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Emerging Updates on the Posterior Cruciate Ligament

A Review of the Current Literature

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The posterior cruciate ligament (PCL) is recognized as an essential stabilizer of the knee. However, the complexity of the ligament has generated controversy about its definitive role and the recommended treatment after injury. A proper understanding of the functional role of the PCL is necessary to minimize residual instability, osteoarthritic progression, and failure of additional concomitant ligament graft reconstructions or meniscal repairs after treatment. Recent anatomic and biomechanical studies have elucidated the surgically relevant quantitative anatomy and confirmed the codominant role of the anterolateral and posteromedial bundles of the PCL. Although nonoperative treatment has historically been the initial treatment of choice for isolated PCL injury, possibly biased by the historically poorer objective outcomes postoperatively compared with anterior cruciate ligament reconstructions, surgical intervention has been increasingly used for isolated and combined PCL injuries. Recent studies have more clearly elucidated the biomechanical and clinical effects after PCL tears and resultant treatments. This article presents a thorough review of updates on the clinically relevant anatomy, epidemiology, biomechanical function, diagnosis, and current treatments for the PCL, with an emphasis on the emerging clinical and biomechanical evidence regarding each of the treatment choices for PCL reconstruction surgery. It is recommended that future outcomes studies use PCL stress radiographs to determine objective outcomes and that evidence level 1 and 2 studies be performed to assess outcomes between transtibial and tibial inlay reconstructions and also between single- and double-bundle PCL reconstructions.

Keywords: knee; posterior cruciate ligament; anatomy; posterior translation; stress radiographs; double bundle

The understanding of posterior cruciate ligament (PCL) anatomy, epidemiology, biomechanics, clinical diagnosis, and treatment methods arising from recent investigations is evolving. Therefore, a thorough consideration of the available knowledge is essential in clinical decision making for patients with PCL injury. Recent studies on the clinically relevant anatomy and biomechanical function of the PCL and its individual bundles have greatly elucidated its overall functional role and provided new perspectives on both nonoperative and operative treatment of PCL injuries.

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CLINICALLY RELEVANT ANATOMY

The PCL is composed of 2 bundles, the larger anterolateral bundle (ALB) and the smaller posteromedial bundle (PMB), which are most readily identified at their femoral locations.[4,17,45,70] However, at their tibial attachment to the PCL facet, the bundles are more compact and difficult to separate.[4,17] The distances between the centers of the femoral and tibial attachments of the 2 bundles are 12.1 and 8.9 mm, respectively.[4] The increased distance between the femoral attachments and the differences in bony attachments have implications for PCL reconstruction techniques, further explained later in this work. The femoral and tibial attachments of both bundles have been qualitatively and quantitatively defined, as described below.[4,17,45,70,88,93,117]

The Anterolateral Bundle

The size of the femoral attachment of the ALB is nearly twice the size of its tibial attachment and has been reported to range from 112 to 118 mm^2 in area.[4,70] The surgically relevant landmarks of the ALB have been quantified in reference to several arthroscopic[4,70] and radiographic reference points[45,93] on the femur. With regard to arthroscopic reference points, the center of the

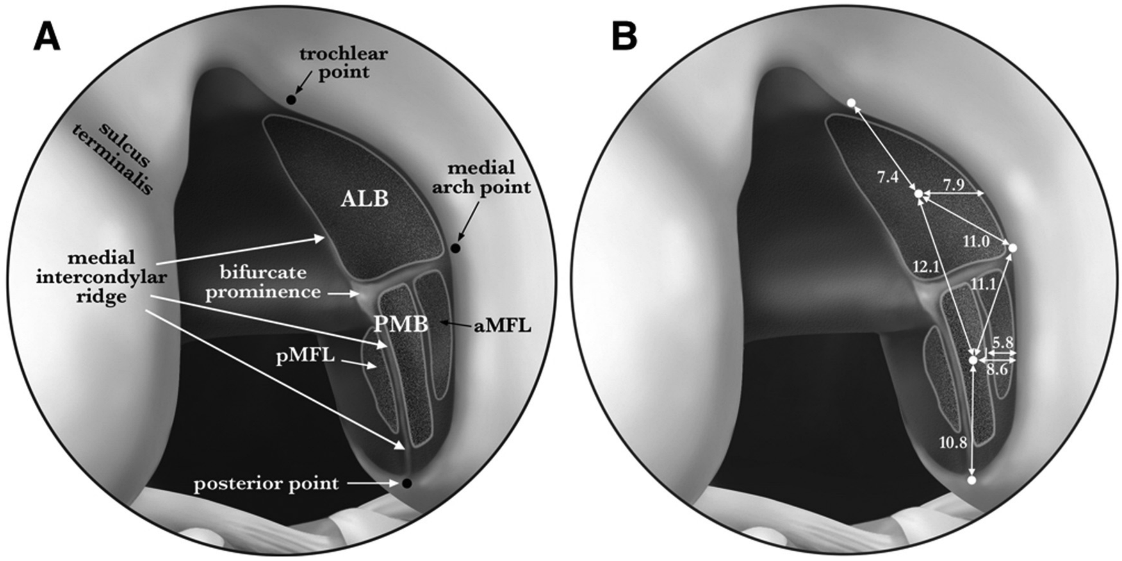

Figure 1. (A) Arthroscopic view of the femoral attachment of the posterior cruciate ligament (PCL) in a right knee, demonstrating pertinent landmarks. (B) Quantitative measurements for the femoral attachment of the PCL. The values are reported in millimeters. ALB, anterolateral bundle; aMFL, anterior meniscofemoral ligament; PMB, posteromedial bundle; pMFL, posterior meniscofemoral ligament. (Reproduced with permission from Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94:1936-1945.)

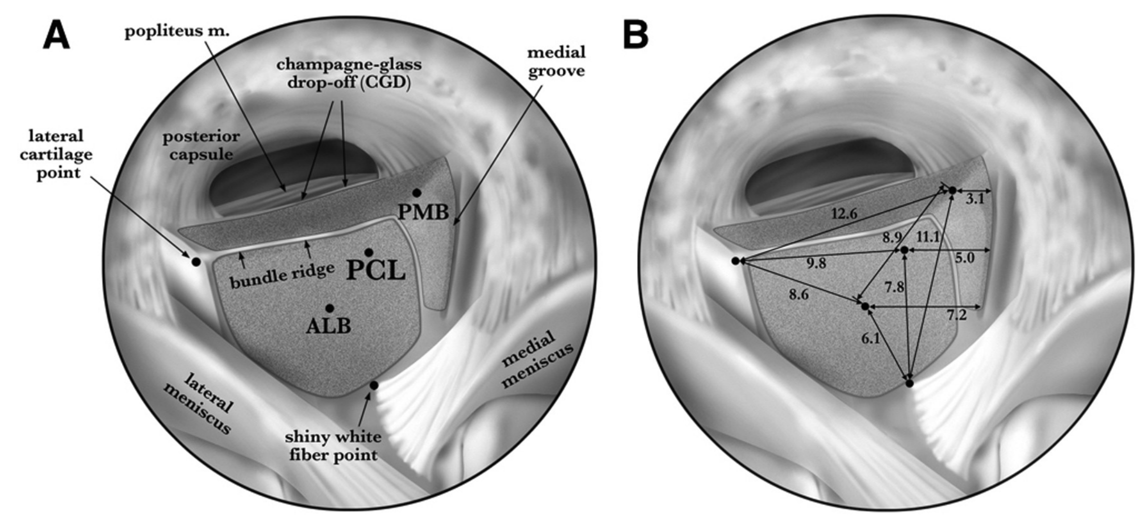

Figure 2. (A) Arthroscopic view of the tibial attachment of the posterior cruciate ligament (PCL) of a right knee, demonstrating the pertinent landmarks. (B) Quantitative measurements for the tibial attachment of the PCL. The values are reported in millimeters. ALB, anterolateral bundle; PMB, posteromedial bundle; m, muscle. (Reproduced with permission from Anderson CJ, Ziegler CG, Wijdicks CA, Engebretsen L, LaPrade RF. Arthroscopically pertinent anatomy of the anterolateral and posteromedial bundles of the posterior cruciate ligament. *J Bone Joint Surg Am*. 2012;94:1936-1945.)

ALB has been described as 7.4 mm from the trochlear point, 11.0 mm from the medial arch point, and 7.9 mm from the distal articular cartilage (Figure 1).[4]

Anderson et al[4] reported that the tibial attachment area of the ALB was 88 mm^2 and that it was bordered medially and posteriorly by the PMB. A horizontal bony prominence, called the bundle ridge, separates the ALB from the PMB.[4] In relation to important arthroscopic reference points, the center of the ALB tibial attachment site is located 6.1 mm from the shiny white fibers of the posterior medial meniscus root, 4.9 mm from the bundle ridge, and 10.7 mm from the champagne glass drop-off (Figure 2).[4]

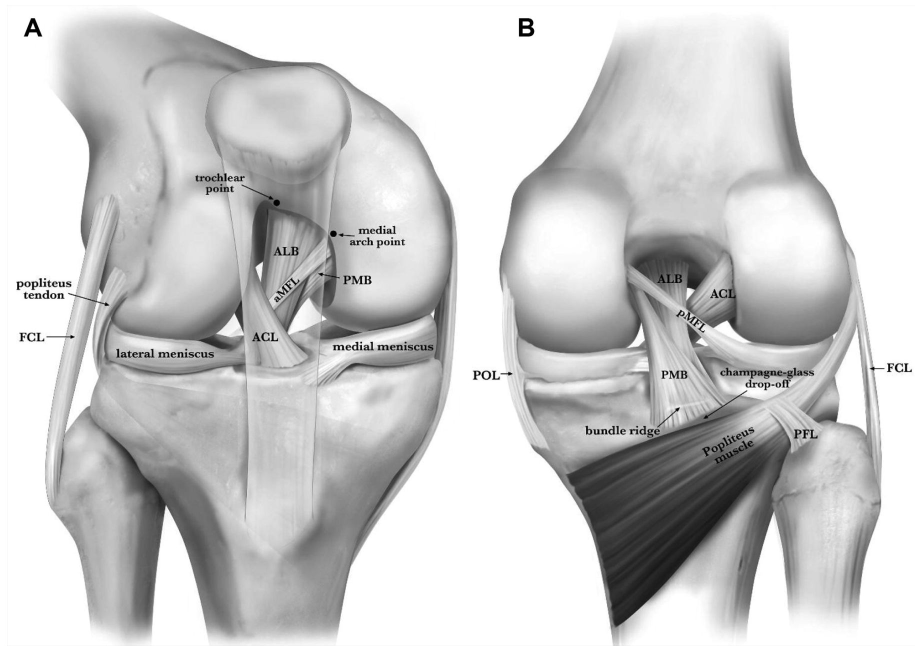

Figure 3. (A) Anterior and (B) posterior views of the native posterior cruciate ligament (PCL). Emphasized are the femoral and tibial attachments of the anterolateral bundle (ALB) and posteromedial bundle (PMB) of the PCL and the osseous landmarks: the trochlear point, the medial arch point, the bundle ridge, and the champagne-glass drop-off. ACL, anterior cruciate ligament; aMFL, anterior meniscofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament. (Reproduced with permission from Kennedy NI, Wijdicks CA, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 1: the individual and collective function of the anterolateral and posteromedial bundles. *Am J Sports Med*. 2013;41(12):2828-2838.)

The Posteromedial Bundle

The femoral attachment of the PMB has been reported to range from 60 to 90 mm^2 in area.[4,70] Anderson et al[4] qualitatively described the PMB as being bordered by the medial intercondylar ridge proximally, the ALB anteriorly, and the anterior meniscofemoral ligament (aMFL), when present, distally. In reference to clinically relevant arthroscopic landmarks, the center of the PMB femoral attachment was 11.1 mm from the medial arch point and 10.8 mm from the posterior point of the articular cartilage margin (Figure 1).[4]

The tibial attachment of the PMB has an area of approximately 105 mm^2 and is more compact than the ALB.[4] The PMB fans out in its attachment border along the posteromedial aspect of the ALB, and thus it is sometimes described as having “2 arms.”[4] The thickest portion of the PMB, including the functional center of the bundle, is located posteromedial to the ALB. Quantitatively, the functional center of the PMB was found to be 3.1 mm lateral from the medial groove of the medial tibial plateau articular surface and 4.4 mm anterior to the champagne glass drop-off (Figure 2).[4]

The Meniscofemoral Ligaments

The meniscofemoral ligaments (MFLs) are intimately associated with the bundles of the PCL (Figure 3). The aMFL, also known as the ligament of Humphrey, and the posterior MFL (pMFL), or ligament of Wrisberg, have been reported to be present in 74%-75% and 59%-80% of knees, respectively.[3,4,33,117] The aMFL has a femoral attachment area of 35 mm^2 and a distal attachment that combines with the posterior horn of the lateral meniscus.[3,4] Its femoral attachment has been reported to be variable, with 80% of specimens attaching distally to the PMB and the remaining 20% attaching distally to the ALB.[4] The pMFL has a similar femoral attachment area of 31 mm^2 and is located proximal to the medial intercondylar ridge and PMB.[4] The pMFL also attaches distally to the posterior horn of the lateral meniscus.[3]

CLINICALLY RELEVANT BIOMECHANICS

Native Biomechanics

Classically, the 2 bundles of the PCL were believed to function independently, with the ALB primarily functioning in flexion and the PMB in extension.[28,120] However, in light of recent biomechanical investigations, a more synergistic and codominant relationship between the 2 bundles has been validated.[1,36,53,95] Ahmad et al[1] investigated the spatial orientation of the PCL bundles and reported that changes in the orientation of each bundle during knee flexion and extension prevented either bundle from exercising complete dominance in the restraint of posterior tibial motion. Papannagari et al[95] also found that the 2 bundles did not act in a reciprocal fashion in an in vivo analysis.

The PCL has historically been considered a primary restraint to posterior tibial translation, and more recent studies have also identified it as a secondary restraint to rotation, particularly between 90° and 120° of flexion.[§] A recent robotic study by Kennedy et al[53] further explored the role of each individual bundle in providing stability to the knee and ensuring proper function. The investigators reported that each bundle had a small but significant primary role in resisting posterior tibial rotation, and they revealed a codominant relationship between the ALB and PMB throughout a full range of flexion (0°-120°) (Figure 4).[53]

Complete sectioning of the PCL has reportedly led to a significant increase in posterior tibial translation at 0° to 120° of flexion and an increase in internal rotation at 90° to 120° of flexion.[53] Thus, the magnitude of abnormal translation and rotation appears to depend on whether one or both of the bundles are injured. Markolf et al[79] reported a maximal overall increase in posterior tibial translation for isolated PMB sectioning of 1.06 mm at 0° with no measureable increase at 90°. Kennedy et al[53] reported that at 90° of flexion, there was an increase from the intact state in posterior tibial translation of 0.9 mm with isolated sectioning of the PMB and 2.6 mm with isolated sectioning of the ALB. Complete sectioning of both bundles resulted in significantly more posterior tibial translation throughout 0° to 120° of flexion compared with the sectioning of each individual bundle and an increase of 11.7 mm at 90°.[53] Similarly, Harner et al[36] found that complete PCL deficiency resulted in an increase of 11.4 mm of posterior tibial translation at 90° of flexion. Thus, it is clear that an isolated tear of either PCL bundle results in a minimal clinically important increase in posterior tibial translation.

Aside from providing restraint to posterior tibial translation, the PCL is reported to have a considerable role in providing rotational stability to the knee. Previous in vitro biomechanical studies reported a significant increase in external rotation after PCL resection under an applied posterior tibial load.[27,67] As a result, more recent studies identified external and internal rotation examinations as important tests for analyzing PCL kinematics in a more comprehensive manner.[50,51,53,126] A sectioned PCL resulted in significantly increased external rotation and internal rotation when subjected to external and internal rotation torques.[53] Assessment of PCL deficiency in vivo has demonstrated a change in internal rotation during quasi-static weightbearing flexion; however, these changes were not significant.[68] Generally, the literature supports that the PCL has a more expansive role in providing rotational stability than previously thought, and it is important to assess internal and external rotation stability when considering PCL injury.

§References 27, 29, 36, 53, 67, 76, 79, 83, 100, 121.

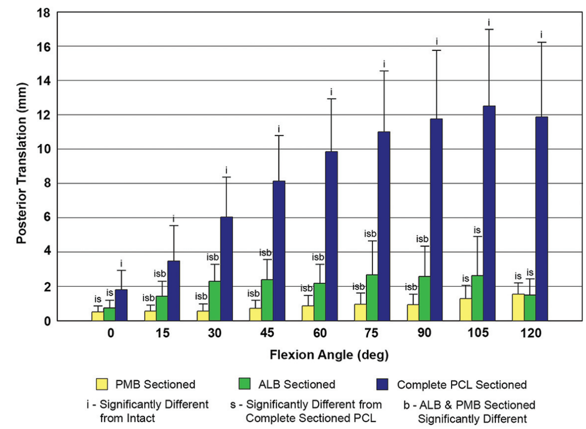

Figure 4. Changes in posterior translation after isolated sectioning of the anterolateral bundle (ALB), isolated sectioning of the posteromedial bundle (PMB), and complete sectioning of the posterior cruciate ligament (PCL). Data are reported as mean increases of posterior translation compared with the intact PCL knee in response to a 134-N posterior tibial force. (Reproduced with permission from Kennedy NI, Wijdicks CA, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 1: the individual and collective function of the anterolateral and posteromedial bundles. *Am J Sports Med*. 2013;41(12):2828-2838.)

With regard to the forces present within each bundle, the literature is conflicting. Fox et al[24] reported that the in situ forces increased in the ALB and PMB as flexion angle increased during applied posterior tibial loads. Contrastingly, Harner et al[36] found that the PMB graft of a double-bundle reconstruction experienced its largest in situ force at 30° of flexion. However, both studies used the principle of superposition to determine the in situ forces of each bundle/graft, which requires that the response given by each individual bundle be independent of the others. Therefore, given that the postulation of bundle interdependence has been validated, it may no longer be valid to use the principle of superposition when determining precise individual PCL bundle forces. Kennedy et al[51] recently addressed this concern by measuring direct ALB and PMB graft forces during an analysis of graft fixation angles in double-bundle reconstructions. The investigators reported that ALB graft force peaked during midflexion and that the PMB graft force peaked at both full extension and deep flexion during a posterior tibial load from 0° to 120° of knee flexion, thus confirming a codominant relationship.[51]

Biomechanical Comparisons Between Single- and Double-Bundle PCLR

Biomechanical investigations comparing the kinematics and graft forces of single-bundle and double-bundle PCL reconstructions have suggested improved stability after a double-bundle PCL reconstruction compared with a single-bundle PCL procedure.[36,126] Moreover, a double-

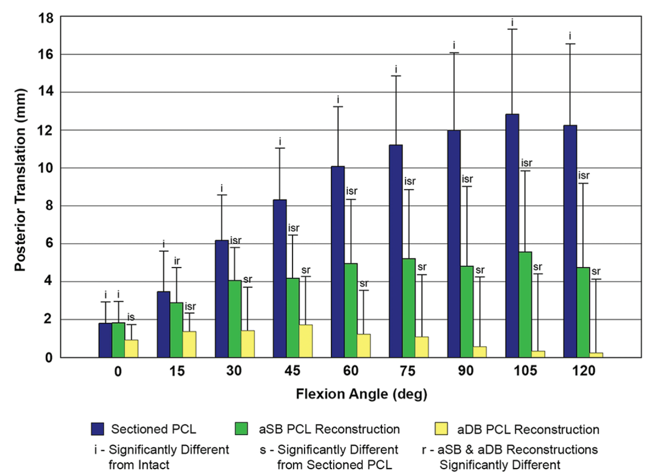

Figure 5. Changes in posterior translation after complete posterior cruciate ligament (PCL) sectioning, anatomic single-bundle (aSB) PCL reconstruction, and anatomic double-bundle (aDB) PCL reconstruction. Data are reported as average increases in posterior translation compared with the intact PCL knee in response to a 134-N posterior tibial force. (Reproduced with permission from Wijdicks CA, Kennedy NI, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. *Am J Sports Med*. 2013;41(12):2839-2848.)

bundle PCL reconstruction has been reported to decrease posterior tibial translation under a 134-N posterior tibial load compared with a sectioned PCL and single-bundle reconstruction.[36,126] Comparing operated knees with intact knees, Wijdicks et al[126] reported that a residual laxity of 4.8 mm at 90° existed for a single-bundle reconstruction whereas only 0.6 mm of increased laxity was observed at 90° of flexion for a double-bundle reconstruction (Figure 5). A similar decrease in the amount of residual laxity for the double-bundle PCL reconstruction was observed for internal and external rotation.[126]

In contrast, findings by Markolf et al[80] suggested that a double-bundle reconstruction overconstrained the knee and exposed the grafts to increased forces. However, the investigators' surgical technique used only 1 tensioning protocol for the grafts with the ALB graft fixed at 90° and the PMB graft at 30°. Kennedy et al[51] recently explored the effects of multiple graft fixation angles for double-bundle PCL reconstructions and reported that fixing the PMB graft at 15° versus 0° resulted in significantly increased forces within the PMB graft. Therefore, it is probable that the overconstraint observed by Markolf et al could be attributed to the 30° fixation angle used for the PMB graft.

The angles at which the grafts are fixed are recognized factors in the residual laxity in both single- and double-bundle PCL reconstructions. Multiple studies have reported that fixing a single-bundle graft at 90° provides the best opportunity to restore knee kinematics and in situ forces.[37,81,97] However, fixation at different angles within the reported range of 75° to 105° has been demonstrated to result in comparable kinematic improvements.[50] With regard to a double-bundle reconstruction, it has been reported that the PMB graft should be fixed at 0° and the ALB graft at 90° or 105° to avoid graft overconstraint.[51] Future studies are needed to evaluate whether these findings translate to clinical success.

EPIDEMIOLOGY AND PATHOGENESIS

Posterior cruciate ligament injury, which rarely exists in isolation, typically presents concurrently with other knee injuries, including anterior cruciate ligament (ACL), medial collateral ligament (MCL), or posterolateral corner (PLC) injury. Recent studies have helped to clarify and elucidate the prevalence of concurrent ligament injuries with a complete (grade III) PCL tear. A majority of grade III PCL tears are associated with multiligament knee injuries, with one study reporting that 79% of multiligament knee injuries involved the PCL in a trauma setting.[6] Furthermore, 46%, 31%, and 62% of PCL injuries have been reported to be concomitant with ACL, MCL, and PLC knee injury in a trauma setting, respectively.[21] These numbers are similar to the findings of Spiridonov et al,[113] who described concomitant procedures with PCL reconstructions, although it should be noted that isolated PCL reconstructions represented 18% of patients in their patient cohort.

The most common PCL injury originates from sports or trauma, specifically motor vehicle or road traffic accidents.[5,21,116] Injury to the PCL has been reported to account for 2% of all American high school knee injuries.[116] In addition, trauma from traffic accidents has been reported to be the cause of 57% of PCL tears at a trauma center.[21] Last, males have been reported to more commonly experience a PCL injury, with studies describing considerably higher rates (range, 73%-97%) of PCL injuries, whether isolated or combined.[5,21,113]

DIAGNOSIS

Obtaining a diagnosis in differentiating between an isolated versus a combined PCL tear is essential for long-term knee health and stability. However, even with a correct diagnosis of a PCL tear, confusion can exist and be further compounded by supplemental ligamentous injury.[64] As a result, it is imperative to acquire a thorough patient history, conduct a comprehensive physical examination, and use applicable imaging techniques to properly identify PCL tears and other concurrently torn knee structures that permit targeted treatment of patients with either an acute or a chronic PCL tear.

Patient History

A comprehensive patient history is vital for the diagnosis of an isolated or combined PCL injury. Whereas a patient with an ACL or MCL injury often describes the feel of a distinct "pop" or "tear," PCL tears typically have vague

TABLE 1
Sensitivity and Specificity of Different Physical Examination Techniques for Isolated Posterior Cruciate Ligament Injuries[a]

Technique	Sensitivity	Specificity
Posterior drawer	0.22-1.00	0.98
Posterior sag	0.46-1.00	1.00
Quadriceps active	0.53-0.98	0.96-1.00
Supplemental tests		
External rotation recurvatum test	0.22-0.39	0.98
Reverse pivot-shift test	0.19-0.26	0.95
Varus-valgus at 0°	0.28-0.94	1.00
Varus at 30°	0.00-0.17	No data
Valgus at 30°	0.20-0.78	No data
Dial test	No Data	No data

[a]Adapted from Kopkow et al.[59]

symptoms such as unsteadiness or discomfort.[75] A patient with an acute isolated PCL injury may have a mild to moderate effusion, pain in the posterior aspect of the knee, or pain with kneeling. In a case of subacute or chronic PCL injury, the patient may describe vague anterior knee pain, pain with deceleration and descending inclines or stairs, or pain with running at full stride.[75]

Physical Examination

Several physical examinations, such as the posterior sag sign, quadriceps active test, and posterior drawer test, can help to diagnose PCL tears (Table 1).[59] Clinicians use the posterior sag sign to assess posterior tibial translation by placing the patient in a supine position on an examination table with both knees flexed to 90°, hips flexed to 45°, and feet resting on the table. If the PCL is torn, an abnormal contour or sag may be evident at the proximal anterior tibia when viewed from a lateral position,[102] especially in comparison with the normal contralateral knee (Figure 6).[72] The quadriceps active test is performed with the knee placed in 90° of flexion and the foot held in place against the examination table. The patient attempts to slide the fixed foot anteriorly along the table, inducing a quadriceps contraction, which causes a sagging or posteriorly subluxated tibia to be drawn anteriorly. If the tibia shifts anteriorly by at least 2 mm, the test is considered indicative of a PCL tear.[15] Last, the posterior drawer test is performed with the patient positioned supine and the knee flexed to 90°. The examiner applies a posterior tibial load to the injured knee and notes the resultant posterior translation compared with the uninjured contralateral knee (Figure 7).[41] A valid concern of the posterior drawer test is that it provides only a subjective assessment of increases in posterior tibial translation, and the degree of translation assessed varies among clinicians.[59]

As previously noted, the PCL is often torn with a concomitant injury to the MCL or PLC. Therefore, it is recommended to incorporate supplemental physical examination

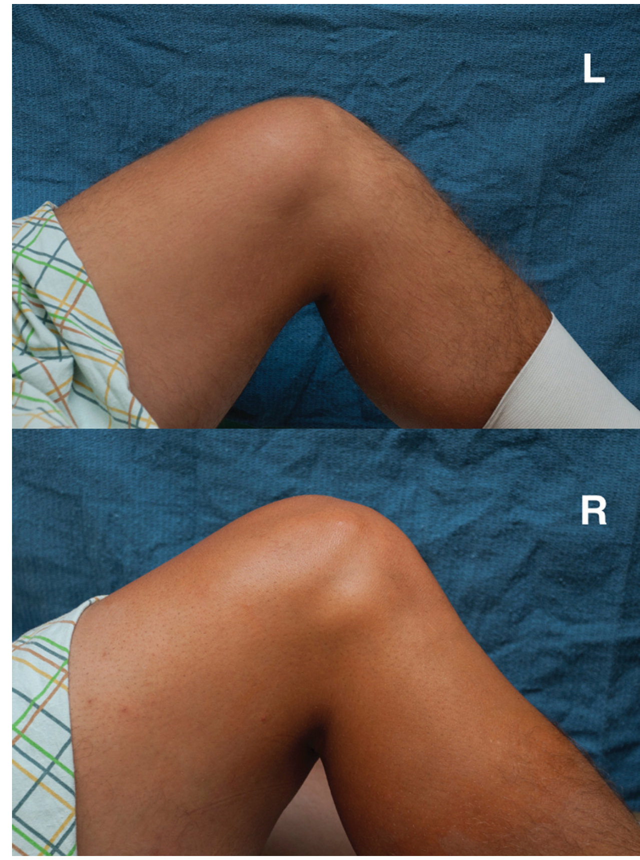

Figure 6. Sag sign examination reveals a noticeable difference in tibial plateau posterior translation between the uninjured left (L) and injured right (R) knee.

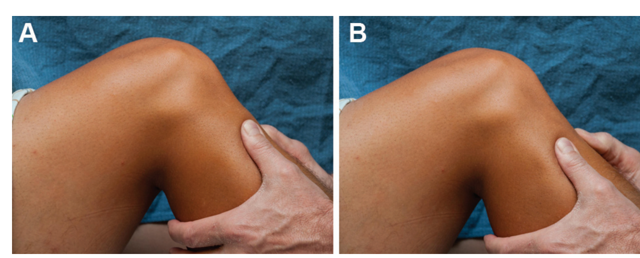

Figure 7. The reduced starting position for the posterior drawer test (A) in comparison to the posteriorly translated tibia (B).

procedures that are indicative of associated MCL or PLC injuries whenever a PCL injury is suspected. Particularly, the valgus and varus stress tests at full extension and in 30° of flexion are useful. The valgus stress test determines gapping in the medial joint line with an applied valgus force, while the varus stress test determines gapping in the lateral joint line with an applied varus force.[72] The anteromedial and posterolateral drawer tests are also useful to assess for the presence of posteromedial or posterolateral structure injury.[63,125] A positive reverse pivot-shift test, as indicated by the available palpation of the posterolateral subluxation of the tibia, may be another useful examination for determining a combined PCL injury.[63] Although the dial test has been questioned regarding its clinical diagnostic accuracy,[59] it has been biomechanically validated for the assessment of the amount of medial and posterolateral knee injury.[30,31,121] The external rotation recurvatum test[61,72] may indicate a combined PLC plus ACL or PCL injury.[122] Last, the patient's gait should be examined for a varus thrust, which may indicate a combined PLC injury.

Imaging of PCL Injuries

When available, multiple imaging modalities should be incorporated to supplement the patient history and physical examination. In addition to plain radiographs, the use of fluoroscopy, PCL stress radiographs, and magnetic resonance imaging (MRI) should be explored. New advances in imaging modalities can provide more detailed information into injury and help guide decision making for treatment options.

Radiographs and Intraoperative Fluoroscopy. Plain radiographs are advocated when one is examining the presence of avulsion fracture fragments, Segond fractures, fibular head avulsions, and lateral joint space widening.[34,85,111] Any perceptible degree of posterior tibial sag should be documented. It is important to note that reduction of the knee in the clinical setting does not preclude the joint from a previous dislocation.[35]

Because of the relative difficulty in arthroscopic visualization of the posterior tibial attachment of the PCL, the use of intraoperative fluoroscopy (Figure 8) or radiographs has been strongly advocated. The senior author (R.F.L.) prefers fluoroscopy, because intraoperatively, true anteroposterior and lateral views can be obtained more reliably than on plain radiographs and because rotation on any view can result in misinterpretation of intraoperative guide pin positioning. Recently, Johannsen et al[45] defined the clinically relevant radiographic landmarks for the overall PCL and its individual bundles. On lateral radiographs, the overall PCL attachment center was 5.5 mm proximal to the champagne glass drop-off of the posterior tibia.[45] In reference to anteroposterior radiographic landmarks, Johannsen et al[45] reported that the center of the PCL tibial attachment was 1.6 mm distal to the proximal tibial joint line.

PCL Stress Radiographs. The use of stress radiographs to diagnose PCL injuries has been increasingly advocated because of their ability to provide a reproducible objective assessment of the degree of posterior tibial translation between the injured and normal contralateral knee.[40,46,75,113,114] Several techniques have been described to deliver a posteriorly directed force during stress radiography, including active hamstring contraction,[75] gravity assistance,[115] the Telos device (Austin and Associates), and single-leg kneeling.[71] Particularly, the Telos device and the single-leg kneeling technique have been characterized as reliable diagnostic methods.[42,105] While both methods have been reported to be similar in objectively evaluating increased posterior tibial translation for a PCL tear, the kneeling technique (Figure 9) has been reported to provide a more cost-effective, accessible, and faster approach to identifying posterior knee instability.[42,46,53,91] Any of the aforementioned techniques can be used to compare the amount of increased side-to-side posterior tibial translation of the injured versus the uninjured knee. It has been reported that partial PCL tears result in <8 mm of increased posterior tibial translation, isolated complete PCL tears in 8-12 mm, and combined complete PCL tears (usually with a PLC injury) in >12 mm.[77,106,107]

Figure 8. Fluoroscopic lateral image of transtibial tunnel guide pin placement at the posterior aspect of the tibia.

Magnetic Resonance Imaging

Magnetic resonance imaging techniques have proven to be very accurate for diagnosing acute PCL tears, with reported sensitivity values of 100% and reported specificity values of 97% to 100%.[22,32,39,60,99] The normal appearance of a PCL is a well-defined continuous band of low signal intensity in all pulse sequences with a maximum anteroposterior diameter of 6 mm when measured on sagittal T2-weighted images.[103] Conversely, a torn PCL (Figure 10) has been reported to have an abnormally large (>7 mm) anteroposterior diameter.[103] This anteroposterior diameter has also been reported to be the most important criterion among the sonographic findings of a torn PCL.[12] However, in patients with chronic PCL injuries, it is possible for the healing process to mask the extent of the deficiency upon MRI examination. In these cases, stress radiographs provide a more objective means to assess the structural integrity of the PCL.[42,46,105] In addition, Mair et al[74] reported that PCL injury, without ACL injury, commonly resulted in bone bruising to the medial or lateral compartments of the knee. In particular, bone bruises in the medial compartment were significantly more often

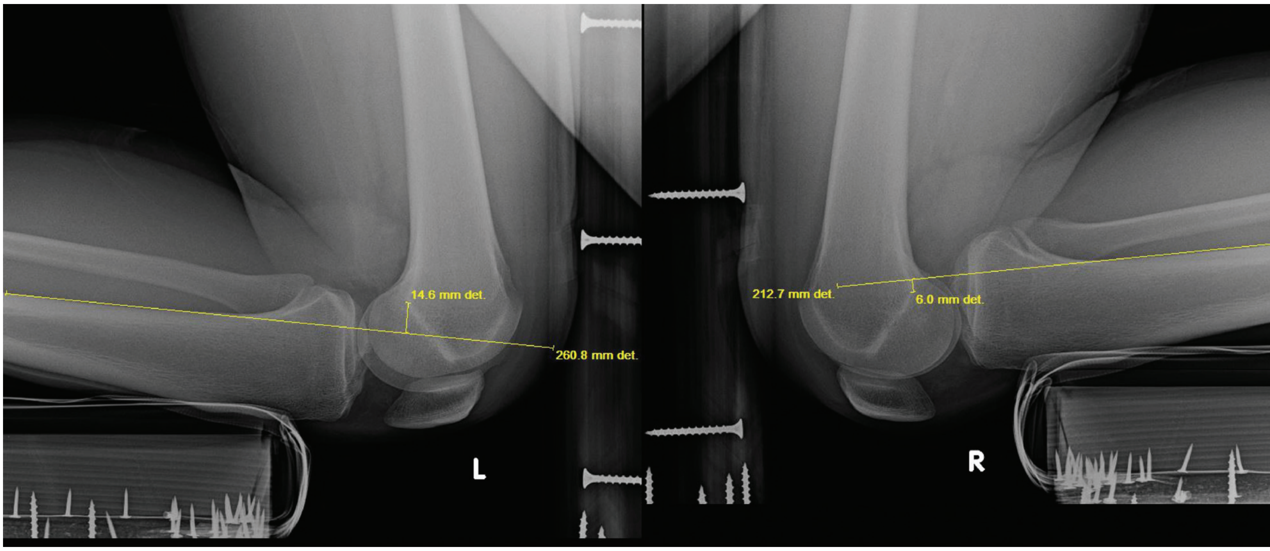

Figure 9. Lateral kneeling stress radiographs that demonstrate 20.6 mm of increased posterior tibial translation between the uninjured knee (L) and injured knee (R).

associated with a PCL-PLC combined injury, while lateral compartment bone bruises were significantly more often associated with a concomitant PCL-MCL injury.[74]

Indications for PCL Reconstruction

The indications for a PCL reconstruction vary depending upon whether the injury is acute or chronic.[35,113] For acute injuries, a PCL tear in conjunction with a knee dislocation, or with a PCL stress radiograph that indicates anteroposterior laxity $\geq$12 mm, is indicative of a probable combined PCL injury. Complete PCL tears, as indicated by PCL stress radiographs with an increased anteroposterior laxity measurement of $\geq$8 mm, combined with repairable meniscal body or root tears are a possible indication for PCL reconstruction.[4,77,101,106,107] Regarding chronic PCL injury, possible indications for reconstruction include functional limitations due to the PCL tear (eg, difficulty with deceleration, incline descent, or stairs), PCL stress radiographic anteroposterior laxity $\geq$8 mm, and absence of contraindications to a ligament reconstruction (eg, arthritis, vascular or skin compromise).[87]

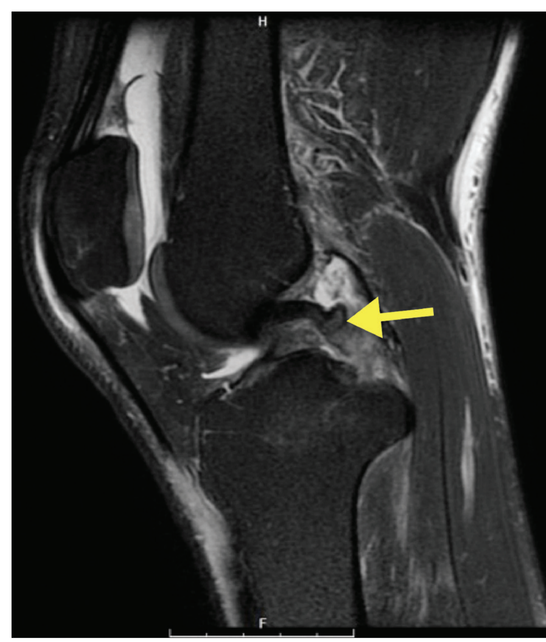

Figure 10. Sagittal magnetic resonance image of posterior cruciate ligament (PCL) tear (arrow denotes torn PCL off the tibia).

TREATMENT

Nonoperative Management

The PCL has been reported to have an intrinsic healing ability after injury, although this healing may occur in a lax or attenuated position.[43,110,118] Therefore, in cases of acute isolated PCL injury, nonoperative management has been described.[43,96,109] However, acute multiligament knee injuries with a concomitant or chronic PCL tear are believed to be best treated by surgery.[48,109,119] The use of a brace intended to protect the PCL, specifically one that applies a constant or dynamic anterior force to counteract the posterior sag of the tibia, may help to increase healing after PCL injury by reducing the ligament to a more physiological position.[43,44,62]

Clinical Evidence of Nonoperative Management

Clinical reports on outcomes after nonoperative treatment of PCL tears have been limited and vary between isolated and combined PCL tear treatment. Torg et al[119] reported

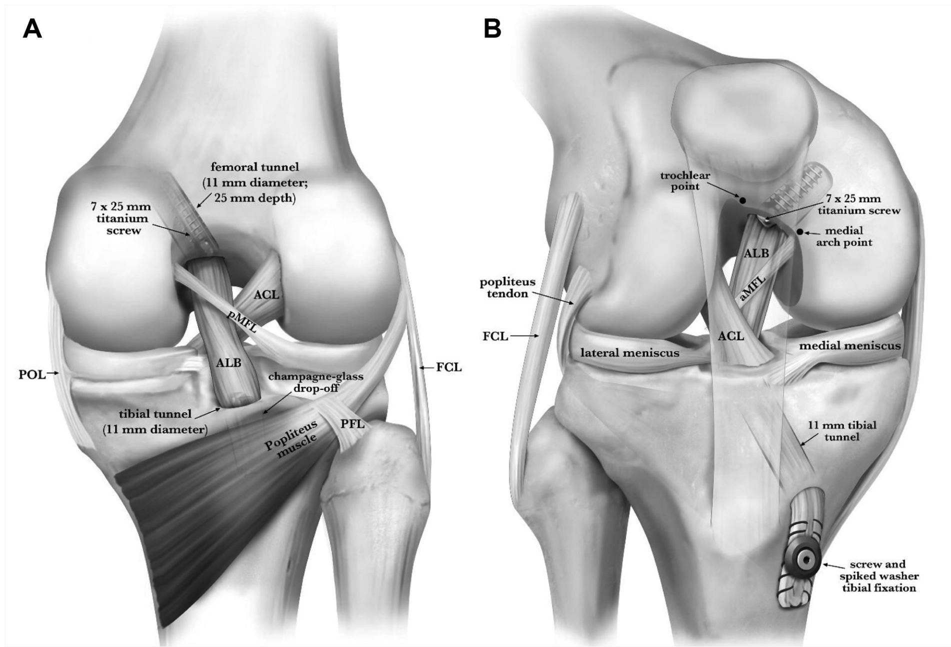

Figure 11. (A) Posterior and (B) anterior views of the anatomic single-bundle (aSB) posterior cruciate ligament reconstruction. Reconstructed anterolateral bundle (ALB) shows the location, size, and shape of the femoral and tibial tunnels. The champagne glass drop-off is the anatomic landmark for drilling of the tibial tunnel. ACL, anterior cruciate ligament; aMFL, anterior meniscofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament. (Reproduced with permission from Wijdicks CA, Kennedy NI, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. *Am J Sports Med*. 2013;41(12):2839-2848.)

that isolated PCL tears responded favorably to nonoperative treatment at a follow-up of 5.7 years; however, the investigators reported that PCL injury with associated ligament tears resulted in significantly higher incidences of fair or poor functional outcomes and osteoarthritic progression.

In general, more recent nonoperative treatment studies have focused on isolated PCL injuries.[43,48,96,109,110,118] Good subjective functional scores and a healed appearance of the PCL on MRI have been reported at short-term follow-up (1.7 and 2.6 years) after isolated PCL injury, but less than satisfactory objective scores were noted.[23,118] As a result, these authors concluded that the PCL treated nonoperatively healed in an attenuated fashion, which led to the decreased objective outcomes.[23,118] Others have described an increased radiographic progression of osteoarthritis and decreased functional outcomes as the time from injury increased for isolated PCL tears treated nonoperatively.[48,109] Investigators who evaluated isolated PCL tears that were treated with nonoperative rehabilitation programs reported radiographic evidence of arthritic changes in 23% of patients at 7-year follow-up[96] and 41% at 14-year follow-up.[109] However, only a small percentage of the patients in the long-term follow-up had moderate or severe osteoarthritis (11%), and the majority of patients had good strength and subjective outcome scores, although stress radiographs were not reported.[109] Last, Jacobi et al[43] reported that the use of a dynamic PCL brace for 4 months after an isolated acute PCL tear significantly reduced the initial posterior sag (7.1 mm) at 12 and 24 months (2.3 and 3.2 mm, respectively) and restored PCL continuity on MRI in 95% of patients at 6 months, although clinically insignificant decreases in Lysholm scores were reported at 12 and 24 months (from 98 preoperatively to 94 at both follow-ups).[43]

Single-Bundle PCL Reconstruction Techniques

Single-bundle PCL reconstruction is typically indicated for symptomatic chronic PCL injuries, either in isolation or combined with other knee ligamentous injury, and for acute, multiligament PCL injuries.[16,56,57] Recent efforts have focused on an anatomic single-bundle reconstruction using arthroscopic and radiographic reference points[4,45] instead of the historical nonanatomic "isometric" reconstruction that has been reported to result in initial joint overconstraint and increased laxity over time.[25,101,126] Two variations in tibial graft fixation for anatomic single-bundle PCL reconstruction have been reported: the transtibial tunnel and tibial inlay techniques.[8,38,73,94,126] The transtibial single-bundle PCL reconstruction (Figure 11) usually involves reconstructing the larger ALB by centering the femoral and tibial reconstruction tunnels on the native ALB footprint.[4,38,54,78,126] A reported concern of the transtibial technique is the "killer turn," which has been described as the sharp angle that a PCL graft forms at the proximal aperture of the tibial tunnel; biomechanical studies have reported that this angle causes a patellar tendon PCL graft to undergo abrasion, attenuation, and increased failure during a cyclic loading protocol.[8,9,82] Therefore, the single-bundle tibial inlay technique has been proposed and used as either an open or an arthroscopic alternative to the transtibial technique.[8,56] The PCL tibial inlay procedure involves creating a bone trough at the tibial attachment and securing a bone plug into the trough with cannulated screws with or without washers. Although arthroscopic techniques are being trialed, this procedure has historically been reported using a posteromedial incision between the semitendinosus tendon and the medial head of the gastrocnemius muscle. The gastrocnemius is then retracted to expose the PCL tibial attachment. This approach has been described with the patient in the prone position as well as with the patient placed on a beanbag and with the hip externally rotated to expose the posteromedial knee.[8,73,94] However, the biomechanical results and clinical outcomes after the anatomic transtibial and tibial inlay techniques remain controversial. For example, it is unknown whether the reported abrasion, attenuation, and failure of the graft in biomechanical studies would be applicable in a biological environment in which remodeling may occur[2] and whether these problems occur in grafts other than patellar tendon grafts.

Additional modifications of each single-bundle PCL reconstruction technique are common. First, the choice of PCL reconstruction graft is variable. In a systematic review of isolated transtibial single-bundle reconstructions, it was reported that autografts, most commonly bone–patellar tendon–bone (BTB) or hamstring, were used approximately 78% of the time, while allografts, usually Achilles tendon, were used 22% of the time.[57] In a porcine biomechanical comparison between these 3 graft types, a quadruple-strand hamstring tendon had significantly higher loads to failure than either the BTB or Achilles grafts; however, BTB grafts were reported to resist elongation significantly more than the quadrupled hamstring tendons.[11] Wang et al[123] reported that patient clinical outcomes were similar between autografts and allografts, noting that an associated increase in complications with autografts (most notably infection and donor-site morbidity) was the only difference between the 2 groups. For the tibial inlay technique, most studies have reported the use of a BTB autograft[9,14,82,94]; however, Kim et al[56] used an Achilles tendon allograft for this technique.

The most commonly reported complications after PCL reconstructions are residual posterior laxity, usually defined as more than 4 mm of increased posterior translation on PCL stress radiographs, and flexion loss due to prolonged immobilization of the knee in extension.[113,130] The reported complications between transtibial reaming and tibial inlay PCL reconstructions differ. The proximity of the popliteal artery to the posterior knee capsule can place the artery at risk for injury if the surgeon uses a smooth bore reamer and inadvertently exits the posterior tibial cortex or if the tibial guide pin or reamer overpenetrates the posterior tibial cortex.[13,86,130] Kennedy et al[52] also reported that proximal placement of the tibial guide pin can result in posterior medial or lateral meniscal root avulsions. For the tibial inlay procedure, there is a risk of saphenous nerve injury during the surgical approach or injury to the popliteal artery for anatomic variations that cross within or medial to the medial head of the gastrocnemius muscle.[130] In addition, there is a potential risk of nonunion of the inlay bone plug and popliteal artery adhesions to the posterior capsule, which can complicate revision reconstructions.

Studies have described the use of single-bundle PCL reconstructions in which the femoral and tibial remnants of the PCL are preserved and used to augment the PCL reconstruction graft.[2,16,65,131] It has been theorized that preservation of the PCL remnant may enhance healing of the PCL graft by providing increased soft tissues for supplemental vascular ingrowth.[16] The vascular supply to the PCL comes from the middle genicular artery.[104] Its innervation is from branches of the tibial nerve. The PCL is an intra-articular structure and is extrasynovial.[47,49,120] The PCL synovial lining covers all but the posterior aspect of the PCL,[47] which may improve its ability to heal with an intrasubstance or minimally displaced tear.

Clinical Outcomes of Transtibial Single-Bundle PCL Reconstruction

Transtibial single-bundle PCL reconstructions were evaluated by a recent systematic review, in which 10 studies met the criteria of an isolated PCL reconstruction of the ALB and at least 2 years of follow-up.[57] The authors of the review found that Lysholm knee scores were significantly higher postoperatively, 75% of patients had normal or nearly normal subjective function on International Knee Documentation Committee (IKDC) scores, and posterior knee laxity was significantly improved postoperatively.[57] Specifically, mean postoperative posterior knee laxity varied in the reviewed studies from 2.0 to 5.9 mm, which was considerably improved over preoperative values ranging from 8.4 mm to 12.3 mm. However, it was concluded that normal knee stability was not fully restored in any of the reviewed studies.[57] These results were similar to those of Hermans et al,[38] who reported on a long-term follow-up of isolated single-bundle PCL reconstructions and found that IKDC, Lysholm, visual analog scale (VAS), and Tegner scores were improved at a mean postoperative follow-up of 9 years. However, the mean anteroposterior laxity as measured by KT-1000 arthrometer and Telos stress radiographs was significantly increased in comparison to the nonoperated knee (4.7 vs 2.1 mm, respectively), and radiographic evaluation demonstrated that 60% of knees had evidence of osteoarthritis.[38]

Similar results have been reported for single-bundle transtibial PCL reconstructions in multiligament injuries. Numerous studies have reported improved postoperative subjective outcome scores after transtibial single-bundle PCL reconstructions with concurrent ACL or posterolateral reconstructions.[19,20,54,65] These same studies also reported a significantly decreased amount of postoperative side-to-side posterior translation in comparison to preoperative knees; however, these knees still exhibited levels of increased posterior translation on stress radiography

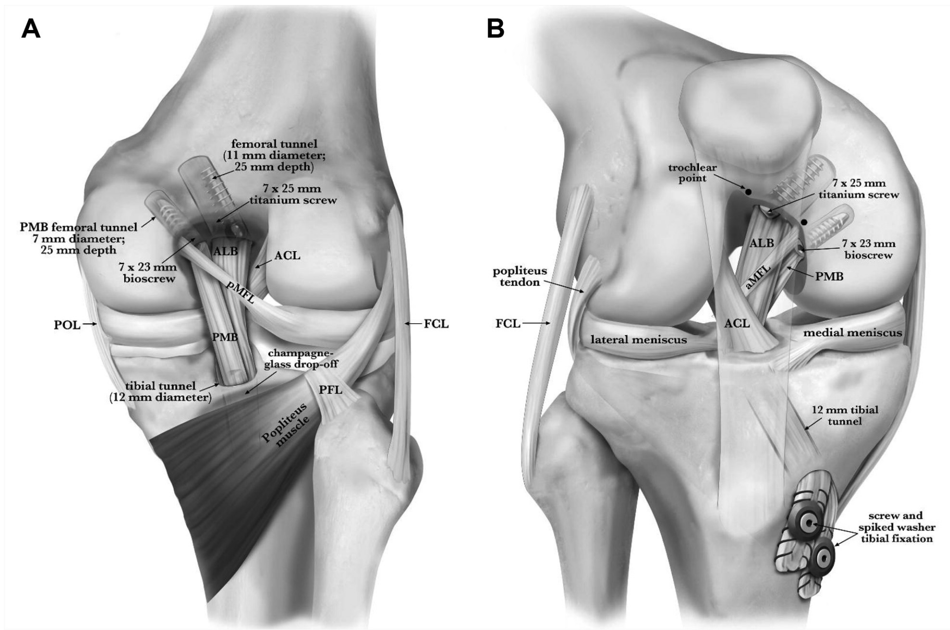

Figure 12. (A) Posterior and (B) anterior views of the anatomic double-bundle, posterior cruciate ligament reconstruction. The reconstructed anterolateral bundle (ALB) and posteromedial bundle (PMB) are shown, as well as the size, shape, and location of their femoral and tibial tunnels. The PMB enters the tibial tunnel posteromedial to the ALB. The PMB is posterior in the transtibial tunnel and exits deep to the ALB and then is fixed medially and distally to the ALB. Femoral fixations of both bundles and the champagne glass drop-off, the anatomic landmark for transtibial tunnel drilling, are also displayed. ACL, anterior cruciate ligament; aMFL, anterior meniscofemoral ligament (ligament of Humphrey); FCL, fibular collateral ligament; PFL, popliteofibular ligament; pMFL, posterior meniscofemoral ligament (ligament of Wrisberg); POL, posterior oblique ligament. (Reproduced with permission from Wijdicks CA, Kennedy NI, Goldsmith MT, et al. Kinematic analysis of the posterior cruciate ligament, part 2: a comparison of anatomic single- versus double-bundle reconstruction. *Am J Sports Med*. 2013;41(12):2839-2948.)

(range, 2.2-4.2 mm) that were higher than the native knee.[19,20,54,65] Last, Kim et al[55] reported that single-bundle transtibial PCL reconstruction with remnant preservation of the PCL resulted in significantly improved postoperative Tegner activity scores, rates of near-return to activity, and subjective IKDC scores compared with conventional reconstruction; however, side-to-side differences in posterior tibial translation (4.1 and 4.3 mm for remnant and conventional reconstruction, respectively), Lysholm scores, return to activity, and objective IKDC scores were not significantly different. These similar results between the conventional single-bundle transtibial PCL reconstruction and the remnant preserving technique were also reported by a recent systematic review.[16]

Clinical Outcomes of Tibial Inlay Single-Bundle PCL Reconstruction

Outcomes for single-bundle reconstruction using the tibial inlay technique have been reported to be similar to those of the transtibial technique. Studies have reported significantly increased Lysholm knee scores and Tegner activity levels after isolated PCL reconstructions.[56,108,112] In addition, studies have reported that side-to-side posterior tibial translation, as determined by Telos device stress radiographs, was significantly improved after isolated single-bundle tibial inlay PCL reconstruction.[108,112] However, these studies reported a range of postoperative posterior translations that were between 2.8 mm and 3.3 mm[108,112] higher than the translation of the native knee. Similarly, clinical studies reported postoperative findings of 4.1 mm and 4.7 mm for isolated or combined reconstructions.[14,56,108]

Double-Bundle PCL Reconstruction Techniques

Double-bundle PCL reconstructions have evolved as an alternative to single-bundle reconstructions with the same indications for surgery.[54,113] As reported by biomechanical studies, the ALB and PMB perform in an codominant manner,[1,53,95] and these roles theoretically would not be restored by a single-bundle PCL reconstruction.[126] Therefore, an anatomic double-bundle PCL reconstruction may be able to more closely restore native kinematics than the single-bundle technique.

An anatomic transtibial double-bundle PCL reconstruction involves the reaming of 2 femoral tunnels and 1 tibial tunnel (Figure 12). The insertions of the ALB and PMB are broader on the femoral side, which allows for the reaming of 2 separate tunnels, a larger tunnel for the ALB and a smaller tunnel for the PMB.[36,84,113,126] The tibial insertion is more compact, and usually only a single tunnel can be reamed.[36,56,84,113,126] Reaming of the femoral tunnels of a double-bundle reconstruction endoscopically, as described by Spiridonov et al,[113] may prevent injury to the vastus medialis obliquus muscle and therefore decrease recovery time. The anatomic double-bundle tibial inlay reconstruction has been described as a modification to the original single-bundle tibial inlay reconstruction.[8,9,56,82] Kim et al[56] described the double-bundle tibial inlay as an arthroscopic procedure involving 2 femoral sockets that were fixed to a split Achilles tendon PCL graft to recreate the ALB and PMB with interference screws. However, a single reamed tibial tunnel was performed in the same manner as the transtibial technique.[56] Other studies have reported fixation of the split PCL graft to a surgically created unicortical window or closed socket on the posterior tibia,[90] attempting to replicate the original description of the single-bundle inlay technique.[8]

Just as with the single-bundle techniques, many different autograft and allograft options have been used for double-bundle PCL reconstruction. For the transtibial technique, the ALB is usually reconstructed with an Achilles allograft[36,84,113,126] or a BTB autograft.[26] The smaller PMB has been reconstructed with a semitendinosus autograft[26] or allograft,[36,113] tibialis anterior allograft,[126] or tibialis posterior allograft.[54] The double-bundle PCL tibial inlay technique is typically performed with a split graft; graft choices have been reported to be Achilles tendon allograft,[56] quadriceps tendon allograft,[90] or BTB allograft.[10] In addition, use of the PCL remnant fibers has been proposed to augment double-bundle PCL reconstructions.[129]

Clinical Outcomes of Transtibial Double-Bundle PCL Reconstruction

Clinical studies have reported on subjective and objective outcomes after isolated or combined transtibial double-bundle PCL reconstruction with follow-ups ranging from 25 to 45 months.[54,113,128,129] These studies have all reported significantly improved postoperative subjective scores.[54,113,128,129] In addition, these studies described a significant decrease in postoperative side-to-side posterior tibial translation on kneeling or Telos device stress radiographs in comparison to preoperative levels.[54,113,128,129] This level of side-to-side posterior tibial translation ranged from 0.9 to 3.9 mm of increased posterior tibial translation in comparison to the intact knee,[54,113,128,129] with the highest residual tibial posterior translation reported in patients with a concomitant posterolateral corner reconstruction.[54] Spiridonov et al[113] reported levels of side-to-side posterior translation that were slightly higher than the contralateral knee (0.9 mm); other studies reported levels of side-to-side posterior translation of 2.4 mm to 3.9 mm more than the native knee.[54,128,129]

Clinical Outcomes of Tibial Inlay Double-Bundle PCL Reconstruction

Results of the tibial inlay double-bundle PCL reconstruction have been reported to be similar to results of the transtibial method. For both isolated and combined PCL reconstructions, studies have reported significantly improved subjective clinical outcome scores after surgery for primary or revision tibial inlay double-bundle PCL reconstructions at a mean follow-up of 29 to 64 months.[56,66,89,112] In addition, increased postoperative side-to-side posterior translation differences of 2.6 to 5.1 mm after isolated reconstructions[56,89] and 2.8 to 6.2 mm of posterior translation in primary or revision surgery with concomitant injury have been reported.[66,89] Last, as indicated by Lee et al,[66] the tibial inlay double-bundle PCL technique may be a viable option for revision PCL reconstruction, with the lowest side-to-side posterior tibial translation reported after revision PCL reconstructions with combined injury (2.4 mm).

Clinical Comparisons Between Single- and Double-Bundle PCLR

Currently, the literature is lacking any evidence level 1 clinical studies comparing the effects of single-bundle and double-bundle PCL reconstructions. However, level 2 and 3 studies have attempted to quantify potential differences between techniques.[54,56,69,112,124,128] Early clinical evidence was limited to retrospective studies that did not indicate clinical differences, including differences in side-to-side increases in posterior translation, between isolated or combined transtibial single-bundle and double-bundle reconstructions.[54,58,124] However, recent level 2 studies have reported that while some clinical outcomes (Lysholm knee scores and Tegner activity scores) were the same between both isolated transtibial reconstruction techniques at approximately 30 months of follow-up, the objective measures of postoperative side-to-side posterior translation and objective IKDC scores were significantly improved for double-bundle compared with single-bundle PCL reconstructions.[69,128] Two studies retrospectively compared tibial inlay single-bundle versus double-bundle PCL reconstructions.[56,112] Shon et al[112] reported no differences in Lysholm knee scores or side-to-side posterior translation between 2 tibial inlay groups after surgery with the Telos device at 90° of knee flexion; the authors found 3.0 mm for the single-bundle group and 2.6 mm for the double-bundle group. However, Kim et al[56] reported higher side-to-side posterior tibial translation for the single-bundle group (4.7 mm) in comparison with the double-bundle group (3.6 mm), although significance was not reported. Therefore, we believe that while the differences between single- and double-bundle tibial inlay techniques still need to be further evaluated with prospective clinical studies, recent higher quality studies indicate that transtibial double-bundle PCL reconstruction may be able to more closely and objectively restore the knee to native levels than transtibial single-bundle reconstructions.

REHABILITATION

After diagnosis and treatment of a PCL injury, rehabilitation plays a fundamental role in determining patient outcomes.[18,127] While a range of prescribed rehabilitation methods and techniques are available, several common themes should be considered. Primarily, rehabilitation should focus on progressive weightbearing, prevention of posterior tibial subluxation, and strengthening of the quadriceps muscles.[98] Since PCL graft healing times have been reported to be almost double the time of ACL graft healing, it has been suggested that PCL reconstruction patients should be kept nonweightbearing for 6 weeks.[7,18,35] Patients are placed in an immobilizer brace in extension after surgery for 3 days before transitioning to a dynamic or static anterior drawer knee brace.[98] The Jack Brace (Albrecht GmbH) and the Rebound PCL brace (Össur Inc), which apply increasing force as a function of flexion angle,[62] are the only currently available dynamic braces, and it has been recommended that the brace of choice should be worn at all times for up to a minimum of 24 weeks postoperatively.[98] A progressive, goal-oriented, 5-phase rehabilitation program after PCL reconstruction has been reported to improve stabilization of posterior tibial translation, varus, and external rotation stresses,[92] and Pierce et al[98] suggested a particular protocol based on this method. In phase I, from 0 to 6 weeks after surgery, progressive range of motion (ROM) exercises are undertaken, beginning with passive prone ROM from 0° to 90° of flexion for the first 2 weeks after surgery and advancing to full ROM as tolerated. Caution is recommended to prevent hyperextension and posterior tibial translation to protect the healing PCL graft from stretching out. Phase II, from 6 to 12 weeks postoperatively, involves similar precautions with progression to crutch weaning and weightbearing activities as tolerated while restricting the knee to less than 70° of flexion during weightbearing exercises. The use of a brace continues in phase III, from 13 to 18 weeks after surgery, with ROM weightbearing exercise progression past 70° of flexion after 16 weeks. Phase IV is considered to occur 19 to 24 weeks postoperatively and is characterized by the introduction of sport-specific drills near the end of the phase. The patient may begin to wean from brace wearing in phase V, from 25 to 36 weeks after surgery, and may undertake a straight line jogging progression with the eventual goal of multiplanar agility exercises and, ultimately, return to preoperative activities.[98] It should be noted that this protocol is an outline for rehabilitation after an acute isolated PCL reconstruction. While a chronic isolated or combined ligament PCL reconstruction may be rehabilitated in a similar fashion, PCL stress radiographs may be required to objectively gauge postoperative progression and to determine any modifications for a patient with concomitant MCL, PLC, or meniscal injury.[42]

FUTURE DIRECTIONS

Many of the current recommendations and guidelines for nonoperative and operative PCL treatment and rehabilitation are based on biomechanical and evidence level 3 and 4 studies. To further validate the contribution of these factors in vivo, it will be important to pursue prospective level 1 and 2 outcomes studies that use preoperative and postoperative PCL stress radiographs to objectively determine the difference in treatments. Specifically, primary consideration of these prospective studies should be focused on management (nonoperative vs operative) and technique (tibial inlay vs transtibial, single bundle vs double bundle, graft fixation angle, and graft type) to improve both subjective and objective outcome scores. In addition, prospective level 1 investigations into more aggressive postoperative rehabilitation protocols are warranted to prevent formation of arthrofibrosis and to facilitate reactivation of the quadriceps and lower extremity musculature without the risk of having the graft(s) stretch out. Knowledge about the treatment of PCL tears has increased considerably over the past few years, and future prospective studies should further improve the outcomes of PCL tears.

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