Review Article

Surgical Treatment of Posterior Cruciate Ligament Tears: An Evolving Technique

Matthew J. Matava, MD
Evan Ellis, MD
Brian Gruber, MD

Abstract

Major advances have been made recently in the areas of posterior cruciate ligament (PCL) anatomy and biomechanics, and several basic science studies have attempted to clarify the variables relevant to the optimal methods of PCL reconstruction. The emerging science concerning the PCL relates primarily to the biomechanical benefits of the inlay technique of tibial fixation compared with traditional tunnel fixation, use of one versus two reconstructive graft bundles, location of the femoral tunnels, and the ideal degree of graft tensioning. Despite these advances, the conclusions concerning these relevant issues are often in conflict, even with well-conceived experimental designs. Although basic knowledge regarding evolving reconstructive methods is improving, many questions remain unanswered. As a result, it is difficult to advocate one particular reconstructive technique. The optimal method of PCL reconstruction can be determined only with continued advances in basic science studies and the implementation of carefully conceived clinical trials isolating one reconstructive variable.

Dr. Matava is Associate Professor, Department of Orthopedic Surgery, Washington University School of Medicine, Chesterfield, MO. Dr. Ellis is Sports Medicine Fellow, Department of Orthopedic Surgery, Washington University School of Medicine. Dr. Gruber is Orthopaedic Surgeon, Arizona Bone and Joint Specialists, Scottsdale, AZ.

Dr. Matava or a member of his immediate family serves as a paid consultant to or is an employee of ISTO Technologies and Schwartz Biomedical, and has received research or institutional support from Breg. Neither of the following authors nor a member of their immediate families has received anything of value from or owns stock in a commercial company or institution related directly or indirectly to the subject of this article: Dr. Ellis and Dr. Gruber.

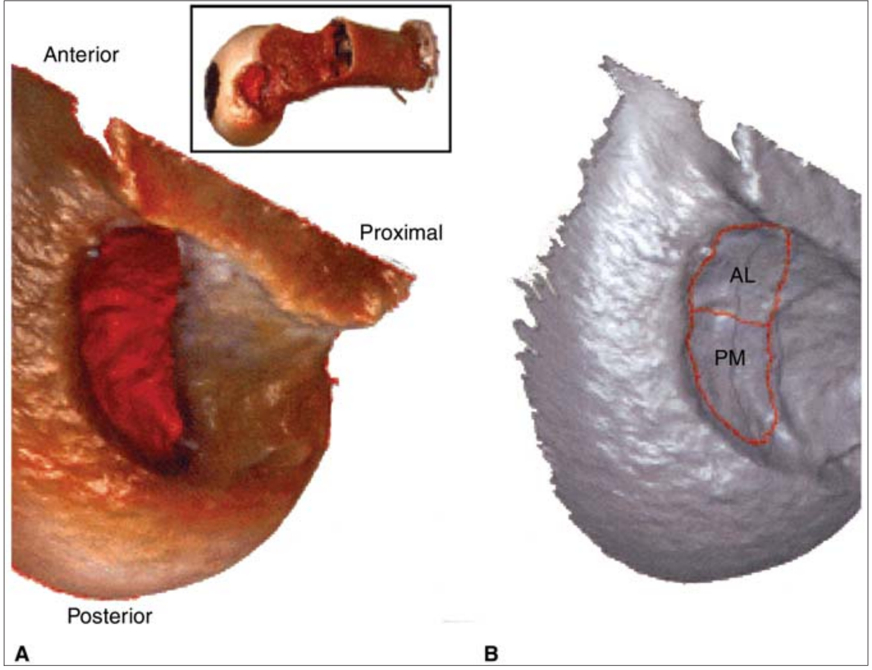
Reprint requests: Dr. Matava, Department of Orthopedic Surgery, Washington University School of Medicine, 14532 South Outer Forty Drive, Chesterfield, MO 63017-5701.

J Am Acad Orthop Surg 2009;17: 435-446

Treatment of posterior cruciate ligament (PCL) tears has advanced over the past two decades as a result of improved understanding of the basic science of the PCL and the natural history of injury to that structure. PCL tears are classified by the degree of increased posterior tibial translation compared with that of the contralateral knee: grade I, 1 to 5 mm; grade II, 6 to 10 mm; and grade III, >10 mm.[1] Nonsurgical treatment, consisting of reducing inflammation, reestablishing knee motion, and emphasizing quadriceps strengthening, is recommended for grade I and II (ie, partial) tears. Gradual return to activity is typically possible within 3 to 6 weeks, depending on the grade of injury and demands of the patient's sport or occupation.[1,2] Additional injury to the posterolateral corner (PLC) often is associated with grade III PCL laxity. This combined injury pattern has the potential to lead to premature degeneration of the articular cartilage of the medial femoral condyle and failure of the PCL graft.[3-5] Thus, surgical intervention is recommended for the PCL/PLC-deficient knee with >10 mm increased posterior translation and ≥15° increased external rotation.[6]

Surgery to reconstruct the PCL has become more common as the recognition of PCL injury has increased and as surgical techniques have improved. Despite such advances, the results of PCL reconstruction have lagged behind those of anterior cru-

Figure 1



Three-dimensional laser photographic image of the lateral surface of the medial femoral condyle of a left knee showing the footprint of the posterior cruciate ligament **(A)** and the attachment of the anterolateral (AL) and posteromedial (PM) bundles onto the footprint landmark **(B)**. The inset image of the distal femur shows the orientation of the specimen. (Reproduced with permission from Lopes OV Jr, Ferretti M, Shen W, Ekdahl M, Smolinksi P, Fu FH: Topography of the femoral attachment of the posterior cruciate ligament. *J Bone Joint Surg Am* 2008;90:249-255.)

ciate ligament reconstruction. This is likely because several factors affecting the outcome of PCL surgery remain controversial. The most notable of these are method of tibial fixation, number of graft bundles, placement of the femoral tunnel or tunnels, and degree of intraoperative graft tensioning.

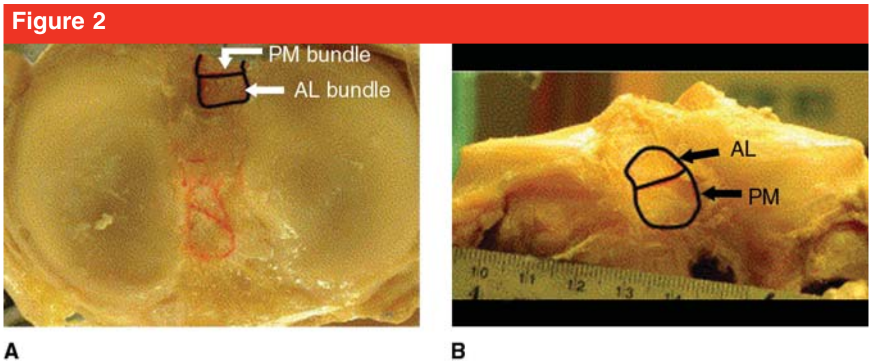
Anatomy

The PCL lies within the joint capsule of the knee, yet it is considered extra-articular because it is enclosed within its own synovial sheath. The PCL is 32 to 38 mm long, with a cross-sectional area of 11 mm^2 at its midpoint.[7] The midsubstance of the ligament is approximately one third the diameter of both the femoral and tibial insertion sites.[8] The PCL can be functionally divided into two components: a larger anterolateral (AL) bundle and a smaller posteromedial (PM) bundle.[7] This terminology is derived from the relationship of the anatomic location of the femoral insertion (anterior or posterior) to the tibial insertion (lateral or medial). Some researchers believe that this subdivision of the PCL into two discrete bundles is an arbitrary simplification because the ligament is more accurately defined as a continuum of fibers comprising, at minimum, three or four bundles.[9,10] For the purpose of PCL reconstruction, the two-bundle concept has more theoretical than practical value, although double-bundle techniques attempt to reproduce the two-bundle configuration.

A better understanding of the osseous landmarks of the PCL might assist surgeons in selecting the anatomic location of the femoral tunnels for either a single- or a double-bundle reconstruction. In general, the PCL has a broad, relatively vertical femoral footprint[9,11] at the anterolateral aspect of the medial femoral condyle, with a midpoint approximately 1 cm proximal to the articular surface.[11] Lopes et al[12] qualitatively and quantitatively evaluated the insertional topography of the femoral footprint of the PCL, with an emphasis on the individual AL and PM fiber bundles. Using a three-dimensional laser digitizer camera to analyze 20 human cadaveric knees, these authors found that the PCL footprint was semicircular in three-quarters (15) of the specimens and oval in the remainder. The average area of the femoral footprint was found to be 209 ± 33.82 mm^2, with the mean area of the AL bundle measuring 118 ± 23.95 mm^2 and that of the PM bundle measuring 90 ± 16.13 mm^2 (Figure 1). These measurements are considerably larger than previously reported values.[13-15] The average shortest distance from the center of the AL and PM bundles to the articular edge was 7 mm and 8 mm, respectively.[12] Lopes et al[12] also identified two osseous prominences intimately associated with the femoral footprint. The longer of the two, which they labeled the medial intercondylar ridge, is an osseous prominence 14 mm in length and proximal to the femoral footprint. This ridge runs from proximal to distal and anterior to posterior. The second prominence, which was present in fewer than half of the specimens, was located between the two fiber bundles and was termed the medial bifurcate ridge.

The tibial insertion of the PCL is more consistent than the femoral inser-

Figure 2



Axial **(A)** and posterior **(B)** views of the tibial insertions of the anterolateral (AL) and posteromedial (PM) bundles (outlined) of the posterior cruciate ligament onto the tibial plateau in a left knee. (Reproduced with permission from Edwards A, Bull AM, Amis AA: The attachments of the fiber bundles of the posterior cruciate ligament: An anatomic study. *Arthroscopy* 2007;23:284-290.)

Figure 3

Cadaveric cross-section of a left knee illustrating the location of the posterior cruciate ligament (PCL) facet, which is the area that provides the bony surface for ligament insertion. (Reproduced with permission from Moorman CT III, Murphy Zane MS, Bansai S, et al: Tibial insertion of the posterior cruciate ligament: A sagittal plane analysis using gross, histologic, and radiographic methods. *Arthroscopy* 2008;24:269-275.)

tion.[15,16] The two PCL fiber bundles insert without anatomic separation in a centrally located fovea, or facet, on the posterior aspect of the tibia approximately 1.0 to 1.5 cm distal to the joint line, with the posterior horn of the medial meniscus being the anterior-most extent[15] (Figure 2). The center of the two fiber bundles is located, medial to lateral, 48% of the mediolateral width of the tibial plateau from the medial tibial edge.[15] Moorman et al[17] found that the mean distance from the anterior edge of the PCL tibial insertion to the posterior tibial cortex was 15.6 mm (range, 14 to 18 mm). The center of the PCL insertion was, on average, 7 mm anterior to the posterior tibial cortex, with the bulk of the ligament located in the posterior half of the PCL facet (Figure 3). A few fibers were found to extend inferiorly ≤2 cm down the posterior tibial cortex. The authors recommended that, during transtibial PCL reconstruction the center of the tibial tunnel be placed one quarter of the total facet length anterior to the posterior tibial cortex (ie, 7 mm anterior to the posterior cortex). Placement of the tunnel more posteriorly or inferiorly will fail to reproduce normal PCL anatomy and risks injury to the popliteal neurovascular bundle. In addition, placement of the tunnel more anteriorly could potentially jeopardize the posterior meniscal horns.

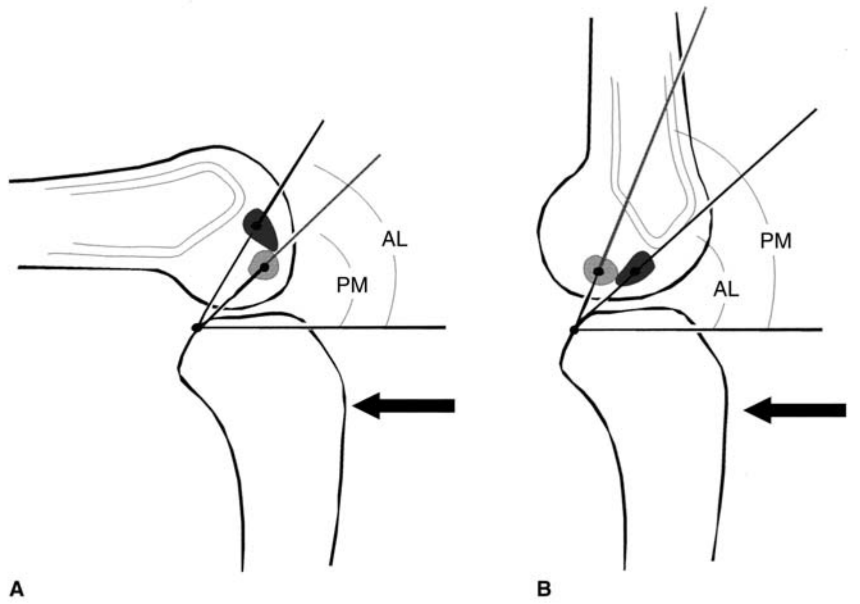
The meniscofemoral ligaments (ie, ligament of Humphry, ligament of Wrisberg) and the PCL, together, are termed the PCL complex.[13] The meniscofemoral ligaments, variably present in approximately 90% of individuals,[18] constitute 17.2% of the cross-sectional area of the PCL complex.[19] The cross-sectional area of the anterior and posterior meniscofemoral ligaments is, on average, 2.3 mm^2 and 7.5 mm^2, respectively.[18] Both of these ligaments originate from the posterior horn of the lateral meniscus, with the ligament of Humphry passing anterior to the PCL and the ligament of Wrisberg passing posterior to the PCL. Both ligaments insert on the lateral wall of the medial femoral condyle. Current methods of PCL reconstruction have not taken the meniscofemoral ligaments into consideration.

Ligament Biomechanics

The PCL provides the primary restraint to posterior tibial translation.[20] The mean ultimate load for the AL bundle is 1,120 ± 362 N, which is more than twice the mean ultimate load of the PM bundle (419 ± 128 N).[8] Similarly, the mean stiffness of the AL component was found to be 120 ± 37 N/mm, compared with 57 ± 22 N/mm for the PM component. Markolf et al[21] confirmed that the AL bundle provides the primary restraint to posterior tibial translation. These authors found nearly normal knee kinematics when the AL bundle was preserved and the PM bundle was sectioned. Consequently, the AL bundle has been the focus of traditional single-bundle reconstruction.[8,22]

Biomechanical studies have also

Figure 4



Schematic depiction of the changes in orientation angle of the anterolateral (AL) bundle and the posteromedial (PM) bundle with knee flexion and extension. The arrow in each panel represents a posteriorly directed force. **A,** With knee flexion, the AL bundle is more vertical and the PM bundle is more horizontal. **B,** With knee extension, the AL bundle is more horizontal and the PM bundle is more vertical. (Reproduced with permission from Ahmad CS, Cohen ZA, Levine WN, Gardner TR, Ateshian GA, Mow VC: Codominance of individual posterior cruciate ligament: An analysis of bundle lengths and orientation. *Am J Sports Med* 2003;31:221-225.)

shown that the PCL is a nonisometric structure with unequal tension throughout knee motion.[23] In an anatomic study evaluating the native PCL fiber orientation and length, Ahmad et al[24] found that the AL bundle became longer and more vertical at from 0° to 120° of knee flexion. The PM bundle became shorter and more horizontal with progressive flexion. This increased horizontal orientation of the PM bundle places the restraining force vector of this ligament bundle more in line to resist posterior tibial translation as flexion increases. Conversely, with progressive knee flexion, the AL bundle becomes less oriented (ie, less horizontal) to resist posterior tibial translation (Figure 4). This relationship between length and orientation indicates that neither bundle is dominant in restraining posterior tibial translation at any specific angle. These data differ from those of Papannagari et al,[25] who noted an increase in length of both bundles with progressive knee flexion in seven healthy participants studied with MRI and three-dimensional dual orthogonal fluoroscopy. This lack of reciprocal function may have implications for the surgical reconstruction of both bundles because graft fixation at <90° of flexion, as is commonly done for the PM bundle, may overconstrain the knee at higher flexion angles.

Recent cadaveric tensioning studies have indicated that the anterior meniscofemoral ligament is taut in knee flexion and the posterior meniscofemoral ligament is taut in knee extension.[26] It has been postulated that the meniscofemoral ligaments aid in functional knee stability, particularly when the main bulk of the PCL has been injured.[26] Sectioning studies by Gupte et al[18] have shown that the meniscofemoral ligaments contribute 28% to the total force resisting posterior tibial translation at 90° of flexion in the intact knee. However, these researchers found that sectioning the meniscofemoral ligaments had no effect on rotatory laxity.

Biomechanical Models of Surgical Treatment Options

The primary goal of PCL reconstruction is to restore normal anatomy. Although many surgical techniques have been described, the clinical results of PCL reconstruction have not been as predictable as those for reconstruction of the anterior cruciate ligament. Controversy exists regarding the optimal location of tibial fixation, number of graft bundles, ideal placement of the femoral tunnel or tunnels, and appropriate graft tension during reconstruction. The current basic science literature is difficult to interpret because many studies differ by several of these variables, making comparison challenging. Compounding the situation is the fact that no prospective clinical trial compares one reconstructive method with another, with only one surgical variable isolated.

Transtibial Reconstruction

The approach to tibial fixation during PCL reconstruction is a subject of controversy. Historically, the most common method for tibial fixation during PCL reconstruction used the transtibial technique, in which the graft passes proximally and posteriorly through the tibia and makes a 90° turn around the superior edge of the posterior aperture of the tibial tunnel before entering the knee joint.

This 90° bend, or "killer curve," in the graft has been shown to create increased internal tendon pressures and to possibly lead to graft elongation and failure[27,28] (Figure 5). These effects may be attributable to the so-called sawing phenomenon that is elicited when the graft continually abrades the posterior tibia during knee motion.[27,28] Aperture fixation, whereby the graft is fixed at the posterior aperture of the tunnel, thereby creating the shortest possible graft, is preferable and has been supported by cadaveric testing. Markolf et al[29] found that 15% of recessed grafts failed at the killer curve after 2,000 loading cycles, while all specimens with flush bone blocks survived testing. In addition, graft length increased 17% when the bone block was placed in a posterior orientation compared with an anterior orientation. The authors hypothesized that this difference was related to the path the graft had to traverse around the posterosuperior corner of the tunnel, effectively increasing its radius of curvature. This finding is consistent with the work of Weimann et al,[30] who found that a rounded posterior edge of the tibial tunnel resulted in less graft damage, with more grafts surviving 2,000 test cycles, compared with grafts exposed to sharp tunnel edges that are typically encountered clinically.

Margheritini et al[31] studied the kinematic effects and in situ PCL forces of various types of tibial fixation with the use of transtibial reconstruction. Using a cadaveric model under a 134 N posterior tibial load at 0°, 30°, 60°, 90°, and 120° of knee flexion, the researchers examined distal tibial fixation alone (using a 4.5-mm cortical screw and a 9- × 13-mm soft-tissue washer) as well as combined distal and proximal tibial interference fixation (using a 9- × 28-mm bioabsorbable interference screw) with Achilles tendon allografts. Combined tibial fixation resulted in significantly less posterior tibial translation at 30°, 90°, and 120° ($P < 0.05$) as well as higher in situ graft forces at all angles of knee flexion tested, with a statistically significant difference observed at 90° of flexion ($P < 0.05$) and a shorter effective graft length than reconstruction with distal fixation alone. The authors theorized that these effects would result in less graft motion in the tibial tunnel, decreased graft deformation, and increased graft stiffness, and would eliminate the so-called windshield wiper effect that may cause tunnel widening.

Despite such proven biomechanical advantages, aperture fixation with the transtibial technique is not without difficulty; it requires an interference screw to be placed all the way up the tunnel, which can be both technically challenging and potentially dangerous. Such screw placement also makes revision reconstruction more difficult if a metallic screw has to be removed. This problem may be avoided through the use of a bioabsorbable screw; however, to our knowledge, there has not been a comparison study of metal and bioabsorbable screws used for this purpose. Furthermore, caution is warranted when drilling the tibial tunnel because of the risk of injury to the adjacent popliteal neurovascular bundle.[32] All of these factors combined may contribute to the variable clinical results reported for the transtibial technique.

Tibial Inlay Technique

Berg[33] popularized the tibial inlay technique for tibial fixation. This alternative to the transtibial method involves the arthroscopic placement of the femoral tunnel or tunnels and the open creation of a bone trough in the posterior tibia. The theoretic benefit of this procedure is that the graft is secured to the anatomic tibial attachment site of the PCL, thus avoiding the killer curve associated with the transtibial tunnel (Figure 6).

Figure 5

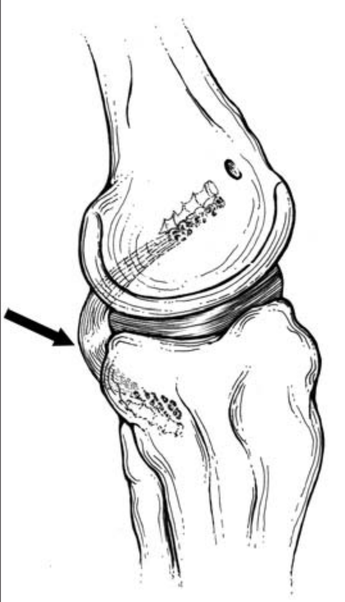


Illustration demonstrating transtibial posterior cruciate ligament reconstruction with the site of graft attenuation denoted by frayed graft because of the killer curve (arrow), located where the tendinous portion of the graft exits the tibial tunnel.

In an attempt to evaluate the effect of tibial fixation location on graft function, Bergfeld et al[28] assessed the posterior laxity of cadaveric knees reconstructed with the inlay technique compared with the transtibial method. They used a custom six-degrees-of-freedom testing apparatus and stressed the knees with 150 N of posteriorly directed force at 0°, 30°, 60°, and 90° of knee flexion. Significantly less total anteroposterior laxity was found in the inlay group than in the tunnel group from 30° to 90° of knee flexion and after repetitive loading at 90° of flexion. Furthermore, direct evaluation of the PCL grafts revealed evidence of mechanical degradation in the tunnel group but not the inlay group (Figure 7). The authors concluded that the anatomic inlay technique was superior

Figure 6

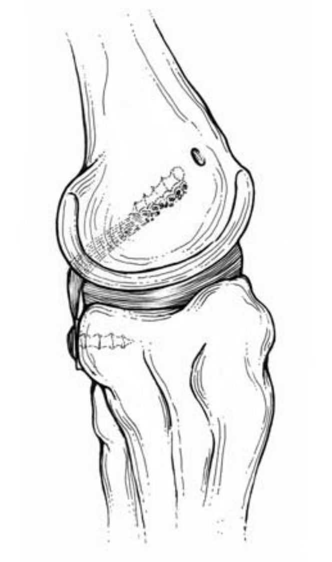


Illustration demonstrating tibial inlay reconstruction without the killer curve. The graft has a more direct approach to the femoral tunnel than in the transtibial technique.

Figure 7

Transilluminated grafts from a matched pair of knees after the completion of mechanical testing. **A,** Graft from a knee that underwent inlay reconstruction demonstrating the normal homogeneous thickness of the tendinous portion of the graft. **B,** Graft from a contralateral knee that underwent transtibial tunnel reconstruction demonstrating an attenuation of the tendinous portion of the graft (arrow) adjacent to the bone block. (Reproduced with permission from Bergfeld JA, McAllister DR, Parker RD, Valdevit AD, Kambic HE: A biomechanical comparison of posterior cruciate ligament reconstruction techniques. *Am J Sports Med* 2001;29:129-136.)

to the transtibial technique in correcting posterior knee laxity because the former potentially decreases internal graft forces.

In a similar study, Markolf et al[34] compared various graft properties (ie, thinning, total elongation, elongation during a single loading cycle) between patellar tendon allografts reconstructed with either the inlay or the transtibial technique. Each graft was subjected to 2,000 cycles of tensile loading at 0.5 Hz. All specimens from the inlay technique group survived testing, whereas 32% of the transtibial specimens failed before the completion of testing. Graft thickness, measured at three different locations, was significantly less with the transtibial grafts at all three locations compared with the inlay grafts. The mean elongation of the tunnel grafts was significantly greater than the mean elongation of the inlay constructs during the first loading cycle only. Both the tunnel and inlay grafts significantly increased in length following cyclic loading. After 2,000 cycles, the mean increases in length of the inlay and tunnel grafts were 5.9 and 9.8 mm, respectively.

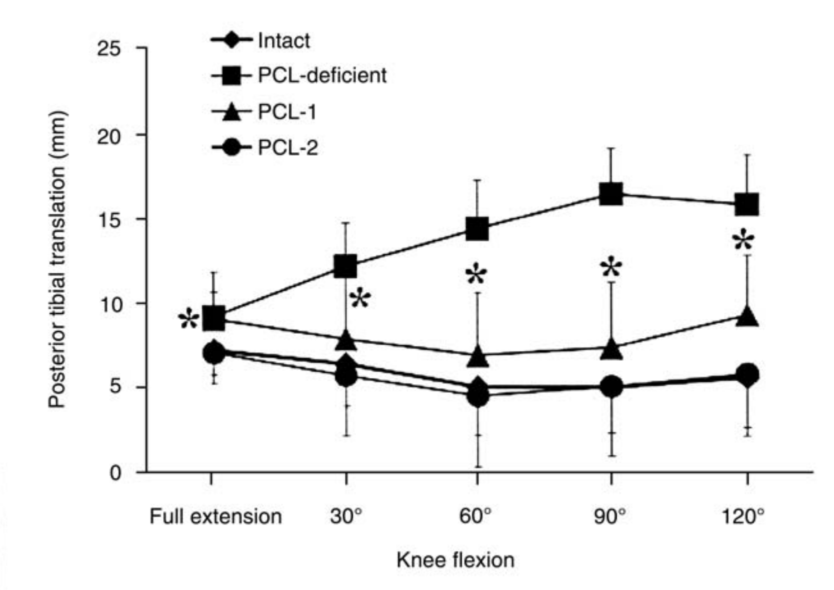
Graft Bundle Options

One area of controversy in PCL reconstruction involves the question of whether to reconstruct one or two fiber bundles. Of the two main PCL bundles, the AL bundle is approximately twice the width of the PM bundle; the AL bundle is also stiffer and has a higher ultimate load to tensile failure.[21] Thus, surgeons who perform single-bundle reconstructions have historically focused on reconstructing just the AL bundle. However, because the PCL is composed of two main fiber bundles, there has been renewed interest in replacing both bundles so as to provide a consistent restraint to posterior tibial translation throughout knee flexion. The double-bundle PCL reconstruction is not new; it was initially described by Wirth and Jager[35] in 1984 as a dynamic reconstruction consisting of the semitendinosus and gracilis passed through two tunnels in the femoral condyle.

Several recent studies have been conducted to evaluate the biomechanical efficacy of one- versus two-bundle reconstructive grafts. Harner et al[36] compared single- and double-bundle PCL reconstructions. For the single-bundle reconstruction, a 10-mm Achilles tendon graft was placed through the insertion site of the native AL bundle. For the double-bundle construct, a similar graft was placed at the site of the native AL bundle. The PM bundle was reconstructed with a 7- to 8-mm doubled semitendinosus tendon, with the tunnel position drilled through the insertion site of the PM bundle (Figure 8). However, in this study, transtibial fixation was performed distally. A robotic/universal force-moment sensor testing system was used to place a 134 N posterior force at full extension and four knee flexion angles: 30°, 60°, 90°, and 120°. Posterior tibial translation of the intact knee ranged from 4.9 ± 2.7 mm at 90° to 7.2 ± 1.5 mm at full extension. After the single-bundle reconstruction, posterior tibial translation increased to 7.3 ± 3.9 mm at 90° and 9.2 ± 2.8 mm at full extension; the corresponding in situ forces in the graft were as much as 44 ± 19 N lower than those in the intact ligament. Conversely, with the double-bundle reconstruction, the posterior tibial translation did not differ significantly from the intact knee at any flexion angle tested. This reconstruction also restored in situ forces more closely than did the single-bundle reconstruction. The authors interpreted these findings to show that double-bundle PCL reconstruction more closely restores the biomechanics of the intact knee than does single-bundle reconstruction throughout knee flexion.

Similarly, Bergfeld et al[37] compared single- with double-bundle Achilles tendon reconstruction, both fixed distally with the tibial inlay technique. The AL bundle footprint of the native PCL was used for the femoral tunnel in the single-bundle reconstruction, and the double-bundle reconstruction used the AL bundle and PM bundle footprints of the native PCL as the sites of the femoral tunnels. Following mechanical testing with a 100 N posterior tibial force at 10°, 30°, 60°, and 90° of flexion, no difference was found in tibial translation at any position. The authors concluded that both techniques reproduced the posterior stability of the intact knee, at least with the graft fixed distally with the inlay technique (Figure 9). Thus, there are conflicting data as to the necessity of a two-bundle graft.

Figure 8



Graphic representation of posterior tibial translation with the knee in full extension through 120° flexion in response to a 134 N posterior tibial load. Included in the testing were an intact knee, a posterior cruciate ligament (PCL)–deficient knee, a single-bundle (PCL-1) reconstructed knee, and a double-bundle (PCL-2) reconstructed knee. The asterisks indicate a significant difference in posterior tibial translation in the PCL-1 reconstruction and the intact knee. (Reproduced with permission from Harner CD, Janaushek MA, Kanamori A, Yagi M, Vogrin TM, Woo SL: Biomechanical analysis of a double-bundle posterior cruciate ligament reconstruction. *Am J Sports Med* 2000;28:144-151.)

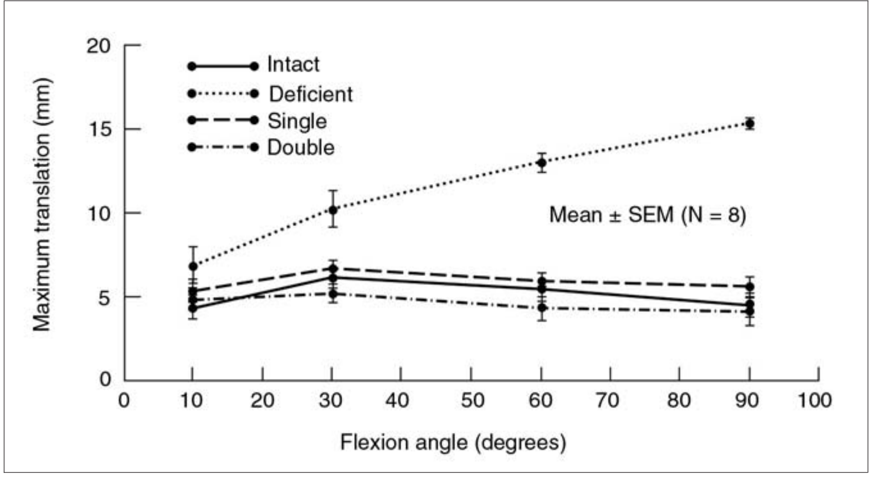
Femoral Tunnel Positioning

It is well established that femoral tunnel position strongly influences bundle tension and the ability of the graft bundle to restore normal posterior tibial translation.[22,38,39] In the case of a single-bundle reconstruction, it is the proximal-distal attachment location in the femur, rather than the anterior-posterior location, that determines where the graft will be most functional based on length-tension behavior. A distally placed single-bundle graft will be tense when the knee is in extension, and a proximal graft will be tense when the knee is in extension.

Markolf et al[40] studied the effects of PCL reconstruction with different femoral tunnel positions. They used a cast replica of the PCL footprint with tunnels placed in the AL, central, and PM femoral regions. The PCL reconstruction was performed using an 11-mm bone–patellar tendon–bone (BPTB) construct fixed distally using the inlay technique, with laxity testing performed under each tunnel condition. Their results showed that AL tunnel reconstruction reproduced normal PCL forces but was associated with increased laxity from 0° to 45° of flexion. Central tunnel reconstruction best reproduced normal knee laxity but had high graft forces between 0° and 45° of flexion. The PM position overconstrained the knee and generated higher graft forces in the same flexion range. These authors concluded that, with a single-bundle reconstruction, the graft should be placed either in the AL or central aspect of the native PCL footprint, and the PM region should be avoided.

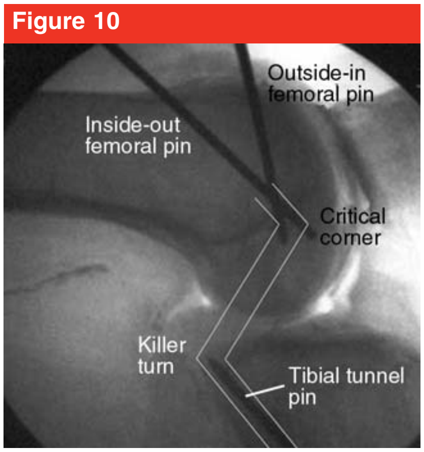
Petersen et al[41] also investigated the effect of femoral tunnel placement on kinematics and in situ forces in the double-bundle hamstring reconstructive graft in 10 fresh-frozen cadaveric knees. Two different femoral tunnel positions—anterior and posterior—were studied, with similar tibial tunnel position in both groups. The authors found that the femoral tunnel position had a significant ef-

Figure 9



Graphic representation of the effect of single- and double-bundle posterior cruciate ligament reconstruction on posterior knee translation at the different flexion angles for each testing condition. No statistically significant differences were noted. Results are shown for an intact knee and a deficient knee for comparison. SEM = standard error of the mean. (Reproduced with permission from Bergfeld JA, Graham SM, Parker RD, Valdevit AD, Kambic HE: A biomechanical comparison of posterior cruciate ligament reconstructions using single- and double-bundle tibial inlay techniques. *Am J Sports Med* 2005;33:976-981.)

Figure 10



Lateral fluoroscopic image of a left knee demonstrating inside-out femoral guide pin placement and outside-in femoral guide pin placement in posterior cruciate ligament (PCL) reconstruction. The approximate projected course of the PCL graft is outlined by the white lines. The "inside-out" pin technique significantly increases the critical corner compared with the "outside-in" technique. This may put the graft at increased risk for failure at the femoral tunnel aperture. (Reproduced with permission from Handy MH, Blessey PB, Kline AJ, Miller MD: The graft/tunnel angles in posterior cruciate ligament reconstruction: A cadaveric comparison of two techniques for femoral tunnel placement. *Arthroscopy* 2005;21:711-714.)

fect on the resulting posterior tibial displacement. Anterior femoral tunnel position provided significantly less posterior tibial translation than did the posterior tunnel position. The authors concluded that an anterior femoral tunnel position of the bone tunnels of a double-bundle reconstruction restores normal knee kinematics more closely than does posterior tunnel positioning.

These results are in agreement with the work of Mannor et al,[42] who examined different tunnel positions for double-bundle grafts. These authors combined an anterior ("shallow") AL tunnel position (S1: 5.2 mm from the articular margin) with either a shallow, more distally placed tunnel (S2: 7.1 mm from the articular cartilage margin) or a deeper, more posteriorly placed tunnel (D: 12.5 mm from the articular margin) for the PM tunnel. With the S1-S2 construction, both bundles became taut in flexion, whereas with the S1-D construct, the deep bundle tension was greatest in extension and the S1 bundle tension was greatest in flexion. This deep bundle position more closely resembled the posterior tunnel position of the AL bundle used by Petersen et al.[41] Thus, the load-sharing characteristics of the double-bundle positions were quite similar between the two studies.

The angle at which the graft enters the femoral tunnel may be a factor in graft failure. This is analogous to the killer curve phenomenon associated with the transtibial tunnel. Handy et al[43] critically evaluated the contribution of the femoral tunnel to PCL graft attenuation and failure. They termed the angulation of the graft into the femoral tunnel the "critical corner" (Figure 10). In the study, the authors compared two femoral tunnel placement techniques: the traditional outside-in technique, in which the femoral tunnel is drilled in an antegrade direction starting outside the femur, and the inside-out technique, in which the tunnel is drilled in a retrograde fashion from inside the joint. With the outside-in technique, the PCL guide pin was placed 15 mm from the articular surface at the 11 o'clock position (for a left knee) on the medial femoral condyle. The inside-out technique was performed on the same knee by advancing a guide pin from the inferolateral portal to the same starting point on the femoral cortex as that used in the outside-in technique. As measured radiographically, the average angle of the femoral tunnel aperture (ie, critical corner) in flexion and extension was 50° ± 16° and –14° ± 18° with the outside-in method and 87° ± 8° and 27° ± 14° with the inside-out method, respectively. The authors concluded that the inside-out technique is, at least theoretically, at a biomechanical disadvantage compared with the outside-in technique because it is associated with an increase in graft angulation at the femoral aperture. This increased angulation may contribute to graft attenuation over time. It should be noted, however, that no biomechanical or clinical data support this hypothesis.

Drilling two tunnels in the medial femoral condyle removes additional bone, may interfere with condylar blood supply, and, ultimately, may cause an increased risk of fracture and subchondral collapse. Wiley et al[44] tested this hypothesis using synthetic femoral bone under three test conditions: no tunnel, single anterolateral 10-mm tunnel, and double tunnels (ie, 10-mm anterolateral and 8-mm posteromedial tunnels). The mean load to failure in the double-tunnel group was significantly lower than in the intact group ($P < 0.008$), with a trend toward reduced stiffness of the synthetic bone. As a result of this study, these authors recommended a period of protected weight bearing in the early postoperative period to reduce the risk of fracture in patients undergoing double-bundle reconstruction. To date, no clinical study has specifically evaluated the effect of postoperative rehabilitation on clinical outcome.

Effect of Combined Instability Patterns

Most studies evaluating the PCL-deficient state have been conducted on knees with simulated isolated PCL injuries. However, it is also important to consider the effect of various PCL reconstructive variables on the restoration of knee stability in more than one plane. Research in this area is limited.

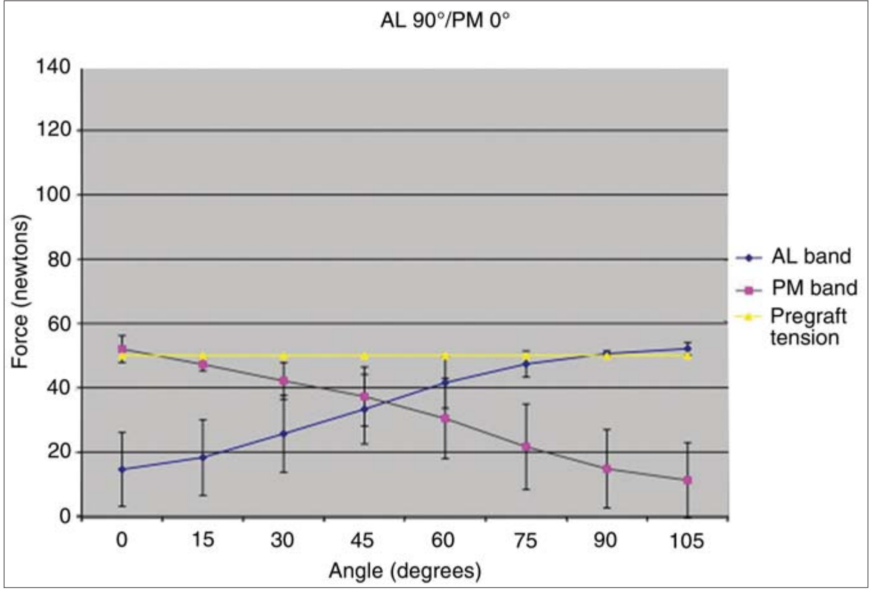
Wiley et al[45] evaluated the kinematic laxity patterns of the knee before and after PCL reconstruction with either a single- or a double-bundle graft following controlled sectioning of the PCL and the PLC. They tested four conditions: intact, combined PCL- and PLC-deficient (ie, release of the fibular collateral ligament, popliteus tendon, posterolateral capsule, and arcuate complex), and PCL-reconstructed using either a single-bundle Achilles tendon replicating the AL bundle or a double-bundle reconstruction using the same graft through both the AL tunnel and the PM tunnel. Both reconstructions were found to restore posterior laxity to normal. The double-bundle technique tended to more closely mimic the intact condition with regard to posterior laxity, with statistically significant differences at 30°, 60°, and 90° of flexion compared with the single-bundle technique ($P < 0.05$). However, a tendency was noted of the double-bundle construct to overconstrain the knee, as evidenced by an anteriorly subluxated tibial resting position compared with normal at ≥30°. Neither construct corrected the abnormal varus or external rotation laxity. These researchers concluded that, following either method of PCL reconstruction, additional PLC reconstruction is necessary with these combined injury patterns to restore normal knee stability.

Whiddon et al[46] evaluated the effect of single-bundle and double-bundle BPTB reconstruction using a tibial inlay fixation technique on posterior tibial translation and on external rotation. Using standard clinical and stress radiographic examinations, these authors found that double-bundle reconstruction offered improved rotational stability and posterior translation in the setting of an untreated PLC injury compared with the single-bundle reconstruction. With the PLC intact, the double-bundle reconstruction overconstrained the knee on external rotation at 30° of flexion, with no further reduction in posterior tibial translation, compared with the single-bundle construct. With PLC deficiency, double-bundle reconstruction permitted significantly less external rotation at 30° compared with the single-bundle technique ($P = 0.03$). Neither reconstruction restored external rotation laxity at 90° of flexion compared with the intact knee. Posterior stress radiographic evaluation demonstrated that only the single-bundle construct in the PLC-deficient state resulted in increased posterior tibial translation compared with the intact knee. Therefore, the double-bundle reconstruction provided increased rotational and posterior control, which was most pronounced in the setting of an untreated PLC injury. Although this "increased stability" at time zero may be beneficial in the clinical setting, the fact is that PCL reconstructive grafts tend to stretch over time, and the overconstraint associated with the double-bundle reconstruction at 30° of flexion may be a risk factor for osteoarthritis.

Graft Forces

Excessive graft forces have been hypothesized to be one factor in suboptimal outcomes in PCL reconstruction. Excessive graft forces during the graft remodeling phase may translate into excessive knee constraint or decreased posterior stability. Oakes et al[47] studied graft forces in cadaveric knees after PCL reconstruction using a single femoral AL bundle reconstructed with both the tibial inlay and the transtibial methods. Load cells were employed to measure intra-articular graft forces as the knees were taken through pas-

Figure 11



Graphic representation of the results of posterior cruciate ligament reconstruction with a double-bundle tibial inlay technique. The anterolateral (AL) bundle was tensioned in 90° of flexion, and the posteromedial (PM) bundle was tensioned in full extension (0°). A symmetric reciprocal force pattern is noted with the AL and PM bundles, and graft tension (50 N) of one limb of the graft is maintained throughout the entire arc of motion. (Reproduced with permission from Carson EW, Deng XH, Allen A, Wickiewicz T, Warren RR: Evaluation of in situ graft forces of a 2-bundle tibial inlay posterior cruciate ligament reconstruction at various flexion angles. *Arthroscopy* 2007;23:488-495.)

sive knee flexion. Graft forces from both techniques were significantly higher than the forces present in the native PCL with the knee flexed >90°. However, there was no difference in graft forces between the inlay-reconstructed and transtibial-reconstructed PCL grafts. The one exception was with passive knee flexion >95°, during which the mean graft forces with the transtibial technique were approximately 10 to 20 N higher than those with the inlay technique. The authors believed that the frictional effects of the killer curve on the graft may account for this difference.

Traditional single-bundle reconstruction techniques have emphasized replacement of the larger AL bundle tensioned with the knee at between 70° and 90° of flexion; however, residual knee laxity has been observed in full extension and during early flexion. To evaluate the effect of differential tensioning of both limbs of a two-bundle graft, Carson et al[48] examined the in situ forces of knees that were reconstructed using two bundles tensioned in different degrees of knee flexion. In eight cadaveric knees, the PCL was reconstructed with a double-bundle inlay technique with equally sized 7-mm BPTB grafts. There were three different tensioning parameters: the AL and PM bundles tensioned at 90°, the AL and PM bundles tensioned at 45°, and differential tensioning of the AL bundle at 90° and PM bundle tensioning at 0°. Differential tensioning of the AL bundle at 90° and the PM bundle at 0° resulted in reciprocal in situ forces similar to those of the native PCL (Figure 11). The other two reconstructive methods, however, produced excessive force in the PM bundle at lower degrees of knee flexion and at full extension.

Markolf et al[49] analyzed PCL graft forces in cadaveric knees to assess the force generated in the femoral end of the graft as a function of the amount of pretension applied directly to the opposite bone plug in the tibial tunnel. This study also sought to determine the amount of pretensioning needed to restore normal anterior-posterior laxity. Cadaveric knees were first tested with their native PCL and then with the PCL reconstructed using a single-bundle BPTB graft through a transtibial tunnel. The mean level of graft pretension needed to restore normal anterior-posterior laxity at 90° of flexion was 43 N. As expected, graft tension increased with progressive knee flexion with nonisometric, anteriorly placed femoral tunnels. The authors concluded that the femoral end of the graft should be tensioned to avoid frictional losses from the severe bend in the graft as it passes over the tibial plateau (ie, killer curve), that correct pretensioning of the graft results in normal anterior-posterior laxity from 0° to 90°, and that nonisometric tunnel placement should be avoided.

Summary

Major advances have been made in the understanding of PCL anatomy, basic science, and biomechanics. These advances are important steps toward the goal of establishing a definitive technique for successful reconstruction of the injured PCL. However, many questions remain unanswered because of several variables, specifically optimal tunnel positioning, graft type, and graft tension. Although improved short-term surgical outcomes following PCL reconstruction have been documented, the data are limited to retrospective, nonrandomized case series without control groups for comparison. This shortcoming, along with biomechanical data that are still emerging, makes it difficult to advocate one particular reconstructive technique. Only with well-designed, long-term, randomized controlled trials that take into account patient comorbidities and activity levels will it be possible to identify the ideal surgical technique for PCL reconstruction.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. Reference 1 is a level I study. References 2, 3, 6, 33, and 35 are level IV case series. The remaining articles are original research.

Citation numbers printed in **bold type** indicate references published within the past 5 years.

1. Shelbourne KD, Davis TJ, Patel DV: The natural history of acute, isolated, nonoperatively treated posterior cruciate ligament injuries: A prospective study. *Am J Sports Med* 1999;27:276-283.

2. Parolie JM, Bergfeld JA: Long-term results of nonoperative treatment of isolated posterior cruciate ligament injuries in the athlete. *Am J Sports Med* 1986;14:35-38.

3. Strobel MJ, Weiler A, Schulz MS, Russe K, Eichhorn HJ: Arthroscopic evaluation of articular cartilage lesions in posterior-cruciate-ligament-deficient knees. *Arthroscopy* 2003;19:262-268.

4. Skyhar MJ, Warren RF, Otiz GJ, Schwartz E, Otis JC: The effects of sectioning of the posterior cruciate ligament and the posterolateral complex on the articular contact pressures within the knee. *J Bone Joint Surg Am* 1993;75:694-699.

5. Harner CD, Vogrin TM, Höher J, Ma CB, Woo SL: Biomechanical analysis of a posterior cruciate ligament reconstruction: Deficiency of the posterolateral structures as a cause of graft failure. *Am J Sports Med* 2000;28:32-39.

6. Noyes F, Barber-Weston S, Grood E: Newer concepts in the treatment of posterior cruciate ligament ruptures, in Insall JN, Scott WN (eds): *Surgery of the Knee*, ed 3. New York, NY: Churchill Livingstone, 2001, pp 841-878.

7. Girgis FG, Marshall JL, Monajem A: The cruciate ligaments of the knee joint: Anatomical, functional and experimental analysis. *Clin Orthop Relat Res* 1975;106:216-231.

8. Harner CD, Xerogeanes JW, Livesay GA, et al: The human posterior cruciate ligament complex: An interdisciplinary study. Ligament morphology and biomechanical evaluation. *Am J Sports Med* 1995;23:736-745.

9. Mejia EA, Noyes FR, Grood ES: Posterior cruciate ligament femoral insertion site characteristics: Importance for reconstructive procedures. *Am J Sports Med* 2002;30:643-651.

10. Makris CA, Georgoulis AD, Papageorgiou CD, Moebius UG, Soucacos PN: Posterior cruciate ligament architecture: Evaluation under microsurgical dissection. *Arthroscopy* 2000;16:627-632.

11. Fuss FK: Anatomy of the cruciate ligaments and their function in extension and flexion of the human knee joint. *Am J Anat* 1989;184:165-176.

12. Lopes OV Jr, Ferretti M, Shen W, Ekdahl M, Smolinksi P, Fu FH: Topography of the femoral attachment of the posterior cruciate ligament. *J Bone Joint Surg Am* 2008;90:249-255.

13. Harner CD, Baek GH, Vogrin TM, Carlin GJ, Kashwaguchi S, Woo SL: Quantitative analysis of human cruciate ligament insertions. *Arthroscopy* 1999;15:741-749.

14. Takahashi M, Matsubara T, Doi M, Suzuki D, Nagano A: Anatomical study of the femoral and tibial insertions of the anterolateral and posteromedial bundles of the human posterior cruciate ligament. *Knee Surg Sports Traumatol Arthrosc* 2006;14:1055-1059.

15. Edwards A, Bull AM, Amis AA: The attachments of the fiber bundles of the posterior cruciate ligament: An anatomic study. *Arthroscopy* 2007;23:284-290.

16. Dargel J, Pohl P, Tzikaras P, Koebke J: Morphometric side-to-side differences in human cruciate ligament insertions. *Surg Radiol Anat* 2006;28:398-402.

17. Moorman CT III, Murphy Zane MS, Bansai S, et al: Tibial insertion of the posterior cruciate ligament: A sagittal plane analysis using gross, histologic, and radiographic methods. *Arthroscopy* 2008;24:269-275.

18. Gupte CM, Smith A, McDermott ID, Bull AM, Thomas RD, Amis AA: Meniscofemoral ligaments revisited: Anatomical study, age correlation and clinical implications. *J Bone Joint Surg Br* 2002;84:846-851.

19. Nagasaki S, Ohkoshi Y, Yamamoto K, Ebata W, Imabuchi R, Nishiike J: The incidence and cross-sectional area of the meniscofemoral ligament. *Am J Sports Med* 2006;34:1345-1350.

20. Butler DL, Noyes FR, Grood ES: Ligamentous restraints to anterior-posterior drawer in the human knee: A biomechanical study. *J Bone Joint Surg Am* 1980;62:259-270.

21. Markolf KL, Feeley BT, Tejwani SG, Martin DE, McAllister DR: Changes in knee laxity and ligament force after sectioning the posteromedial bundle of the posterior cruciate ligament. *Arthroscopy* 2006;22:1100-1106.

22. Race A, Amis AA: PCL reconstruction: In vitro biomechanical comparison of ‘isometric’ versus single and double-bundled ‘anatomic’ grafts. *J Bone Joint Surg Br* 1998;80:173-179.

23. Covey DC, Sapega AA, Sherman GM: Testing for isometry during reconstruction of the posterior cruciate ligament: Anatomic and biomechanical considerations. *Am J Sports Med* 1996;24:740-746.

24. Ahmad CS, Cohen ZA, Levine WN, Gardner TR, Ateshian GA, Mow VC: Codominance of the individual posterior cruciate ligament bundles: An analysis of bundle lengths and orientation. *Am J Sports Med* 2003;31:221-225.

25. Papannagari R, DeFrate LE, Nha KW, et al: Function of posterior cruciate ligament bundles during in vivo knee flexion. *Am J Sports Med* 2007;35:1507-1512.

26. Moran CJ, Poynton AR, Moran R, Brien MO: Analysis of meniscofemoral ligament tension during knee motion. *Arthroscopy* 2006;22:362-366.

27. Sidles JA, Clark JM, Garbini JL: A geometric theory of the equilibrium mechanics of fibers in ligaments and tendons. *J Biomech* 1991;24:943-949.

28. Bergfeld JA, McAllister DR, Parker RD, Valdevit AD, Kambic HE: A biomechanical comparison of posterior cruciate ligament reconstruction techniques. *Am J Sports Med* 2001;29:129-136.

29. Markolf K, Davies M, Zoric B, McAllister D: Effects of bone block position and orientation within the tibial tunnel for posterior cruciate ligament graft reconstructions: A cyclic loading study of bone-patellar tendon-bone allografts. *Am J Sports Med* 2003;31:673-679.

30. Weimann A, Wolfert A, Zantop T, Eggers AK, Raschke M, Petersen W: Reducing the “killer turn” in posterior cruciate ligament reconstruction by fixation level and smoothing the tibial aperture. *Arthroscopy* 2007;23:1104-1111.

31. Margheritini F, Rihn JA, Mauro CS, Stabile KJ, Woo SL, Harner CD: Biomechanics of initial tibial fixation of posterior cruciate ligament reconstruction. *Arthroscopy* 2005;21:1164-1171.

32. Matava MJ, Sethi NS, Totty WG: Proximity of the posterior cruciate ligament insertion to the popliteal artery as a function of the knee flexion angle: Implications for posterior cruciate ligament reconstruction. *Arthroscopy* 2000;16:796-804.

33. Berg EE: Posterior cruciate ligament tibial inlay reconstruction. *Arthroscopy* 1995;11:69-76.

34. Markolf KL, Zemanovic JR, McAllister DR: Cyclic loading of posterior cruciate ligament replacements fixed with tibial tunnel and tibial inlay methods. *J Bone Joint Surg Am* 2002;84:518-524.

35. Wirth CJ, Jager M: Dynamic double tendon replacement of the posterior cruciate ligament. *Am J Sports Med* 1984;12:39-43.

36. Harner CD, Janaushek MA, Kanamori A, Yagi M, Vogrin TM, Woo SL: Biomechanical analysis of a double-bundle posterior cruciate ligament reconstruction. *Am J Sports Med* 2000;28:144-151.

37. Bergfeld JA, Graham SM, Parker RD, Valdevit AD, Kambic HE: A biomechanical comparison of posterior cruciate ligament reconstructions using single- and double-bundle tibial inlay techniques. *Am J Sports Med* 2005;33:976-981.

38. Race A, Amis AA: The mechanical properties of the two bundles of the human posterior cruciate ligament. *J Biomech* 1994;27:13-24.

39. Saddler SC, Noyes FR, Grood ES, Knochenmuss DR, Hefzy MS: Posterior cruciate ligament anatomy and length-tension behavior of PCL surface fibers. *Am J Knee Surg* 1996;9:194-199.

40. Markolf KL, Feeley BT, Jackson SR, McAllister DR: Where should the femoral tunnel of a posterior cruciate ligament reconstruction be placed to best restore anteroposterior laxity and ligament forces? *Am J Sports Med* 2006;34:604-611.

41. Petersen W, Lenschow S, Weimann A, Strobel MJ, Raschke MJ, Zantop T: Importance of femoral tunnel placement in double-bundle posterior cruciate ligament reconstruction: Biomechanical analysis using a robotic/universal force-moment sensor testing system. *Am J Sports Med* 2006;34:456-463.

42. Mannor DA, Shearn JT, Grood ES, Noyes FR, Levy MS: Two-bundle posterior cruciate ligament reconstruction: An in vitro analysis of graft placement and tension. *Am J Sports Med* 2000;28:833-845.

43. Handy MH, Blessey PB, Kline AJ, Miller MD: The graft/tunnel angles in posterior cruciate ligament reconstruction: A cadaveric comparison of two techniques for femoral tunnel placement. *Arthroscopy* 2005;21:711-714.

44. Wiley WB, Owen JR, Pearson SE, Wayne JS, Goradia VK: Medial femoral condyle strength after tunnel placement for single- and double-bundle posterior cruciate ligament reconstruction. *J Knee Surg* 2007;20:223-227.

45. Wiley WB, Akew MJ, Melby A III, Noe DA: Kinematics of the posterior cruciate ligament/posterolateral corner-injured knee after reconstruction by single- and double-bundle intra-articular grafts. *Am J Sports Med* 2006;34:741-748.

46. Whiddon DR, Zehms CT, Miller MD, Quinby JS, Montgomery SL, Sekiya JK: Double compared with single-bundle open inlay posterior cruciate ligament reconstruction in a cadaver model. *J Bone Joint Surg Am* 2008;90:1820-1829.

47. Oakes DA, Markolf KL, McWilliams J, Young CR, McAllister DR: Biomechanical comparison of tibial inlay and tibial tunnel techniques for reconstruction of the posterior cruciate ligament: Analysis of graft forces. *J Bone Joint Surg Am* 2002;84:938-944.

48. Carson EW, Deng XH, Allen A, Wickiewicz T, Warren RR: Evaluation of in situ graft forces of a 2-bundle tibial inlay posterior cruciate ligament reconstruction at various flexion angles. *Arthroscopy* 2007;23:488-495.

49. Markolf KL, Slauterbeck JR, Armstrong KL, Shapiro MS, Finerman GA: A biomechanical study of replacement of the posterior cruciate ligament with a graft: Part I. Isometry, pre-tension of the graft, and anterior-posterior laxity. *J Bone Joint Surg Am* 1997;79:375-380.