundle-equivalent construct (P=.74 and P=.36, respectively). With results stratified by flexion angle and compared with the native knee (Figure 4A), both constructs allowed slightly greater translation between 0° and 60° flexion, more so with double-bundle fixation. At 90° and 120°, translation for the double-bundle construct was 0.25±1.85 mm less and 0.10±1.55 mm more relative to the native knee, respectively, whereas the single-bundle construct tended to overtighten the knee by approximately 0.75±1.92 mm and 1.17±1.72 mm, respectively. None of these differences reached statistical significance (P>.05).

Without applied tibial torque, no significant difference was seen in overall translation between the native knee and either the single-bundle or double-bundle-equivalent construct (P=.39 and P=.11, respectively). With results stratified by flexion angle and compared with the native knee (Figure 4B), both constructs allowed greater translation from 0° to 90° flexion, more so with double-bundle fixation. At 120°, the single-bundle construct...
overtightened the knee by 1.15±2.90 mm, whereas translation with double-bundle fixation was within 0.03±2.94 mm of the native knee. None of these differences reached statistical significance (P>.05).

Under external tibial rotational torque, overall translation was significantly greater for the double-bundle-equivalent construct (P=.025) and similar for the single-bundle construct (P=.12) vs the native knee. With results stratified by flexion angle and compared with the native knee (Figure 4C), both constructs allowed greater average translation from 0° to 90° flexion, more so with the double-bundle construct. At 120° flexion, average translation for single-bundle and double-bundle reconstruction was 0.38±3.46 mm less and 0.32±3.07 mm more, respectively. None of these differences reached statistical significance, except for the increase of 3.65±1.66 mm in translation with double-bundle fixation at 30° flexion (P=.027).

**Coupled External Rotation**

With or without applied tibial torque, no significant difference was seen in coupled tibial external rotation between the native knee and both reconstruction groups at all flexion angles with respect to the 0 N to 150 N posterior drawer (P>.05) (Figure 5). At 90° flexion with neutral tibial torque, the single-bundle reconstruction permitted approximately 5° more external tibial rotation than the native knee; however, the difference was not significant (P=.066).

**Mediolateral Stability**

Mediolateral translation was within 1.3 mm of the intact state for both reconstruction groups, regardless of tibial torque, with no difference reaching significance at any flexion angle (P>.05) (Figure 6).

**Rotational Stability**

For each flexion angle and for the flexion arc as a whole, no statistically significant differences in tibial rotation were found between the native knee and both reconstruction groups under either internal or external tibial torque (P>.05) (Figure 7).

**DISCUSSION**

This study provides the first biomechanical comparison of the authors’ described methods for single-bundle and double-bundle-equivalent PCL reconstruction using an all-inside aperture compression femoral fixation device and a single femoral tunnel. Data showed that single-bundle reconstruction closely approximated native knee kinematics under all loading conditions across a 120° arc of motion. Although average translations for the authors’ single-bundle construct were slightly greater at lower flexion angles, regardless of applied moment, the differences were not significant. The double-bundle-equivalent reconstruction had less posterior stability with applied external tibial torque, particularly at 30° flexion, and there was a trend toward increased laxity at 0° (P=.097) and 60° (P=.076) flexion. These results differ from those of other studies that showed that double-bundle reconstruction provided equal or greater stability compared with single-bundle reconstruction, with the former either approximating native knee stability or causing excessive constraint. Still, the current findings are consistent with those of Bergfeld et al and Whiddon et al in that single-bundle reconstruction adequately restored native knee stability, with double-bundle reconstruction providing
The biomechanical rationale for double-bundle PCL reconstruction is predicated on restoring the reciprocal tension of the native anterolateral and posteromedial bundles throughout knee range of motion. Conventional single-bundle reconstruction may not adequately replicate the posterior stability of the native knee at lower flexion angles.\textsuperscript{5,6,22} However, single-bundle PCL reconstruction improves stability so that consistently good functional outcomes are achieved in most patients.\textsuperscript{23,24} Still, altered translational and rotational biomechanics can persist after reconstruction, even in cases with clinical success and posterior stability similar to that of the intact condition.\textsuperscript{15,25} Subclinical residual instability could potentiate to some degree the negative sequelae seen in the PCL-deficient state.\textsuperscript{13,26} For this reason, some authors believe that absolute restoration of normal ligament function in all degrees of freedom should be the goal of PCL reconstruction, possibly through the addition of a second bundle.\textsuperscript{11,15,21,25}

Previous studies focused solely on posterior stability with the tibia in neutral position to gauge the efficacy of specific single-bundle or double-bundle PCL constructs. For a more comprehensive analysis, the authors also measured posterior stability under combined translational and rotational loads as well as rotational stability alone. Tibial rotation alters the relative contributions of the PCL and surrounding ligamentous structures to restraining posterior tibial translation; in neutral rotation, the contribution of the PCL is maximized.\textsuperscript{27} The role of the PCL in posterior restraint also varies with flexion. At higher angles, it is the dominant restraint. At lower angles, it becomes secondary.\textsuperscript{28} With internal rotation, posteromedial structures tighten and become major restraints to posterior translation, particularly at lower flexion angles.\textsuperscript{27,29} External rotation tightens posterolateral structures and to some degree medial structures, also limiting posterior tibial translation, but more so in extension than in flexion.\textsuperscript{29} Highlighting these concepts, Bergfeld et al\textsuperscript{27} found no differences in posterior stability between PCL-deficient and intact cadaver knees at 0° and 30° flexion under internal or external tibial rotation.

In another study by Markolf et al,\textsuperscript{5} single-bundle PCL reconstruction allowed significantly more posterior translation between 0° and 30° flexion compared with the intact knee. Average translation increased 1 to 2 mm at those positions. Consistent with the results of their sectioning study,\textsuperscript{5} the addition of a posteromedial bundle improved stability near extension without having an appreciable effect on posterior stability at higher degrees of flexion. Still, the authors endorsed single-bundle reconstruction based on its more physiologic ligament force profiles compared with the substantially higher forces seen in the posteromedial bundle with double-bundle reconstruction. The authors’ single-bundle reconstruction allowed similar increases in translation near extension, which may reflect a type II error because the differences did not reach significance. A key distinction between testing protocols is that coupled tibial rotation was permitted in their model. This has been shown to increase observed anteroposterior translation by 30%, and it also provides a less constrained, more natural measure of PCL function.\textsuperscript{30} If all other variables were held constant, measured translation would be greater in the authors’ system than in those that locked rotation during loading. Nonetheless, it is safe to conclude that the stability of the single-bundle construct is comparable to that of other single-bundle constructs.\textsuperscript{6,22} What they do not know, however, as these and other authors have stated, is what level of stability imparts long-term clinical equivalence.\textsuperscript{5,25,31}

The PCL is a secondary restraint to tibial rotation. External tibial rotation increases from approximately 10° in the
intact state to approximately 15° with isolated PCL deficiency and normalizes after single-bundle PCL reconstruction based on manual measurements. However, using a more precise robotic testing model, another study showed that both single-bundle and double-bundle reconstructions permitted equally small but significant increases in external rotation compared with the native knee at 0° to 120° flexion. Particularly with injury to the posterolateral structures, the stabilizing role of the posteromedial bundle may be more critical, which is seldom addressed in most biomechanical studies.

Akin to the dial test, the authors measured angular displacement under internal and external tibial torque from the neutral position. Although the authors found minor differences in allowed tibial rotation after both types of reconstruction vs the native knee, none reached statistical significance. These values are comparable to those measured in previous studies. Both types of reconstruction allowed relatively more external rotation at 60° and 90° flexion vs lower angles, similar to findings of Apsingi et al. On average, the authors’ single-bundle reconstruction permitted less internal and more external rotation than the native knee, a difference that was most pronounced at 90° flexion. An explanation is that the tibial resting position became more internally rotated after single-bundle reconstruction.

Although no differences were found, results for coupled external rotation with posterior load were variable, yet comparable to those of previous studies. The single-bundle construct allowed greater coupled external rotation than the double-bundle-equivalent construct with neutral torque, which was most evident at 60° and 90° flexion, similar to findings of Gill et al. However, it better approximated the intact knee under internal and external torque. This may reflect improved rotational stability afforded by double-bundle reconstruction because medial and lateral structures likely are less able to aid in rotational restraint when they are not under tension. Similar to speculation based on the dial testing results, these discrepancies also suggest shifted tibial resting positions that might affect the size of the moment arm as well as the amount of potential displacement. In general, the amount of coupled external rotation decreased as the applied tibial torque transitioned from internal to external.

A larger sample size may have shown other significant differences in translation, especially for double-bundle-equivalent reconstruction. Not testing the PCL-deficient state is an obvious limitation of the study and was the result of financial and logistical constraints. However, the most relevant comparisons are with the intact condition. The authors believe that this calculated omission would not significantly weaken their study. Also, there was no quantitative evaluation of the femoral and tibial tunnel positions in this study, although they were similar for reconstructions in a given specimen. The laxities in this study are most relevant to those present at time 0 on the operating table. Changes in graft tension and possible elongation or rupture over time may occur. The authors did not quantify graft tensioning forces during fixation but relied on subjective measures for graft tensioning, as is typically done in the clinical setting. Unrecognized injury and/or specimen damage during testing may have occurred, decreasing the validity of the results.

A clear discrepancy was found between the actual and hypothesized stability of the single-tunnel–double-bundle-equivalent construct. The authors attribute this discrepancy at least in part to methodologic error. Not completely splitting the graft may have resulted in less efficient tensioning than would have occurred had the graft been completely split. In addition, complete splitting also may have allowed for toggling during tensioning despite aperture compression with this implant, further dissipating graft tension. In preliminary testing of a single specimen, complete graft splitting improved stability, as initially expected, for both single-tunnel–double-bundle and single-bundle constructs. Perhaps the use of 2 divergent femoral tunnels and smaller-diameter implants would better fit the native footprint and better restore native kinematics.

**Conclusion**

Single-bundle PCL reconstruction closely approximated native knee rotational and translational kinematics, whereas double-bundle-equivalent reconstruction permitted increased posterior translation with applied external tibial torque, particularly at lower flexion angles.

**References**


