

A Biomechanical Comparison of Posterior Cruciate Ligament Reconstructions Using Single- and Double-Bundle Tibial Inlay Techniques

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Background: The efficacy of using a double-bundle versus single-bundle graft for posterior cruciate ligament reconstruction has not been demonstrated.

Hypothesis: A double-bundle graft restores knee kinematics better than a single-bundle graft does in tibial inlay PCL reconstructions.

Study Design: Controlled laboratory study.

Methods: Eight cadaveric knees were subjected to 6 cycles from a 40-N anterior reference point to a 100-N posterior translational force at 10°, 30°, 60°, and 90° of flexion. Testing was performed for the intact and posterior cruciate deficient knee as well as for both reconstructed conditions. Achilles tendons, divided into 2 equal sections, were prepared as both single-bundle and double-bundle grafts. Both grafts were employed in the same knee, and the order of graft reconstruction was randomized.

Results: There were no statistical differences in translation between the intact state and either of the reconstructions ($P > .05$) or between either of the reconstructions at any flexion angle ($P > .05$).

Conclusion: No differences in translation between the 2 graft options were identified.

Clinical Relevance: The use of a double-bundle graft may not offer any advantages over a single-bundle graft for tibial inlay posterior cruciate reconstructions.

Keywords: posterior cruciate ligament (PCL); double bundle; reconstruction; ligament; knee

Injury to the PCL has recently become an intriguing topic of discussion in the sports medicine arena. Advancements in the understanding of PCL functional anatomy, injury incidence, natural history of PCL-deficient knees, and methods of reconstruction have led to more interest in treatment options.[¶]

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The complex anatomy of the PCL has initially been described as consisting of 2 functional primary bundles.^{15,19,29} The anterolateral bundle is the primary restraint at 90° of flexion, is approximately twice the width of the posteromedial bundle, is stiffer, and has a higher ultimate load to tensile testing.^{19,29} Because of these findings, reconstruction of the PCL has focused on the anterolateral bundle.

Many operative techniques have been described for PCL reconstruction. Unfortunately, no current surgical procedure has been able to consistently correct abnormal posterior laxity or to provide consistent functional results.^{1,5,22} Clinical results after PCL reconstruction have not been as predictable as those after ACL reconstruction.¹ It is currently unclear whether PCL reconstruction techniques can

[¶]References 3-5, 8-12,16-18, 23, 25, 27, 28, 30.

restore normal knee laxity in vivo and thus alter the natural history of the PCL-deficient knee.

The reconstruction of the PCL varies from surgeon to surgeon with respect to ligament graft selection and technique of fixation. An important variable is the orientation of the graft on the tibia (ie, tibial inlay vs tibial tunnel). Jakob and Rügsegger,²⁰ as well as Berg,³ have advocated the tibial inlay technique for its theoretical advantages regarding graft fiber orientation. Previous research has shown that at initial fixation and after cyclic loading, the posterior tibial inlay technique results in decreased posterior translation with less graft degradation when compared with the tunnel technique of PCL reconstruction.^{5,25}

Recent discussions have focused on a more anatomical PCL reconstruction method using a double-bundle (DB) graft. Although no clinical outcome studies have been published, previous authors have evaluated DB grafts and have concluded that this method of reconstruction may be superior.^{17,23,30} Two authors have advocated using a DB graft with the arthroscopic (tibial tunnel) method of reconstruction,^{17,23} while other researchers showed that DB reconstruction using the tibial inlay technique of fixation provided improved stability over a range of knee motion.³⁰ In these biomechanical studies, the authors added a second graft for their DB reconstructions, demonstrating that 2 grafts were an improvement over a single graft. There are no published mechanical studies evaluating DB PCL reconstructions that control for the quantity of graft used for each testing condition.

The purpose of this study was to compare the resultant laxity provided by the tibial inlay technique using both single-bundle (SB) and DB grafts for PCL reconstruction while using the same quantity of graft material. We hypothesized that with the tibial inlay method of PCL reconstruction, a DB reconstruction would restore knee kinematics better than an SB reconstruction would.

MATERIALS AND METHODS

A total of 4 male and 4 female unpaired fresh-frozen cadaveric knees with a mean age of 48.5 years (range, 37-63 years) was used in this study. The specimens did not show signs of injury or degenerative joint disease.

For sample size determination, we assumed a statistical power of 90% ($\beta = .1$) and a significance level (α) of .05, while using the method described by Lieber.²¹ Standard deviations from an initial study⁵ were used, and a difference in the translation data equal to 2 times the standard deviation was obtained. For a power of 0.9, 6 knees per group were needed at the various angles. In our study, we used 8 knees per angle.

Specimen Preparation

Before testing, each specimen was thawed overnight at room temperature. Each specimen was dissected free of skin, sparing the joint capsule, ligaments, popliteus tendon and muscle, and the extensor mechanism. A medial arthrotomy was performed for joint inspection along with

a vertical posterior arthrotomy to evaluate the intact PCL. The arthrotomies remained open throughout all testing. The fibula was resected 4 cm distal to the tibiofibular joint and stabilized to the tibia with a fully threaded Steinmann pin. The proximal end of the femur and the distal end of the tibia were potted in aluminum tubes with polymethylmethacrylate. Crossing transfixion pins were used to eliminate any rotation between the bones and respective holding tubes. Specimens were then mounted in a custom testing apparatus described previously,⁵ with 6 degrees of adjustability that did not overconstrain the knee while allowing for testing through flexion and extension.

Testing Protocol

The custom testing apparatus was similar to that described by Fleming et al¹³ and used by Bergfeld et al⁵ (Figure 1). The potted femoral end of the specimen was clamped into a yoke attached to the load ram of a servo-hydraulic universal testing machine (MTS Systems Corp, Eden Prairie, Minn) that applied an anterior-posterior (AP) shear force to the knee. The tibial mechanism was mounted on a translating table that allowed free motion of the tibia in the coronal plane and that locked in neutral rotation. The epicondylar axis of the knee joint was placed at the pivot axis of the femoral yoke. The knee joint flexion angle was adjusted with the yoke and locked at the desired flexion angle before each test. A bearing system allowed free motion of varus-valgus angulation. A posterior-to-anterior tibial force (simulated anterior drawer) of 40 N was used to establish an initial reference point from which posterior translation was measured. Since the ACL is not involved in the surgery, it is reasonable that the reference for displacement should be established using an anteriorly applied load to the tibia that will engage the ACL. This position was reproduced at each angle by the MTS machine and was used as the reference point from which posterior translation was measured. During loading cycles, this same point was used as the anterior limit. Six sequential AP loading cycles from the initial anterior reference point to 100 N of posterior-directed force were then applied. These loading cycles were performed at 1 mm/s at the level of the joint line while AP translation was measured by the linear variable displacement transducer (LVDT) of the MTS machine. In all cases, the load-deformation curve became reproducible after 2 loading cycles. The testing was conducted at 10°, 30°, 60°, and 90° of flexion. Each knee served as its own control and was tested with an intact and transected PCL, followed by both SB and DB PCL reconstructions with the tibial inlay technique (Figure 2). The order of graft reconstruction was randomized throughout the study.

PCL Sectioning

After laxity data had been obtained from the intact knees, the PCL and meniscomfemoral ligaments were resected using the anterior and posterior arthrotomy previously made. The meniscomfemoral ligaments were removed, as they

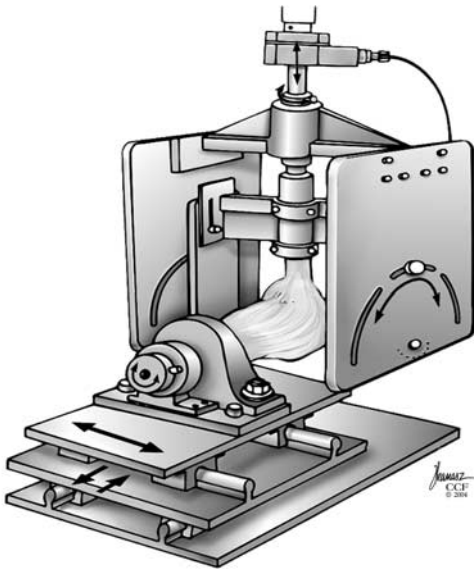


Figure 1. A custom test jig with 6 degrees of adjustability was mounted on an MTS testing machine.

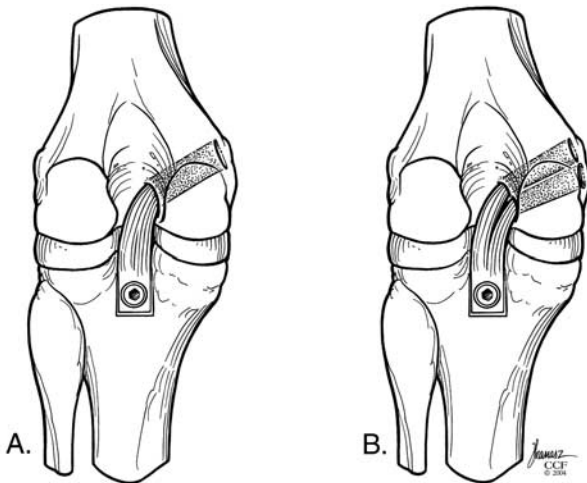


Figure 2. Illustrations from a posterior view of single-bundle (A) and double-bundle (B) reconstructions using the tibial inlay technique.

are closely associated with the PCL and have previously been shown to contribute to posterior knee stability.¹⁹ Each specimen was removed from the testing jig between the loading conditions to ensure removal of the PCL without damaging other structures. The specimen was then returned to the jig in the same position. The zero-load neutral position was maintained after reloading the specimens. The AP loading was repeated using the previously described anterior reference point and testing conditions.

PCL Reconstruction

Each knee underwent PCL reconstruction with both an SB and a DB graft using the tibial inlay technique. Both grafts were employed in the same knee, and the order in which each graft was used for reconstruction was randomized. From this design, each knee was able to serve as its own control.



Figure 3. Separation of an Achilles tendon to generate both a single-bundle and double-bundle graft of equal amounts of tissue from the same allograft specimen. One half of the graft was split sagittally into 2 equal bundles for the double-bundle graft.

To retain comparable structural and material properties for each graft, allograft material from 1 specimen was used for both grafts (Figure 3). Allograft Achilles tendons (MTF, Edison, NJ), including the os calcis bone block, were separated into 2 equal sections (average age for grafts, 48 years). One half was used for the SB graft while the second half was split again into 2 bundles. The bone block of this second half was left intact, thereby creating a DB graft. Special care was taken to tease the tendon apart from distal to proximal, as the fibers of the Achilles tendon are not purely longitudinal in direction. The 2 grafts had essentially the same material properties and quantity of collagen, thus the translational differences observed stemmed from graft geometry and not merely from the addition of a second graft. A No. 5 Ticron suture (Syneture, Norwalk, Conn) was woven through the end of each limb in a Krakow-type fashion so that the suture would extend from within the bone tunnel and not be intra-articular. This method was used for graft tensioning and improved interference graft fixation.

Bone tunnels were created through the medial femoral condyle (MFC) in the anatomical footprint of the PCL with an outside-in technique, by use of a PCL femoral drill guide (Acufex, Mansfield, Mass). The tunnel reproducing the anterolateral bundle was made anterior and distal in the footprint of the native PCL, while the tunnel reproducing the posteromedial bundle, when used, was made posterior and slightly proximal (Figure 4).^{17,23} The directions used for the guidewire for each tunnel were convergent and directed toward the proximal posterior tibia with the knee at 90° of flexion.

The previously made posterior capsulotomy was opened to expose the proximal posterior tibia. A bone trough measuring 10 × 14 mm was created with osteotomes at the tibial insertion site of the PCL. The matching bone block of the graft was secured flush to the posterior surface of the

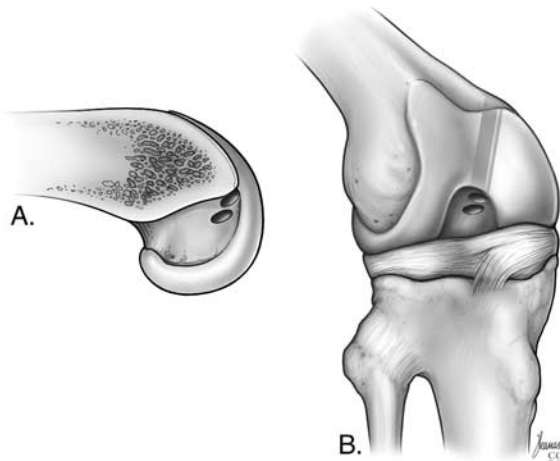


Figure 4. For double-bundle reconstructions, an anterior and distal (shallow) femoral tunnel reproducing the anatomical anterolateral bundle was used. A posterior and slightly proximal second tunnel was added to reproduce the anatomical posteromedial bundle while staying within the native PCL footprint. Both images are of a right knee.

proximal tibia with a 4.5-mm bicortical screw (Synthes, Paoli, Pa), with a washer and a nut securing the fixation on the anterior aspect of the tibia.

An anterior force of 40 N was applied to the proximal tibia, simulating an anterior drawer maneuver while femoral interference screw(s) (Acufex) were placed to secure the graft(s). The SB graft, reproducing the anterolateral bundle, was tensioned to 89 N (Chatillon digital tensioner, Ametek, Largo, Fla) at 90° of knee flexion. For the DB reconstruction, the anterolateral and posteromedial bundles were each tensioned to 89 N at 90° and 30° of flexion, respectively. Biomechanical evaluation has shown that at these angles, the 2 respective portions of the PCL become taut.¹⁹ In addition, this method of tensioning closely resembles that which may be used clinically. While under tension, additional soft tissue clamps were placed across each graft where the woven suture was placed as it exited the MFC. This procedure further improved immediate graft fixation by buttressing the graft against the outer cortex of the MFC. Laxity testing was then repeated under the same conditions as previously described. At the conclusion of mechanical testing, the grafts were removed from the knees of both groups and inspected for defects. No specimens from either group showed evidence of mechanical abrasion.

When specimens underwent an SB reconstruction first, a single femoral tunnel was drilled with a 9-mm drill through the anterodistal aspect of the femoral anatomical attachment site of the PCL. This tunnel reproduced the anterolateral bundle of the PCL. The 9-mm graft was then tensioned as described and secured with a 7-mm interference screw. Testing then took place. After completion of the SB testing, the graft was removed and the knee was prepared for a DB graft. For the following DB reconstruction of the same knee, a second tunnel was drilled with a 7-mm drill through the posterior aspect of the anatomical attachment site for the posteromedial bundle. Because both arms

of the DB graft measured 7 mm, a 9-mm interference screw was placed in the first tunnel (9-mm anterolateral tunnel), while a 7-mm interference screw was used for the second tunnel (7-mm posteromedial tunnel). Testing again took place.

When specimens underwent a DB reconstruction first, the 9-mm anterolateral and the 7-mm posteromedial tunnels were initially drilled. The DB graft was then secured with the same fixation as described above. Testing then took place. After completion of the DB testing, the graft was removed and the knee was prepared for an SB graft. This procedure simply entailed the placement of a 9-mm interference screw into the posteromedial tunnel to fill it. The SB graft could then be brought through the previously placed 9-mm anterolateral tunnel and secured in place with a 7-mm interference screw, as was performed when the order of testing was reversed. By following this protocol, each testing situation used the same diameter tunnels and interference screws, regardless of the order of reconstruction.

Each graft was measured with a graft sizer (Acufex) to within 0.5-mm diameter. The SB grafts averaged 9.0 mm in diameter, while each arm of the DB grafts averaged 6.5 mm. The total cross-sectional area of each graft used for any single knee (SB vs DB) was within 5%.

STATISTICAL ANALYSIS

The total AP translation from the final loading cycle of each specimen was extracted for each flexion angle tested. Translational measurements (mm) from the same knee under 4 different conditions (intact, PCL-deficient, SB, and DB graft reconstructions) and at 4 different angles were statistically compared. The translational data of the PCL-deficient and reconstructed groups were compared to those of the intact knees. The reconstructed groups were also compared to each other. A repeated-measures analysis of variance, in conjunction with a Newman-Keuls analysis, was used for comparison between the groups. Statistical significance was taken as $P = .05$.

RESULTS

There was a trend for the DB construct to slightly overtighten the knee from 30° to 60°, whereas the SB construct tended to allow slightly more translation between 10° and 90° (Figure 5). However, no differences in translation between the intact state and either of the reconstructions were found to be statistically significant at any flexion angle tested ($P > .05$). Additionally, no statistical differences between the SB and DB reconstructions were found at any angle ($P > .05$) (Figure 5). With the tibial inlay technique, both the SB and DB PCL reconstructions closely reproduced the stability seen in the intact knee.

DISCUSSION

In our review of the current literature, few articles have been published about biomechanical testing of DB PCL

EFFECT OF SINGLE- AND DOUBLE-BUNDLE PCL RECONSTRUCTIONS ON KNEE TRANSLATION

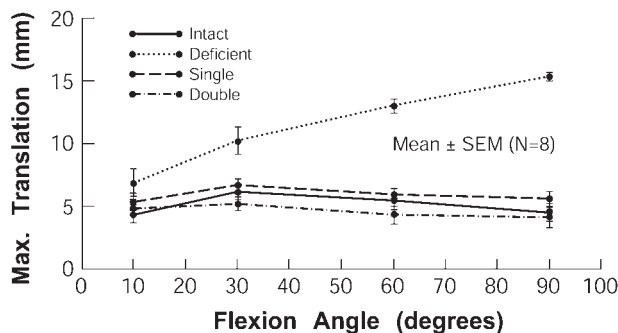


Figure 5. Posterior translation at the different flexion angles for each of the testing conditions. No statistically significant differences were noted.

reconstructions,^{17,23,30} although many technical notes and surgical methods have been described.^{4,16,26,31} This relatively new concept has been initiated because of the varied clinical outcomes seen after PCL reconstruction.^{8,22} Studies have documented the importance of femoral tunnel placement^{2,23,30} in PCL reconstruction and have shown that nonisometric positioning of the graft best corrects abnormal posterior laxity.^{6,10,14,30} For either SB or anterolateral bundle reconstruction, Bomberg et al,⁶ Burns et al,⁷ and Galloway et al¹⁴ suggested making the femoral tunnel in the anterior distal footprint of the native PCL.

Mannor et al²³ performed an *in vitro* analysis of PCL graft placement and tension. The authors evaluated the relationship between SB and DB reconstructions, with varying positions of the femoral tunnels for each. Although no conclusion was drawn regarding the superiority of SB versus DB grafts, the authors did conclude that femoral tunnel position affected translation and bundle tension. A shallow SB reconstruction did restore posterior translation to within 2 mm of that of the intact knee over the entire range of knee flexion. The DB reconstruction was evaluated with a high and shallow first bundle and then either a low and shallow or a deep second bundle. While both reconstructions controlled posterior translation, each did so with different load-sharing characteristics. Our reconstructions were similar to those of Mannor et al.²³ An anterior and distal (S_1) femoral tunnel reproducing the anatomical anterolateral bundle was used for SB reconstruction. For our DB reconstructions, a posterior and proximal (S_2) second tunnel was added to reproduce the anatomical posteromedial bundle while staying within the native PCL footprint. However, unlike Mannor et al,²³ who tensioned both of their grafts at 90° of flexion, our second bundle was tensioned at 30° of knee flexion.

Harner et al¹⁷ found that a DB reconstruction better reapproximated both normal knee laxity and PCL forces throughout the range of knee flexion using a robotic manipulator and the principle of superposition. However, like Race and Amis,³⁰ they also simply added a second graft to simulate a DB reconstruction. A 10-mm Achilles tendon graft was used for the SB reconstruction, while a

second 8-mm doubled semitendinosus graft (≈ 18 mm total) was added for the DB reconstruction. This procedure may not have tested the benefit of a DB graft but that of a larger graft with a greater cross-sectional area and origin footprint. The authors used an arthroscopic tibial tunnel method, which may have introduced bias, as the simple addition of more graft material is likely to provide improved stability. Markolf et al²⁵ revealed that the arthroscopic tunnel method of PCL reconstruction places grafts at risk of degradation and loosening with cycling. Harner et al¹⁷ also tensioned the grafts from the tibial side. Tensioning on the femoral side has been shown to result in higher tension on the intra-articular portion of the graft when compared to tensioning being performed on the tibial side of the graft.²⁴ Final tensioning is performed on the femoral side using the tibial inlay method, as in our study. This practice may be because of the decreased turn the graft must make with the tibial inlay method and the reduced resistance to tension as it becomes extra-articular.

Race and Amis³⁰ reported that only a DB reconstruction restored normal knee laxity across the full range of knee motion when compared to an anatomical SB and an "isometric" SB PCL reconstruction. Their isometric point did not appear to fall within the femoral anatomical attachment site, which may explain the overconstraint in extension and the laxity in flexion that they found. We agree with Ortiz et al²⁷ that no true isometric point exists, as the point shifts under different loading conditions. In comparing their anatomical SB to a DB graft reconstruction, Race and Amis³⁰ used the femoral footprints of the native PCL while securing the tibial bone block with a posterior tibial inlay technique. Like Harner et al,¹⁷ the authors used a 10-mm graft for the SB and then added a second 8-mm graft for the DB (≈ 18 mm total). This method may also have introduced bias by simply adding a second graft. We controlled for this discrepancy by using the same quantity of graft for each reconstruction (ie, SB vs DB). Race and Amis³⁰ tensioned the posteromedial bundle at 130°, whereas we tensioned it at 30°, closer to extension, where the posteromedial bundle acts as a restraint to posterior translation in a more functional manner.^{15,19}

There were 3 reasons we chose to use Achilles tendon grafts. Harner et al¹⁹ felt Achilles tendons have an advantage, as they are more rounded and provide good reproduction of the native PCL. Secondly, a single Achilles graft is large enough to be formed into both an SB and a DB graft while maintaining similar material properties. Lastly, the use of Achilles tendon allografts for PCL reconstruction is a common clinical practice.

Double-bundle PCL reconstruction may not be necessary when using the tibial inlay method. Previous research has shown that graft abrasion and compromise occur with repetitive cycling when using the arthroscopic tunnel technique. These problems are not seen in grafts placed with the tibial inlay technique.^{5,25} These issues might be more responsible for the variable clinical results that have been reported rather than the use of SB grafts. The tibial inlay method negates the killer turn and provides secure bone-to-bone fixation of the graft to the tibia.

Using the tibial inlay technique, we evaluated whether a DB graft would differ from an SB graft in reproducing stability to a PCL-deficient knee while controlling for the amount of graft used under each testing condition. Our results did not find any significant difference in translation between either of the reconstruction methods (ie, SB vs DB) and the intact knee ($P > .05$). In addition, no statistical differences between the SB and DB reconstructions were found at any angle ($P > .05$). The DB construct appeared to allow less posterior translation than seen with the SB construct across all angles tested. This restraint to posterior translation, however, was greater than that of the intact knee from 30° to 60°.

There are limitations to our study. We did not perform testing at flexion angles greater than 90°. Testing at flexion angles greater than 90° could show differences that were not revealed in our study. Additionally, our protocol did not evaluate how the different grafts behaved over time with extensive cycling. Such differences, if noted, may be clinically relevant.

In conclusion, we did not identify any biomechanical superiority in performing a DB reconstruction compared to the SB technique and therefore did not support our hypothesis. Although authors have reported advantages with the DB method, we believe that by using the posterior tibial inlay technique, the more technically challenging DB PCL reconstruction may not offer any advantages over an SB graft.

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