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PCL UPDATE (K JONES AND M ALAIA, SECTION EDITORS)

Graft Considerations in Posterior Cruciate Ligament Reconstruction

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Abstract

Purpose of Review To highlight current and established concepts regarding PCL injury and reconstruction.

Recent Findings Recent biomechanical and clinical studies have brought attention to improved surgical techniques and clinical outcomes of PCL reconstruction.

Summary In contrast to anterior cruciate ligament (ACL) injuries, isolated posterior cruciate ligament (PCL) injuries occur much less frequently and have traditionally been treated non-operatively. Even when a PCL injury meets operative indications, outcomes of PCL reconstruction historically do not match the success rates of ACL reconstruction procedures. As such, there remains controversy regarding appropriate indications and techniques for surgical repair leading to a paucity of conclusive data regarding surgical outcomes. Recently, however, there has been an increase in focus on the role of the PCL in proper knee biomechanics and negative long-term sequelae of chronic PCL insufficiency. This improved understanding has led to advancements in surgical technique and graft options for PCL reconstruction.

Keywords Posterior cruciate ligament · PCL reconstruction · PCL graft · PCL surgical technique

Introduction

While the posterior cruciate ligament (PCL) lies within the joint capsule, it is considered an extraarticular structure due to the presence of a synovial sheath. The intraarticular portion of the PCL is between 32 and 38 mm long, with an average midsubstance diameter of 11 mm^2 [1]. It consists of two main bundles, named after their femoral origin: a posteromedial bundle (PMB) and a more substantial anterolateral bundle (ALB). These bundles are best differentiated at their femoral origin due to the much larger footprint of the ALB ranging from 112 to 118 mm^2 compared to the PMB footprint of 60–90 mm^2 [2]. The difference in size and orientation of these two bundles allows them to function in synergy. Biomechanical studies have shown that the PCL is a non-isometric structure with unequal tension throughout knee motion [3]. Ahmad et al. reported that the ALB became longer and more vertical from 0° to 120° of knee flexion, and the PMB became shorter and more horizontal with progressive flexion, placing its restraining force vector in line to resist posterior tibial translation as flexion increases. Other studies have found the ALB to primarily resist translation in flexion while the PMB predominantly functions in extension [4]. The meniscofemoral ligaments, variably present in approximately 90% of individuals, are considered part of the PCL complex and constitute 17.2% of its cross-sectional area [5]. Their role in functional knee stability remains controversial, and current methods of PCL reconstruction have not taken the meniscofemoral ligaments into consideration [6].

PCL injuries are usually associated with a posteriorly directed force on a flexed knee with the foot in plantar flexion. This mechanism of injury is most commonly seen in contact sports and motor vehicle collisions (i.e., "dashboard injuries") [7, 8], although these injuries can also occur during knee hyperextension. Clinical classification of these ligamentous injuries is based on the amount of posterior subluxation of the tibia relative to the femoral condyles when a posteriorly directed load is placed on the proximal tibia with the knee positioned at 90° of flexion. Grade 1, indicating a low grade partial tear, demonstrates up to 5 mm of posterior tibial translation. However, the tibia will remain aligned anterior to the femoral condyles. Grade 2 is a near-complete tear of the PCL

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associated with > 5–10-mm posterior tibial translation. Anatomically, the anterior tibia will now rest flush with the distal femoral condyles. Finally, a Grade 3 injury indicates a PCL injury in combination with either an ACL, MCL, capsular, and/or posterior lateral corner injury. The tibia in this instance will have translated > 10 mm posteriorly and rest posterior to the femoral condyles with the knee in flexion (sag sign).

Of note, this posterior "set point" due to sagging at rest can limit active posterior excursion on exam. This exam finding can give the spurious impression of increased anterior excursion, thereby mimicking ACL laxity as the knee is reduced to its neutral position on anterior drawer testing. The Quad Active maneuver involves an isometric quadriceps contraction while the examiner sits on the ipsilateral foot and performs the anterior and posterior drawer tests. This test is aimed at reducing sag and allowing for a more focused exam.

LaPrade et al. postulated a grading system based on stress radiographs to ensure a more objective and reproducible assessment of these injuries. In their study, uninjured PCLs demonstrated posterior translation of 0–4 mm on lateral bodyweight stress view; while isolated PCL tears showed 5–12 mm of translation. Combined posterior knee injuries to the PCL, posterolateral corner, and/or posteromedial corner had increased posterior displacement measuring ≥ 12 mm [9•]. Comparison views of the uninjured, contralateral knee can provide an important reference for the patient's normal baseline, especially in the case of confounding issues such as general ligamentous laxity. Jackman et al. described their validated algorithm, where 0–7 mm of side-to-side difference in posterior displacement constitutes a partial PCL tear, 8–11 mm represents an isolated PCL tear, and ≥ 12 mm of posterior translation indicates a combined PCL and posterolateral corner or posteromedial corner knee injury [10•].

Once injury of the PCL is suspected or confirmed, magnetic resonance imaging (MRI) of the knee is usually obtained to confirm the diagnosis, and to assess for concomitant injuries. Since the common PCL injury mechanism usually results in stretch deformation of the ligament, this often maintains continuity on MRI with apparent thickening. However, it will display increased anteroposterior diameter with low intrasubstance signal intensity on sagittal T2-weighted images and increased intrasubstance signal intensity on proton-density images [11].

Historically, most acute, isolated PCL injuries have been treated conservatively with a non-operative approach because of the inherent healing capacity of the PCL. Multiple studies have shown good outcomes with non-operative management for grade 1 and 2 injuries [12, 13]. However, for more severe injuries such as multi-ligamentous, combined meniscus root, or bony avulsion injuries that result in instability, surgical reconstruction is often performed in patients of appropriate age and activity level. Nevertheless, even when indicated, long-term outcomes of surgical versus conservative management for PCL injuries have been an area of recent debate. Even within the operative cohort, outcomes between graft selection double versus single bundle repairs, and the results of differing reconstruction techniques remain controversial, and multiple variants including tunnel position, number of graft bundles, and graft tensioning make comparison challenging.

Indications

When treating a PCL injury, several patient-specific factors should be considered including the grade of PCL injury, presence of concomitant injuries (isolated vs. combined), chronicity, clinical presentation (symptom level), and patient demands or activity level [14]. Typically acute, truly isolated PCL injuries (grades I and II) are treated non-surgically. Most of these patients are able to return to sports within 4–6 weeks of non-operative treatment, generally involving a quad focused physical therapy regimen and dynamic Jack bracing [12, 13]. A non-surgical trial can also be considered for isolated grade 3 tears in elderly or low-demand individuals.

The historical paradigm of non-operative management for posterior cruciate ligament tears is being challenged as long-term follow-up data has begun to demonstrate increased incidence of premature osteoarthritis and early decline of knee function [15–17]. Operative management is usually indicated in isolated grade 3 PCL tears that remain symptomatic despite an adequate course of conservative therapy and for PCL injuries in the setting of concomitant-associated injuries [18]. These include PLC injury, or in the presence of a repairable meniscal body/root tear or MCL insufficiency [9•, 19, 20]. Finally, the authors also recommend acute osseous avulsion injuries of the PCL to be considered for primary reduction and fixation.

Surgical Techniques

Two prevalent techniques exist for PCL reconstruction based on the tibial insertion site: the transtibial and the tibial inlay techniques. Historically, the transtibial technique was the most common tibial fixation method. Here, the PCL graft is passed retrograde through the tibial tunnel before making a right angle turn at the intraarticular aperture of the tibial tunnel to reach the femoral condyle at the anterior notch. This "killer turn" in the graft around the bony edge of the aperture has been shown to create increased tensile forces on the graft, leading to graft elongation and, eventually, failure [21]. It is thought that these effects may be caused by the "windshield wiper" effect, with the bony edge of the tunnel continually shearing against the graft during knee motion, also potentially leading to tunnel widening.

In response to this, Berg et al. described the tibial inlay technique in 1995 as a way to avoid this "killer turn" associated with the transtibial approach [22]. Classically, this technique was performed via an open posteromedial approach between semitendinosus and medial gastrocnemius for securing the tibial attachment, but several arthroscopic options have since been popularized. Using the tibial inlay technique, the PCL is fixed directly onto the native insertion site of the tibia using concepts of aperture fixation, thereby creating a shorter and stiffer graft leading to decreased graft motion and deformation. The biomechanical superiority of this technique is supported by multiple cadaveric studies. Bergfeld et al. found significantly less total anteroposterior laxity and less mechanical degradation in the inlay group when compared to a tunnel group after applying a posteriorly directed load from 30° to 90° of knee flexion and after repetitive loading at 90° of flexion [21]. A later study compared various graft properties (i.e., thinning, total elongation, elongation during a single loading cycle) and found a significantly different failure rate of 0% for the onlay graft versus 32% of the transtibial specimens, although tunnel and inlay grafts significantly increased in length following cyclic loading [23].

To date, multiple studies have evaluated these two methods in terms of biomechanical strength and clinical outcomes. Macgillivray et al. performed a retrospective study evaluating outcomes using arthroscopic transtibial versus tibial inlay techniques in which they evaluated 20 patients at an average follow up of 5.7 years. They found no significant differences in posterior drawer testing, KT-1000, functional testing, or Lysholm, Tegner, and AAOS knee scores at a minimum 2 year follow-up. The authors concluded that although neither of the methods restore anteroposterior stability to its original state, there does not appear to be a significant difference in terms of post-operative function between the two methods [7].

Similar results were found by Seon et al. when they performed a retrospective case series comparing the clinical and radiographic results of PCL reconstruction using these two techniques. In their study, the transtibial technique was performed using triple hamstring autografts with the tibial inlay group using bone-patellar-bone autografts. They also found no difference in post-operative functional results including Lysholm knee scores and Tegner scores. In addition, instrumented posterior laxity testing with mean side-to-side differences were not statistically different between the two groups leading authors to conclude that both techniques lead to equivalent satisfactory results [24].

An additional retrospective study was performed by Kim et al. comparing clinical outcomes of tibial inlay single-bundle and double-bundle techniques with those of the conventional transtibial single-bundle technique. Using Achilles tendon graft for all cases, this study also failed to find any significant difference in Lysholm or side-to-side range of motion at a minimum of 2 years follow-up. The mean side-to-side difference in posterior tibial translation measured on Telos stress radiographs differed significantly between the tibial inlay double-bundle group and the transtibial single-bundle group with the advantage going to the tibial inlay group. However, they did not find a significant difference between the arthroscopic inlay single-bundle group and the transtibial group [25].

A systematic review was performed by Shin et al. in which they compared outcomes after transtibial and tibial inlay techniques evaluated by Tegner scores, Lysholm scores, and posterior residual laxity. All of the patients included underwent PCL single-bundle reconstruction with either transtibial or tibial inlay techniques. They found no significant difference in outcome scores between the two techniques. Based on their findings, the authors recommend the choice of technique should be based on surgeon familiarity and experience [26•].

Based on current literature, there does not appear to be sufficient en vivo evidence supporting a clinically important difference between transtibial and tibial inlay techniques. The decision to perform one technique over the other should largely be decided by surgeon preference and comfort.

Single- Versus Double-bundle Reconstruction

While the PCL bundles are widely considered co-dominant, the mean ultimate failure load on biomechanical testing differs greatly for both PCL fiber bundles. Harner reported that the ultimate load for the anterolateral bundle is 1120 ± 362 N (mean stiffness 120 ± 37 N/mm), which is more than twice the mean ultimate load of the posteromedial bundle at 419 ± 128 N (mean stiffness 57 ± 22 N/mm) [27]. Consequently, the ALB is considered to provide the primary restraint to posterior tibial translation, and thus has been the focus of traditional single-bundle reconstruction.

Multiple studies have evaluated single- versus double-bundle PCL reconstruction techniques in terms of biomechanical strength of repair as well as long-term outcomes with regard to stability and degenerative changes. The double-bundle technique was developed in an attempt to more accurately recreate the anatomic configuration of the native AL and PM bundles and thus more closely restore normal knee kinematics. However, there is still considerable debate as to whether or not this development conveys clinically relevant benefits.

Several studies have found double-bundle reconstruction to be biomechanically superior to single-bundle techniques [21, 27, 28]. Additionally, several studies found significantly improved results after double-bundle reconstruction compared to single-bundle when examining post-operative posterior laxity with posterior drawer test through all flexion angles [29, 30]. However, a systematic review of 14 level II–V studies performed by Qi et al. showed no significant differences when looking at clinical outcomes [31]. Furthermore, Fanelli et al. performed a prospective randomized trial evaluating strength of repair and post-operative function with single- versus double-bundle repair and found no statistical difference as assessed by KT-1000 arthrometer testing, three knee ligament rating scales, and Telos stress radiography [32].

The most recent meta-analysis performed by Lee et al. included four RCTs and a total of 107 single-bundle cases versus 108 double-bundle patients. This review found no significant biomechanical differences between single- versus double-bundle groups with respect to external rotation, varus rotation, or coupled external rotation of the tibia with posterior drawer force at any knee flexion angle [33].

In addition to biomechanical evaluation, multiple studies have investigated clinical outcomes comparing single- and double-bundle methods. To date, none of these studies have provided sufficient data proving superiority of one technique over the other in regard to functional scores, patient satisfaction, or radiographic examination [31, 32, 34, 35].

Based on the current literature, there does not appear to be a consensus regarding superiority of double-bundle over single-bundle reconstruction or vice versa. Some studies have shown a slight biomechanical advantage of double-bundle reconstruction at some knee flexion angles. While this does not appear to equate to clinically significant differences in isolated injuries, it may convey possible benefit in combined PCL and PLC injuries. Meanwhile, many surgeons and authors believe that double-bundle surgeries increase the technical complexity of both primary and revision PCL reconstructions.

Graft Selection

The primary goals of PCL reconstruction are to restore normal knee stability and return the patient to pre-injury functional activity levels. Besides surgical technique, graft selection is the key factor in providing adequate tensile strength and solid fixation to allow for early mobility and rehabilitation; graft healing and maturation; and, ultimately, return to desired activity.

Graft options for PCL reconstruction generally entail autograft or allograft tissues. Autograft choices include bone-patellar tendon-bone (BTB) graft, hamstrings, and quadriceps tendons. Allograft tissues are becoming increasingly popular for primary PCL reconstruction and include Achilles, tibialis anterior/posterior, and peroneus longus tendons. Ideal graft properties are those that simulate anatomic properties of the native PCL including size and geometric shape. Other considerations include technical aspects such as ease of graft insertion/fixation, fast graft incorporation, and cosmesis [36]. Additional factors that must be considered include surgeon experience/preference and necessary additional concomitant ligamentous repairs.

Allografts are the most commonly used graft option for PCL reconstruction as they provide sufficient graft strength without donor site morbidity, utilize smaller incisions, and have been shown to decrease operative time. Concerns involving autografts are mostly related to donor site morbidity. For example, the use of BTB grafts has been associated with increased incidence of anterior knee pain and risk of patella fracture, both intraoperatively and post-operatively. There is also a concern for weakening of the extensor mechanism, which may also be seen with the use of quadriceps tendon graft [36]. This may be of particular concern due to the fact that the quadriceps is considered synergistic to PCL function. Injury to the medial collateral ligament has been described during harvest of the pes anserinus tendons over the anteromedial tibia.

Currently, Achilles allograft remains the most popular graft choice for the reconstruction of both acute and chronic PCL injuries, with soft tissue, all inside graft choices gaining popularity. Achilles allografts possess several inherent advantages. A standard graft will usually yield excellent graft volume, particularly in situations where multiple grafts are desired (double-bundle) or required (multi-ligamentous reconstruction). This is particularly useful in cases where there is relative lack of sufficient autologous tissue sources either due to overall disease burden (in multi-ligamentous injuries) or prior harvest (in revision setting). The presence of the calcaneal bone block allows for bony fixation and gives this graft significant versatility in addressing possible bone voids from prior tunnel placement while ostensibly avoiding the "killer turn" at the tibial intraarticular aperture.

Conversely, there are relative risks and potential complications associated with the use of allografts for PCL reconstruction, which should be discussed with the patient as part of the pre-operative informed consent process. While generally considered extremely safe, the potential risk of disease transmission is inherent to all allograft tissues. Mitigation of this risk by sterilization and storage techniques can potentially weaken the graft tissue. Consequently, allografts may exhibit delayed healing and remodeling compared to autografts. Tunnel widening, cyst formation, and effusions have all been reported [37]. Another drawback of allograft tissue is associated cost and potentially limited availability.

Several head to head studies have evaluated different graft options and associated morbidity factors. Lin et al. compared BTB and hamstring autografts for PCL reconstruction. They found significantly increased incidence of anterior knee pain, posterior drawer laxity, and osteoarthritic changes in the BTB graft group. Meanwhile, Maruyama et al. compared the use of hamstring and BTB grafts and found no significant difference in post-operative stability or Lysholm functional scores [38]. Similarly, autografts were shown to allow less knee laxity when compared to allografts [39].

In summary, no superior graft choice in PCL reconstruction has been identified. However, autografts are associated with concern for donor site morbidity and increased operative time. In addition, patellar and quadriceps grafts appear to be associated with increased anterior knee pain and fracture risk and may contribute to weakened knee extensor function.

Graft Tensioning

Excessive graft forces have been implicated as a crucial factor in suboptimal PCL graft performance and outcomes, potentially leading to excessive knee constraint or decreased posterior stability. Traditionally, single-bundle techniques have favored replacing the larger ALB, commonly tensioned between 70° and 90° of knee flexion. However, residual posterior laxity has been described during early knee flexion, and in full extension. Double-bundle reconstruction techniques allow for differential tensioning of both limbs of a two-bundle graft to more closely replicate the reciprocal in situ forces of the native PCL. In a cadaveric study, Carson et al. examined the in situ forces of differentially tensioned bundles fixed at different degrees of knee flexion. They found that tensioning of the ALB at 90° and the PMB in full extension most closely restored the symmetric reciprocal force pattern of the native AL and PM bundles [40]. Based on these findings, most authors advocate for differential tensioning of the ALB at 90° of knee flexion, with an anterior drawer force applied, while fixing the PMB at 0°/full extension [9•].

Complications

The anatomic proximity of the PCL insertion site to neurovascular structures of the popliteal fossa poses a risk of injury during PCL reconstruction surgery. In a cadaveric study, Matava et al. measured the mean distance between the PCL insertion and the popliteal artery to be 7.6 and 7.2 mm in the axial and sagittal planes respectively between 0° to 100° of flexion [6]. Of note, the distance increases significantly with progressive flexion, up to maximum mean distances of 9.9 mm in the axial plane and 9.3 mm in the sagittal plane at 100° of flexion. This is especially relevant for the transtibial technique. Several case studies have described injury to the popliteal artery during PCL reconstruction surgery [41, 42]. In both of these cases, the artery was injured using the arthroscopic transtibial technique. Makino reported that the injury was likely caused by the displacement of the guide wire during drilling.

Fractures are another potential complication of PCL reconstruction occurring in the tibia, femur, or patella. One risk factor for fracture is tunnel over-drilling, which creates large tibia or femoral tunnels making them more susceptible to fracture. Fractures can also occur during graft fixation. The use of staples appears to increase this risk. Because of this, most surgeons prefer the use of interference screws or screws with spiked ligament washers [43]. Finally, the use of bone-patellar tendon-bone (BPTB) autograft harvesting has been shown to increase the risk of intraoperative fractures with the incidence of patella fracture with BPTB autograft ranging from 0.2 to 2.3% [44, 45]. A biomechanical study performed by Moholkar et al. showed the risk of patellar fractures associated with BPTB harvesting was reduced in specimens with round-cornered bone plugs developed with a curved chisel compared with sharp-cornered patellar defects [45]. Ferrari et al. found that removing no more than 25 to 30 mm of the length and 9 to 10 mm of the width of the patella also reduces the risk of fracture. They also recommended that at least two thirds of the depth of the patella should be preserved [46].

Another complication of PCL reconstruction is graft failure. There are multiple factors that can contribute to graft failure including both diagnostic and technical errors. Technical errors leading to persistent laxity and possible rupture include poor graft size and strength, inadequate fixation, and inappropriate tensioning during graft placement. Imprecise femoral or tibial tunnel placement can also lead to graft abrasion and subsequent failure [43]. A retrospective study by Noyes et al. evaluated 52 cases of failed PCL reconstructions and found the most common probable causes of failure were associated posterolateral ligament deficiency (40%), improper graft tunnel placement (33%), associated varus malalignment (31%), and primary suture repair (25%) [47]. One of the most common factors responsible for failure was the improper placement of tibial or femoral tunnels. In their study, the authors found misplaced tibial tunnels were always proximal to the normal PCL anatomical tibial attachment. This removes the posterior central portion of the tibial eminence, which is behind the tibial spines. In this situation, the graft was placed in a vertical position limiting its ability to resist posterior tibial translation.

Conclusions

Historically, the majority of isolated PCL tears have been managed non-operatively, with surgical reconstruction reserved for PCL injuries unresponsive to conservative management. However, the traditional notion of non-operative management for posterior cruciate ligament tears is being challenged as recent long-term follow-up data has begun to demonstrate increased incidence of premature osteoarthritis and early decline of knee function. Still, surgical outcomes data of these techniques are limited to retrospective, uncontrolled, non-randomized case series with short-term follow-up. While biomechanical and outcomes data continue to emerge, current literature does not conclusively demonstrate significant clinical differences between single- and double-bundle, autograft versus allograft, or transtibial versus tibial inlay reconstruction techniques. Further studies are warranted to further elucidate optimal tunnel positioning, graft type, and graft tensioning as well as the long-term clinical effectiveness of various surgical techniques, to refine surgical techniques and improve patient outcomes following PCL reconstruction.

Compliance with Ethical Standards

Conflict of Interest Simon Görtz reports personal fees from the Joint Restoration Foundation. The other authors declare no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

References

Papers of particular interest, published recently, have been highlighted as:
• Of importance

1. Girgis FG, Marshall JL, Monajem A. The cruciate ligaments of the knee joint. Anatomical, functional and experimental analysis. Clin Orthop Relat Res. 1975;106:216–31.
2. Kennedy NI, LaPrade RF, Goldsmith MT, et al. Posterior cruciate ligament graft fixation angles, part 2: biomechanical evaluation for anatomic double-bundle reconstruction. Am J Sports Med. 2014;42(10):2346–55.
3. 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(6): 740–6.
4. 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(2):221–5.
5. 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(8):1345–50.
6. Matava MJ, Ellis E, Gruber B. Surgical treatment of posterior cruciate ligament tears: an evolving technique. J Am Acad Orthop Surg. 2009;17(7):435–46.
7. MacGillivray JD, Stein BE, Park M, Allen AA, Wickiewicz TL, Warren RF. Comparison of tibial inlay versus transtibial techniques for isolated posterior cruciate ligament reconstruction: minimum 2-year follow-up. Arthroscopy. 2006;22(3):320–8.
8. Meleiro SA, Mendes VT, Kaleka CC, Cury RP. Treatment of isolated lesions of the posterior cruciate ligament. Rev Assoc Med Bras (1992). 2015;61(2):102–7.
9.• LaPrade CM, Civitarese DM, Rasmussen MT, LaPrade RF. Emerging updates on the posterior cruciate ligament: a review of the current literature. Am J Sports Med. 2015;43(12):3077–92. **(Leading review of current literature on PCL reconstruction)**
10.• Jackman T, LaPrade RF, Pontinen T, Lender PA. Intraobserver and interobserver reliability of the kneeling technique of stress radiography for the evaluation of posterior knee laxity. Am J Sports Med. 2008;36(8):1571–6. **(Introduction of validated imaging method for objective quantification of PCL laxity)**
11. Rodriguez W, Vinson EN, Helms CA, Toth APMRI. Appearance of posterior cruciate ligament tears. Am J Roentgenol. 2008;191(4): W155–9.
12. Hermans S, Corten K, Bellemans J. Long-term results of isolated anterolateral bundle reconstructions of the posterior cruciate ligament: a 6- to 12-year follow-up study. Am J Sports Med. 2009;37(8):1499–507.
13. Jackson WF, van der Tempel WM, Salmon LJ, Williams HA, Pinczewski LA. Endoscopically-assisted single-bundle posterior cruciate ligament reconstruction: results at minimum ten-year follow-up. J Bone Joint Surg Br. 2008;90(10):1328–33.
14. Chahla J, Nitri M, Civitarese D, Dean CS, Moulton SG, LaPrade RF. Anatomic double-bundle posterior cruciate ligament reconstruction. Arthrosc Tech. 2016;5(1):e149–e156.
15. Keller PM, Shelbourne KD, McCarroll JR, Rettig AC. Nonoperatively treated isolated posterior cruciate ligament injuries. Am J Sports Med. 1993;21(1):132–6.
16. Patel DV, Allen AA, Warren RF, Wickiewicz TL, Simonian PT. The nonoperative treatment of acute, isolated (partial or complete) posterior cruciate ligament-deficient knees: an intermediate-term follow-up study. HSSJ. 2007;3(2):137–46.
17. Boynton MD, Tietjens BR. Long-term followup of the untreated isolated posterior cruciate ligament-deficient knee. Am J Sports Med. 1996;24(3):306–10.
18. Sekiya JK, Whiddon DR, Zehms CT, Miller MD. A clinically relevant assessment of posterior cruciate ligament and posterolateral corner injuries. Evaluation of isolated and combined deficiency. J Bone Joint Surg Am. 2008;90(8):1621–1627, A Clinically Relevant Assessment of Posterior Cruciate Ligament and Posterolateral Corner Injuries.
19. Montgomery SR, Johnson JS, McAllister DR, Petrigliano FA. Surgical management of PCL injuries: indications, techniques, and outcomes. Curr Rev Musculoskelet Med. 2013;6(2):115–23.
20. Tandogan NR, Kayaalp A. Surgical treatment of medial knee ligament injuries: current indications and techniques. EFORT Open Rev. 2016;1(2):27–33.
21. 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(7):976–981.
22. Berg EE. Posterior cruciate ligament tibial inlay reconstruction. Arthroscopy. 1995;11(1):69–76.
23. 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-A(6): 938–44.
24. Seon JK, Song EK. Reconstruction of isolated posterior cruciate ligament injuries: a clinical comparison of the transtibial and tibial inlay techniques. Arthroscopy. 2006;22(1):27–32.
25. Kim SJ, Kim SH, Jung M, Kim JM, Lee SW. Does sequence of graft tensioning affect outcomes in combined anterior and posterior cruciate ligament reconstructions? Clin Orthop Relat Res. 2015;473(1):235–43.
26.• Shin YS, Kim HJ, Lee DH. No clinically important difference in knee scores or instability between transtibial and inlay techniques for PCL reconstruction: a systematic review. Clin Orthop Relat Res. 2017;475(4):1239–48. **(Systematic review of multiple studies highlighting clinical differences between transtibial and tibial inlay techniques for PCL reconstruction)**
27. 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(2):144–51.
28. 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(6): 833–45.
29. Milles JL, Nuelle CW, Pfeiffer F, Stannard JP, Smith P, Kfuri M Jr, et al. Biomechanical comparison: single-bundle versus double-

bundle posterior cruciate ligament reconstruction techniques. J Knee Surg. 2017;30(4):347–51.

30. Wijdicks CA, Kennedy NI, Goldsmith MT, Devitt BM, Michalski MP, Årøen A, 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):2839–48.
31. Qi YS, Wang HJ, Wang SJ, Zhang ZZ, Huang AB, Yu JK. A systematic review of double-bundle versus single-bundle posterior cruciate ligament reconstruction. BMC Musculoskelet Disord. 2016;17:45.
32. Fanelli GC, Fanelli MG, Fanelli DG. Revision posterior cruciate ligament surgery. Sports Med Arthrosc Rev. 2017;25(1):30–5.
33. Lee DY. Single-bundle versus double-bundle posterior cruciate ligament reconstruction: a meta-analysis of randomized controlled. Trials. 2017;29(4):246–55.
34. Wang CJ, Chan YS, Weng LH, Yuan LJ, Chen HS. Comparison of autogenous and allogenous posterior cruciate ligament reconstructions of the knee. Injury. 2004;35(12):1279–85.
35. Li Y, Li J, Wang J, Gao S, Zhang Y. Comparison of single-bundle and double-bundle isolated posterior cruciate ligament reconstruction with allograft: a prospective, randomized study. Arthroscopy. 2014;30(6):695–700.
36. Hoher J, Scheffler S, Weiler A. Graft choice and graft fixation in PCL reconstruction. Knee Surg Sports Traumatol Arthrosc. 2003;11(5):297–306.
37. Fahey M, Indelicato PA. Bone tunnel enlargement after anterior cruciate ligament replacement. Am J Sports Med. 1994;22(3):410–4.
38. Maruyama Y, Shitoto K, Baba T, Kaneko K. Evaluation of the clinical results of posterior cruciate ligament reconstruction -a comparison between the use of the bone tendon bone and semitendinosus and gracilis tendons. SMARTT. 2012;4:30.
39. Belk JW, Kraeutler MJ, Purcell JM, McCarty EC. Autograft versus allograft for posterior cruciate ligament reconstruction: an updated systematic review and meta-analysis. Am J Sports Med. 2017;46:1752–7. https://doi.org/10.1177/0363546517713164.
40. Carson EW, Deng XH, Allen A, Wickiewicz T, Warren RF. Evaluation of in situ graft forces of a 2-bundle tibial inlay posterior cruciate ligament reconstruction at various flexion angles. Arthroscopy. 2007;23(5):488–95.
41. Makino A, Costa-Paz M, Aponte-Tinao L, Ayerza MA, Muscolo DL. Popliteal artery laceration during arthroscopic posterior cruciate ligament reconstruction. Arthroscopy. 2005;21(11):1396.
42. Wu RW, Hsu CC, Wang CJ. Acute popliteal artery occlusion after arthroscopic posterior cruciate ligament reconstruction. Arthroscopy. 2003;19(8):889–93.
43. Zawodny SR, Miller MD. Complications of posterior cruciate ligament surgery. Sports Med Arthrosc Rev. 2010;18(4):269–74.
44. Lee GH, McCulloch P, Cole BJ, Bush-Joseph CA, Bach BR Jr. The incidence of acute patellar tendon harvest complications for anterior cruciate ligament reconstruction. Arthroscopy. 2008;24(2):162–6.
45. Stein DA, Hunt SA, Rosen JE, Sherman OH. The incidence and outcome of patella fractures after anterior cruciate ligament reconstruction. Arthroscopy. 2002;18(6):578–83.
46. Ferrari JD, Bach BR Jr. Bone graft procurement for patellar defect grafting in anterior cruciate ligament reconstruction. Arthroscopy. 1998;14(5):543–5.
47. Noyes FR, Barber-Westin SD. Posterior cruciate ligament revision reconstruction, part 1: causes of surgical failure in 52 consecutive operations. Am J Sports Med. 2005;33(5):646–54.