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Controversies in PCL Reconstruction: Why Does PCL Reconstruction Still Underperform? Failure Mechanisms, Residual Laxity, and a Risk Management Framework

A Current Concepts Review

Tunay Erden,*†‡ MD, Luke V. Tollefson,§ MD, Benjiman J. Wilebski,§ MD, Ethan R. Sawyer,§ MD, Taylor J. Freetly,§ MD, and Robert F. LaPrade,§ MD
Investigation performed at Twin Cities Orthopedics, Edina, Minnesota, USA

Background: Posterior cruciate ligament (PCL) reconstruction (PCLR) remains among the least standardized procedures in knee ligament surgery. Despite substantial technical advances, objective residual posterior laxity and functional deficits persist at rates far exceeding those observed after anterior cruciate ligament reconstruction.

Purpose: To critically evaluate the principal controversies in PCLR through the lens of failure mechanisms, residual instability, and individualized risk management.

Study Design: Narrative review.

Methods: A comprehensive search of MEDLINE/PubMed, Embase, and the Cochrane Library was conducted from database inception through February 27, 2026. Search terms included PCLR, PCL failure, residual laxity, posterolateral corner (PLC), tibial slope, all-inside PCL, tibial inlay, double-bundle PCL, and suture augmentation. Published consensus statements and relevant knee ligament surgery guidance documents from the American Academy of Orthopaedic Surgeons, the International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine, and the Orthopaedic Research Society were additionally reviewed. Biomechanical investigations, cadaveric studies, prospective cohort studies, systematic reviews, and meta-analyses were prioritized; case series and expert opinion were included when appropriate.

Results: Eight major controversies were identified: (1) single- versus double-bundle reconstruction; (2) transtibial versus tibial inlay technique; (3) autograft versus allograft selection; (4) the clinical significance of residual posterior laxity; (5) management of concomitant PLC deficiency; (6) rehabilitation and hamstring reintroduction timing; (7) the role of posterior tibial slope correction; and (8) suture augmentation. Across all domains, biomechanical advantages of technically superior approaches have failed to consistently translate into superior patient-reported outcomes. Failure to address PLC insufficiency, decreased posterior tibial slope, and graft-loading forces during rehabilitation represents the most common and preventable constellation of failure risk factors. A standardized definition of PCLR failure does not currently exist in the published literature.

Conclusion: Successful PCLR depends less on identification of a universally superior technique and more on individualized management of biomechanical risk factors. A practical risk stratification framework is proposed to guide surgical decision-making. Future progress requires standardized failure definitions, objective instability assessment protocols, and criterion-based rehabilitation pathways.

Keywords: PCL; knee; ligament; multiple ligament injuries; lateral/posterolateral knee ligament

Posterior cruciate ligament (PCL) injuries remain among the most complex and incompletely solved challenges in contemporary knee ligament surgery. Despite substantial advances in surgical technique and postoperative

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rehabilitation, outcomes after PCL reconstruction (PCLR) continue to lag behind those reported after anterior cruciate ligament (ACL) reconstruction (ACLR), with higher rates of residual laxity, persistent instability, and incomplete return to sport.[6,10,32,34,64,72]

Several fundamental aspects of PCLR remain controversial, including bundle configuration, graft selection, reconstruction technique, rehabilitation progression, management of residual laxity, and the role of slope-correcting osteotomy.[57,76] The field also lacks a universally accepted definition of graft failure, as published studies variably define failure according to revision surgery, laxity thresholds, subjective instability, or osteoarthritis progression—substantially limiting cross-study comparisons.[10]

The purpose of this current concepts review was to examine why PCLR continues to underperform relative to ACLR despite ongoing technical evolution, to characterize the principal mechanisms of failure, and to propose a practical risk management framework for individualized surgical decision-making.

WHY DOES PCLR STILL UNDERPERFORM?

Several fundamental biomechanical and biological realities distinguish PCLR from ACLR and likely account for the persistently inferior outcomes reported in the literature. To begin with, the native PCL possesses substantially greater cross-sectional area and tensile strength than the ACL, and replicating this anatomy with currently available graft constructs—particularly in patients with smaller body habitus or those requiring multiligament reconstructions—remains biomechanically demanding.[19] Unlike the ACL, the reconstructed PCL is subjected to repetitive posterior tibial translation forces throughout early rehabilitation, as hamstring contraction, gravity-dependent posterior tibial sag, and flexion-dependent loading expose the graft to cumulative stress during ligamentization and revascularization.[48]

During transtibial reconstruction, the graft bends acutely around the posterior tibial cortex as it exits the tibial tunnel—the so-called killer turn phenomenon—generating frictional and compressive stresses not encountered in ACLR; importantly, substantial graft angulation persists even with optimized tunnel positioning.[22] In addition, untreated posterolateral corner (PLC) insufficiency substantially increases posterior tibial translation, varus instability, and external rotation, thereby overloading the reconstructed PCL graft and likely contributing to many historical failures previously attributed to isolated graft insufficiency.[38,39] Decreased posterior tibial slope (PTS) similarly increases posterior tibial resting position and substantially elevates stress on PCL graft constructs, particularly in cases of combined PCL-PLC deficiency.[14,54] Beyond sagittal instability, persistent coronal and rotational instability further amplify graft loading through asymmetric compartmental loading and abnormal load sharing across the collateral ligament complex. Varus malalignment increases the moment arm across the lateral compartment, whereas untreated medial-sided laxity may likewise impair restoration of normal knee kinematics by allowing persistent coronal instability.[52] Because the PCL functions within a multiplanar stabilizing network, restoration of sagittal stability alone may be insufficient when coronal or rotational instability remains uncorrected.[41] Finally, significant variation persists in published rehabilitation protocols regarding weightbearing progression, bracing duration, hamstring reintroduction timing, and return-to-sport criteria, further contributing to inconsistent outcomes.[66,76]

Collectively, these factors suggest that when PCLR fails, the underlying cause is rarely attributable to a single isolated technical variable; rather, systematic evaluation of multiple contributing biomechanical risk factors is essential to understand and address the failure. Unsuccessful outcomes more commonly reflect cumulative biomechanical overload involving graft forces, associated instability, sagittal alignment, and rehabilitation-related graft stress acting simultaneously during ligamentization. The interplay of these factors is illustrated schematically in Figure 1.

CONTROVERSY 1: SINGLE-BUNDLE VERSUS DOUBLE-BUNDLE RECONSTRUCTION

The biomechanical rationale for double-bundle (DB) reconstruction is well-founded due to the reciprocal loading patterns of the anterolateral bundle (ALB) and posteromedial bundle (PMB) throughout knee flexion. Reconstruction of the ALB alone may therefore fail to fully restore native PCL kinematics across the full range of motion; importantly, the PMB is preferentially loaded near extension, and its absence may contribute to residual instability in early flexion and extension that single-bundle (SB) ALB-only reconstruction does not address.[8,30]

Cadaveric and biomechanical investigations have consistently demonstrated that DB reconstruction more accurately restores native posterior tibial translation and rotational control compared with SB techniques, particularly at lower flexion angles.[27,28,42,44,56,75] Spiridonov et al[72]—in a case series without a concurrent control group performing a DB technique—reported significant improvements in subjective International Knee Documentation Committee (IKDC) scores (39.3-74.3) and near-complete

*Address correspondence to Tunay Erden, MD, Sports Medicine Center, Acıbadem Fulya Hospital, Department of Orthopaedics and Traumatology, Sütlüce, İmrahor Cd. No. 82, 34275 Beyoğlu, Istanbul 34275, Turkey (email: tunayerden@gmail.com).
†Department of Orthopaedics and Traumatology, Istanbul Health and Technology University, Istanbul, Turkey.
‡Sports Medicine Center, Acıbadem Fulya Hospital, Department of Orthopaedics and Traumatology, Istanbul, Turkey.
§Twin Cities Orthopedics, Edina, Minnesota, USA.
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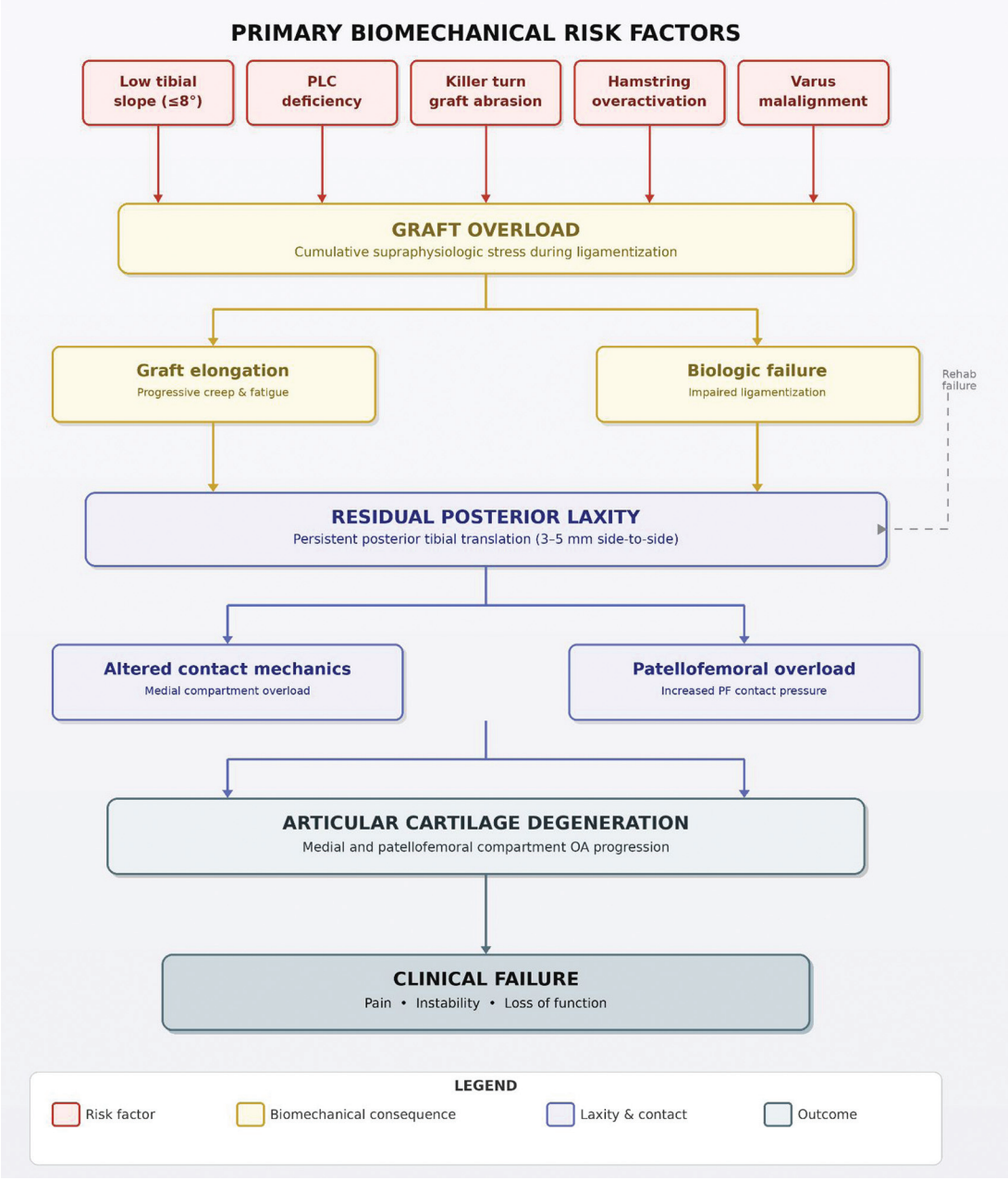


Figure 1. Multifactorial cascade of PCL reconstruction failure. Primary biomechanical risk factors—decreased PTS, PLC deficiency, killer turn graft abrasion, hamstring overactivation, and varus malalignment—converge to produce cumulative graft overload. Graft overload leads to progressive elongation and biologic failure, resulting in residual posterior laxity, altered tibiofemoral and PF contact mechanics, and eventual articular cartilage degeneration. Articular cartilage degeneration is depicted as a downstream consequence of chronic instability and altered joint biomechanics rather than as a defining manifestation of PCL graft failure. OA, osteoarthritis; PCL, posterior cruciate ligament; PF, patellofemoral; PLC, posterolateral corner; PTS, posterior tibial slope.

restoration of posterior tibial translation (15-0.9 mm) at mean 2.5-year follow-up, though the absence of a comparative SB arm limits direct conclusions about technique superiority. A 2023 comprehensive meta-analysis by Dasari et al[9] demonstrated that DB reconstruction yields statistically superior biomechanical outcomes and, when standardized rehabilitation including PCL bracing was applied, significantly superior clinical outcomes compared with SB techniques.

In contrast, multiple systematic reviews including—Chahla et al[7] (441 patients; minimum 2-year follow-up) and Krott et al[31] (603 patients; 13 studies; mean follow-

up not reported as a minimum threshold but ranging from 2 to 10 years across included series)—reported no significant difference in IKDC, Lysholm, or Tegner scores between techniques in pooled analyses. However, these analyses aggregate heterogeneous series in which most included studies used SB techniques without structured bracing protocols, variable rehabilitation regimens, and inconsistent outcome assessment tools—methodological heterogeneity that may systematically obscure a clinically meaningful DB advantage. When rehabilitation variables differ substantially between cohorts, observed equivalence may reflect the diluting effect of inadequate postoperative management rather than true biomechanical parity.[7]

The biomechanical rationale for DB reconstruction is compelling and is supported by consistent cadaveric and in vivo kinematic evidence. However, the current clinical literature remains limited by heterogeneity in rehabilitation protocols, bracing strategies, graft constructs, and instability assessment methods, potentially obscuring clinically meaningful differences in residual laxity and long-term graft durability. Although existing meta-analyses have not demonstrated definitive clinical superiority of DB reconstruction in patient-reported outcomes, available biomechanical evidence consistently demonstrates more anatomic restoration of posterior tibial translation and rotational stability.[30,42,75] Accordingly, DB reconstruction may be considered in selected high-risk patients—including grade 3 injuries, combined instability patterns, and cases in which maximal posterior stability is a primary surgical objective—but higher quality comparative clinical studies remain necessary before it can be recommended as the universal standard. An international expert consensus from 17 countries recently recommended individualized PCL management based on injury grade, patient profile, and associated instability—underscoring that no single technique can be universally recommended at this time.[13]

CONTROVERSY 2: TRANSTIBIAL VERSUS TIBIAL INLAY RECONSTRUCTION

Historically, the killer turn phenomenon has been considered an important biomechanical concern specific to transtibial PCLR.[22] The graft undergoes acute angulation at the posterior tibial cortex as it transitions from the tibial tunnel into the joint, potentially increasing graft stress and abrasion—although the clinical significance of this phenomenon in modern reconstruction remains debated.

The tibial inlay technique was developed to eliminate this angulation by securing the graft directly onto the posterior tibial footprint via a posteromedial approach.[2,58] Biomechanical studies demonstrated reduced graft stress and improved posterior stability with inlay reconstruction under simulated functional loading.[46] However, whether these biomechanical differences translate into clinically meaningful long-term advantages remains uncertain.

However, multiple comparative studies and systematic reviews—including the long-term cohort study by Song et al[70] and the systematic review by Shin et al[69]—have failed to demonstrate consistent clinically meaningful superiority of tibial inlay over transtibial reconstruction with respect to patient-reported outcomes or residual posterior laxity at short- and midterm follow-up. All-inside socket-based approaches represent an evolving middle ground, potentially reducing graft angulation without requiring posterior dissection, though long-term clinical validation remains limited.[45] In addition, the tibial inlay approach introduces important practical challenges, including proximity to the popliteal neurovascular bundle, increased operative complexity, and greater dependence on surgeon experience.[50,59]

Regardless of the reconstruction technique selected, accurate anatomic tunnel placement remains one of the most important determinants of successful PCLR. Malposition of either the femoral or the tibial tunnel alters graft orientation, length-change behavior, and force distribution, potentially resulting in persistent posterior laxity despite an otherwise technically satisfactory reconstruction.[27,28] In particular, anterior femoral tunnel placement has consistently been identified as the most common technical error in revision PCLR, whereas nonanatomic tibial tunnel placement may compromise restoration of the native tibial footprint, increase graft angulation and bending stresses, and adversely affect graft function throughout knee motion.[15] Careful preoperative planning, reproducible anatomic landmarks, intraoperative fluoroscopic confirmation when necessary, and postoperative computed tomography (CT)–based assessment in failed reconstructions are therefore essential components of contemporary PCL surgery.[43]

Current evidence supports both techniques as clinically acceptable strategies. Transtibial reconstruction remains the practical and reproducible standard, benefiting from a fully arthroscopic workflow and lower surgical morbidity. The clinical impact of the killer turn phenomenon in modern PCLR may be less substantial than historically reported, particularly with contemporary soft tissue graft constructs. In revision settings, severe posterior laxity, or cases with borderline graft diameter, strategies that minimize posterior graft angulation—including tibial inlay or all-inside approaches—may offer biomechanical advantages that become clinically relevant over longer follow-up horizons.

CONTROVERSY 3: AUTOGRAFT VERSUS ALLOGRAFT SELECTION

No currently available graft construct fully reproduces the native PCL's structural characteristics: the native PCL has a mean cross-sectional area of approximately 88 mm^2, a reported ultimate tensile load approaching 1620 N, and stiffness substantially exceeding that of commonly used graft constructs—biomechanical parameters that remain unmatched by current autograft or allograft options.[19] Graft selection consequently remains heavily influenced by surgeon preference, patient profile, injury burden, and graft availability.

Autografts provide living tissue capable of biologic incorporation without disease transmission risk. A recent meta-analysis by Belk et al[1] demonstrated modestly superior objective posterior stability with autograft compared with allograft in SB reconstruction. Dzidzishvili et al's[11] 2025 network meta-analysis confirmed that autograft superiority is confined to SB reconstruction, with no significant differences in posterior tibial translation or clinical outcomes when DB techniques are employed. Quadriceps tendon autograft—either with or without a bone plug—has gained increasing interest given its large cross-sectional area (mean, 75-85 mm^2), favorable biomechanical properties, acceptable donor-site morbidity, and versatility in combined ligament reconstructions.[47,67] However, careful graft planning is required, as soft tissue quadriceps tendon grafts without a bone block may provide insufficient graft length for some PCLR techniques. Long-term comparative clinical evidence also remains limited. Bone–patellar tendon–bone has largely fallen out of routine use due to limited graft volume and abrasion concerns at the posterior tibial cortex, and donor-site morbidity—including anterior knee pain—which may be particularly relevant in patients with chronic PCL deficiency because of the increased patellofemoral contact pressures associated with this condition.[22,44]

Allografts—particularly Achilles tendon, tibialis anterior, and tibialis posterior allografts—provide critical advantages in multiligament surgery, revision reconstruction, and situations requiring large graft volume.[49] Processing methodology is the central determinant of allograft performance: irradiated allografts demonstrate significantly inferior mechanical properties and higher clinical failure rates compared with fresh-frozen preparations.[73] Fresh-frozen allograft should therefore be preferred when allograft is selected.

For young, high-demand patients undergoing primary PCLR, autograft—preferably quadriceps tendon or multistrand hamstring or peroneus longus—should remain the preferred option for SB PCLRs. Peroneus longus autograft may represent a reasonable alternative in selected patients requiring greater graft diameter or length, although robust long-term comparative evidence remains limited. In multiligament injury, revision reconstruction, or situations requiring substantial graft volume, fresh-frozen allograft remains indispensable. Graft selection should ultimately be individualized according to biomechanical demands, injury burden, anatomic constraints, and surgeon experience.

CONTROVERSY 4: RESIDUAL POSTERIOR LAXITY—DOES IT REALLY MATTER?

Residual posterior laxity remains one of the most common yet heterogeneously reported outcome measures after PCLR and unlike ACLR, measurable translation frequently persists after PCLR even in patients reporting functional improvement.[10,18,53] Published studies vary substantially in how reconstruction success is operationally defined—failure thresholds for side-to-side posterior translation range from >5 mm to >10 mm, while others define failure according to revision surgery, subjective instability, or inability to return to activity.[17,51] Revision surgery likely underestimates the true incidence of reconstruction failure, as some patients with persistent instability or functional limitations may decline further surgery or are not offered revision because of its technical complexity. This definitional heterogeneity makes cross-study comparison unreliable and pooled meta-analyses difficult to interpret meaningfully.

This definitional heterogeneity creates fundamental interpretation problems and makes cross-study comparison unreliable. To illustrate: Spiridonov et al,[72] using anatomic DB reconstruction with a structured postoperative protocol, reported a mean postoperative posterior tibial translation of 0.9 mm on posterior stress radiography, with significant improvements in subjective IKDC scores from 39.3 to 74.3 at mean 2.5-year follow-up. In pooled analyses of isolated PCLRs, mean postoperative side-to-side posterior tibial translation ranged from 2.7 to 4.1 mm depending on the technique and rehabilitation protocol, with 57% to 82% of patients achieving normal or near-normal objective IKDC scores.[9,10,53] These differences likely reflect the combined effect of reconstruction technique, rehabilitation protocol and postoperative bracing, and outcome assessment methodology—yet they are treated as equivalent failure rates in pooled meta-analyses.

Furthermore, the relationship between objective posterior laxity and patient-reported functional outcomes is more complex than a simple linear correlation. Mygind-Klavsen et al,[53] in a large cohort of 172 patients with a mean follow-up of 5.9 years, reported that patients with a mean side-to-side posterior tibial translation difference of only 2.7 mm achieved subjective IKDC scores of 63.8 and Knee injury and Osteoarthritis Outcome Score Sport and Recreation subscale scores of only 55, suggesting that measurable residual laxity does not reliably predict subjective functional status. Gwinner et al[18] further demonstrated in a magnetic resonance imaging (MRI)–based long-term investigation of 42 patients that degenerative changes after PCLR occurred predominantly in the patellofemoral and medial tibiofemoral compartments and were not consistently correlated with the degree of residual posterior tibial translation. However, interpretation of these findings is limited by potential confounding factors, including chronicity of injury before reconstruction, which may independently influence cartilage degeneration. Some patients tolerate measurable residual laxity remarkably well over the short and medium term, while others remain significantly symptomatic despite relatively small objective instability differences. This dissociation between objective laxity and subjective outcome likely reflects the multifactorial nature of knee function after PCLR, including neuromuscular compensation, activity modification, contralateral limb dominance, and individual pain thresholds—none of which are captured by stress radiography alone.

This apparent disconnect, however, does not diminish the long-term biological significance of residual posterior translation. Even when subjective outcomes appear

acceptable, chronic posterior tibial sag alters tibiofemoral contact mechanics, concentrates load on the medial compartment, and substantially elevates patellofemoral contact pressures. Gill et al[15,16] demonstrated in sequential cadaveric investigations that SB PCLR does not fully restore normal knee kinematics under physiologic muscle loads and that patellofemoral contact pressures remain significantly elevated after reconstruction compared with the intact knee. The clinical relevance of these biomechanical deficits is confirmed by long-term outcome data: Schroven et al,[64] in a systematic review of 27 studies including 5197 patients, reported that operative management was associated with a substantially lower rate of medial compartment degenerative changes compared with nonoperative treatment (21.5% vs 44.1%), underscoring that residual posterior laxity carries measurable long-term articular cost regardless of short-term subjective functional status.

Objective Instability Assessment: A Critical Infrastructure Gap

A major reason residual laxity remains poorly characterized in the literature is the absence of standardized objective assessment protocols. Currently utilized methods include gravity stress radiography (posterior tibial sag view), kneeling stress radiographs, Telos stress device–assisted posterior drawer radiography, and instrumented posterior tibial translation measurement using devices such as the KT-1000 arthrometer or rolimeter.[17,25]

Each modality has distinct advantages and limitations. Gravity sag radiography is simple and reproducible but lacks standardized force quantification. The posterior drawer radiography provides the most standardized force application (typically 150 N) and has demonstrated acceptable interrater reliability in validation studies, but requires specific equipment and positioning protocols not uniformly available.[23,26] Kneeling stress radiographs are increasingly utilized in European and North American centers as a weightbearing assessment of posterior tibial position, but normative data and validated side-to-side difference thresholds remain limited.

Objective stress radiography should be incorporated into all future prospective PCL outcome studies, with side-to-side posterior tibial translation reported in millimeters. Among available methods, kneeling stress radiographs may represent the most practical and clinically reproducible approach for routine assessment among different research centers.[17] Categorical posterior drawer grading based on clinical examination alone is insufficient for objective outcome reporting and should be supplemented by instrumented stress radiography in all research contexts.

Residual posterior laxity should not be dismissed on the basis that short-term patient-reported outcomes appear acceptable. Objective instability represents a continuum with both immediate kinematic consequences and cumulative long-term biological consequences, especially in the younger age patients that typically undergo PCLR. The field clearly requires standardized operational definitions that clearly distinguish between graft rupture, residual laxity without instability, clinically relevant instability, revision failure, and degenerative progression. Until such standardized definitions are adopted, meaningful comparison and meta-analysis of PCLR literature will remain fundamentally limited. The field clearly requires standardized operational definitions that distinguish graft rupture, residual laxity without instability, clinically relevant instability, revision failure, and degenerative progression, together with standardized objective assessment using validated stress radiography.[13,17]

CONTROVERSY 5: MANAGEMENT OF THE PLC

The biomechanical interaction between the PCL and the PLC structures—specifically the fibular collateral ligament (FCL), popliteal tendon, and popliteofibular ligament—is inseparable from a functional standpoint.[38] LaPrade et al[38,39] established through systematic cadaveric investigation that PLC deficiency substantially increases posterior tibial translation, varus instability, and external tibial rotation under functional loading, directly overloading any PCL graft construct. Although direct clinical evidence linking these increased graft forces to subsequent graft rupture or revision remains limited, clinical comparative data indicate that incomplete treatment of combined PCL-PLC instability is associated with greater residual posterior laxity and inferior functional outcomes.[20,39,77]

The popliteal tendon and popliteofibular ligament function not only as static restraints but as dynamic stabilizers of posterolateral rotation, particularly during active terminal extension and single-limb stance.[39] This dynamic role, combined with load sharing that increases significantly at higher flexion angles, explains why PLC-deficient knees subject PCL grafts to forces substantially greater than static loading models alone would predict.[41]

Varus malalignment compounds this problem significantly. In knees with constitutional or posttraumatic varus alignment, the mechanical axis passes medial to the knee center, systematically overloading the FCL–popliteal complex with every step.[38,39] The combination of varus malalignment, PLC deficiency, and posterior tibial translation creates a mechanically hostile environment for PCL graft survival that ligament reconstruction alone may not reliably corrected; in such patients, concomitant evaluation for high tibial valgus osteotomy is warranted.

Rotational instability overload represents an equally important and frequently underappreciated failure mechanism. Persistent external rotation instability from untreated PLC deficiency, primarily in the popliteal tendon and popliteofibular ligament, generates asymmetric torsional forces within the PCL graft substance that are not captured by standard posterior tibial translation measurements.[65] The dial test at both 30° and 90° of knee flexion, combined with external rotation asymmetry of $\geq$10°, should be interpreted as a strong indicator of combined PCL-PLC pathology requiring comprehensive surgical planning.[44,65]

The clinical consequence is unambiguous: isolated PCLR in the presence of unrecognized or undertreated PLC deficiency is among the most preventable causes of PCL graft failure.[20] Yoon et al[77] demonstrated that combined PCL-PLC reconstruction yielded significantly superior posterior and rotational stability compared with isolated PCLR in combined injury patterns—findings supported by the LaPrade group and subsequent meta-analysis data.[33,42]

Despite this well-established evidence, underdiagnosis of PLC injury remains a significant clinical problem, as physical examination findings in the chronic setting may be subtle and require systematic, experience-dependent assessment.[36] Varus stress radiography and dedicated MRI evaluation are essential in the preoperative workup of all patients with posterior tibial laxity greater than grade 2.[35] Several anatomic reconstruction techniques have been described. The fibula-based anatomic PLC reconstruction described by LaPrade et al[37] is among the most extensively studied and has demonstrated excellent biomechanical restoration and clinical outcomes. Other widely adopted techniques include the modified Larson and Arciero reconstructions, which have likewise reported favorable biomechanical properties and clinical outcomes.[68,79]

The evidence on this point is sufficiently strong that this controversy is, in fact, increasingly resolved. In any confirmed combined PCL-PLC injury, simultaneous anatomic PLC reconstruction should strongly be considered standard practice. Failure to systematically evaluate for PLC injury in every patient presenting with posterior tibial instability—and failure to address documented PLC deficiency at the time of PCLR—represents a failure of preoperative planning rather than a technical error. We routinely obtain bilateral varus stress radiographs using a standardized clinician-applied technique with side-to-side comparison in all patients with suspected grade 2 or 3 PCL injuries. Side-to-side differences of approximately 2.7 mm and 4.0 mm are considered suggestive of isolated FCL and grade 3 PLC injuries, respectively. However, because PLC injuries frequently produce rotational instability that may not be detected on varus stress radiographs alone, imaging findings should always be interpreted in conjunction with the clinical examination, including rotational stability testing (particularly the dial test), and MRI.[36]

CONTROVERSY 6: REHABILITATION AND HAMSTRING REINTRODUCTION

Rehabilitation after PCLR remains the least standardized component of the entire treatment pathway—and arguably the one with the greatest potential to undermine an otherwise technically sound reconstruction.[66] The fundamental biomechanical challenge is that hamstring contraction generates posterior tibial translation and directly loads the PCL graft during the ligamentization period, as quantified in cadaveric robotic analyses demonstrating significant increases in PCL in situ forces under isolated hamstring loading across all tested flexion angles.[21,76]

Most contemporary protocols avoid resisted open-chain hamstring exercises for a minimum of 12 to 16 weeks postoperatively, though prolonged hamstring inhibition contributes to quadriceps-dominant muscle imbalance and delayed proprioceptive restoration.[62,66]

The distinction between open- and closed-chain loading is therefore not merely a programming preference but a graft protection strategy. Closed kinetic chain co-contraction exercises—leg press, squat, and step-up—allow progressive hamstring engagement in a quadriceps-dominant context while substantially limiting isolated posterior tibial displacement and graft stress.[21,62]

Dynamic PCL bracing is not merely supportive but serves an important biomechanical role during the early and intermediate phases of rehabilitation. Unlike static knee immobilizers, dynamic braces apply an anteriorly directed force that counteracts gravity-dependent posterior tibial sag and posterior tibial translation during early knee flexion, thereby reducing posterior graft loading during graft ligamentization. Jacobi et al[24] demonstrated that appropriately fitted dynamic PCL bracing substantially reduces posterior tibial sag in the nonweightbearing limb, while LaPrade et al[40] demonstrated that dynamic PCL braces generate an anteriorly directed force across the knee during flexion. Although direct clinical evidence demonstrating that these biomechanical effects translate into improved long-term graft survival or reduced residual laxity after PCLR remains limited, persistent posterior tibial sag during the biologically active ligamentization period provides a strong biomechanical rationale for graft protection and represents a potentially modifiable rehabilitation-related risk factor.

The postoperative rehabilitation environment likely plays a substantially larger role in PCLR outcomes than is currently appreciated. Inadequate static bracing, premature open-chain hamstring loading, and gravity-dependent posterior tibial sag during ligamentization are not minor oversights—they represent modifiable graft overload risk factors. We favor prolonged structured dynamic bracing protocols—for a minimum of 6 months—particularly in grade 3, combined-instability, and DB reconstructions, while recognizing that optimal duration and specific indications remain incompletely defined. Future rehabilitation research should prioritize standardized criterion-based protocols and prospective evaluation of prolonged dynamic bracing strategies.[76]

CONTROVERSY 7: PTS CORRECTION

Interest in the biomechanical role of PTS in PCL-related instability has grown substantially over the past decade.[3-5] Giffin et al[14] first demonstrated through cadaveric analysis that decreased PTS increases posterior tibial resting displacement and elevates strain in the PCL, establishing a mechanistic basis for clinical concern.

A 2024 systematic review by Nedaie et al,[54] comprising 9 studies and 1054 patients, identified decreased medial PTS as a significant independent risk factor for both primary PCL rupture and PCL graft failure, with values below approximately 3.9° representing a clinically meaningful

threshold. These findings identify decreased PTS as a biomechanical risk modifier rather than an independent indication for primary slope-correcting osteotomy. Fahlbusch et al[12] subsequently reported significantly inferior outcomes in patients with decreased PTS undergoing combined PCL-PLC reconstruction, with persistent posterior instability correlating with tibial slope values below 8°.

Slope-correcting anterior open-wedge high tibial osteotomy increases PTS, reduces posterior tibial resting position, and theoretically decreases stress on PCL graft constructs.[61] However, data from Bernhardson et al[4] demonstrated that anatomic DB PCLR may compensate for the adverse effects of decreased PTS on postoperative posterior laxity—suggesting that the clinical importance of slope correction may be technique dependent. No universally accepted PTS threshold for osteotomy indication currently exists, and the added complexity, recovery time, and complications of combined tibial osteotomy and ligament reconstruction must be weighed carefully in the absence of high-level comparative evidence.[14,54]

Routine slope correction for all PCLRs cannot currently be justified by available evidence. However, failure to evaluate sagittal tibial alignment in revision PCLR or severe recurrent posterior instability is increasingly difficult to justify biomechanically. Patients with markedly decreased medial PTS—particularly in the setting of recurrent instability, revision reconstruction, or persistent posterior tibial sag despite technically adequate prior reconstruction—represent a population in whom slope correction deserves serious consideration. Whether decreased PTS should be interpreted as an isolated morphologic threshold or as a biomechanical modifier whose clinical relevance depends on the magnitude of existing instability and the presence of concurrent rotational deficiency remains an important open question. This interaction-based perspective may partially explain why proposed slope thresholds remain inconsistent across published studies, and suggests that future decision-making should integrate slope measurements with objective instability severity rather than relying on slope values alone. We now routinely measure PTS on standardized lateral radiographs in all patients presenting for revision PCL surgery and consider slope correction an integral part of revision planning in appropriately selected patients.

CONTROVERSY 8: SUTURE AUGMENTATION ("INTERNAL BRACE")

Suture augmentation (SA) (commonly referred to as an "internal brace") using ultra–high molecular weight polyethylene tape represents one of the most recent developments in PCLR.[63] The biomechanical rationale is conceptually attractive: a synthetic construct with defined stiffness and elongation characteristics theoretically shields the biologic graft from excessive loading during the vulnerable early ligamentization period, reducing the risk of progressive graft elongation.[74]

Zhao et al[78] reported encouraging short-term posterior stability and acceptable complication profiles in a retrospective cohort undergoing PCLR with SA reinforcement, and Nestorovoski et al[55] described technically feasible reproducibility with early favorable outcomes using an all-inside DB technique with SA augmentation.

High-level comparative evidence, however, remains absent. The central unresolved question is the stress-shielding paradox: does SA augmentation achieve its intended purpose of reducing graft elongation, or does mechanical protection impair the mechanobiologic stimulus required for normal ligamentization and graft remodeling.[71] Mechanobiologic theory holds that physiologic cyclic loading is essential for organized collagen fiber alignment, vascular ingrowth, and progressive tensile strength development.[60,63,71] This creates a potential paradox in which the same construct designed to protect the graft mechanically may simultaneously reduce the physiologic loading stimulus required for optimal biologic remodeling.[60,71] A synthetic augment that shields the graft from its normal loading environment may therefore alter remodeling kinetics in ways that prospective comparative histologic and biomechanical studies have not yet resolved. Additional concerns include long-term synthetic tape fatigue, altered graft remodeling, and added implant burden.

SA represents a biomechanically attractive but still investigational strategy. Current evidence supports cautious selective application in high-risk clinical scenarios—generalized ligamentous laxity (Beighton score ≥ 5), severe grade 3 multiligamentous instability, soft tissue grafts under high tension, and revision reconstruction with prior graft elongation. The long-term mechanobiologic consequences of stress shielding remain incompletely understood, and SA should be considered a selective adjunct rather than a routine component of primary isolated PCLR. Prospective comparative studies with long-term objective instability and graft maturation assessment are required before broader adoption can be recommended.

REVISION PCLR

Revision PCLR represents one of the most technically demanding scenarios in knee ligament surgery.[43] Successful revision planning begins with systematic identification of the primary failure mechanism. Accurate failure classification is not academic taxonomy—it is the foundation of effective revision surgery, because graft replacement without correction of the underlying biomechanical failure mechanism is highly likely to reproduce the primary failure.

PCLR Failure Classification

Contributing failure mechanisms include tunnel malposition, graft elongation, residual or unaddressed PLC deficiency, tunnel widening and osteolysis, untreated sagittal malalignment, and rehabilitation-related graft stretching during the ligamentization period (Table 1).[76] Comprehensive preoperative evaluation should include standardized stress radiography, long-leg alignment radiographs, CT-based tunnel analysis, MRI assessment of PLC integrity

TABLE 1
Proposed Classification of PCL Reconstruction Failure Mechanisms[a]

Failure Category	Specific Mechanisms
Technical failure	Tunnel malposition (most common: anterior femoral tunnel), inadequate graft tensioning, fixation failure, killer turn–related graft abrasion, iatrogenic medial meniscal injury
Biologic failure	Graft necrosis, impaired ligamentization, avascular necrosis related to tunnel positioning, infection
Unrecognized associated instability	Missed PLC deficiency (most common associated failure), missed medial-sided injury, missed ACL codeficiency in multiligament setting
Alignment-related failure	Decreased posterior tibial slope with persistent posterior tibial resting force, varus malalignment with PLC overload, coronal plane deformity
Rehabilitation-related failure	Premature open-chain hamstring loading, inadequate bracing during ligamentization, early return-to-sport before graft maturation

[a]ACL, anterior cruciate ligament; PCL, posterior cruciate ligament; PLC, posterolateral corner.

TABLE 2
Proposed Risk Management Framework for Individualized PCL Reconstruction Decision-Making[a]

Clinical Scenario	Risk Stratification	Recommended Strategy
Isolated grade 1-2 injury, athlete	Low	Structured conservative management + dynamic PCL bracing; delayed reconstruction if failure
Isolated grade 3, recreational patient	Moderate	Anatomic double-bundle reconstruction preferred; allograft preferred; structured postoperative dynamic PCL bracing recommended
Isolated grade 3, elite/high-demand athlete	Moderate-high	Anatomic double-bundle; autograft or allograft; structured rehabilitation with bracing protocol
Combined PCL + PLC injury	High	Simultaneous anatomic PCL (double-bundle preferred) + fibular-based PLC reconstruction; staged if acute/swollen
Generalized ligamentous laxity (Beighton ≥ 5)	High	Double bundle with possible suture augmentation; prolonged dynamic bracing; criterion-based rehabilitation
Decreased PTS ($\leq 8°$) + grade 3	High	Double-bundle reconstruction; slope-correcting osteotomy discussion should be strongly considered in revision settings
Multiligament injury (≥ 3 structures)	Very high	Staged or simultaneous comprehensive double-bundle reconstruction; fresh-frozen allograft; multidisciplinary planning
Revision + tunnel malposition with overlap or widening >12 mm	Very high	Staged: bone grafting $\longrightarrow$ 4- to 6-month delay $\longrightarrow$ revision double-bundle PCL reconstruction + slope and alignment correction
Revision + failed prior reconstruction	Very high	Full biomechanical failure analysis; CT tunnel mapping; long-leg alignment; PLC re-evaluation; structured prolonged bracing protocol

[a]CT, computed tomography; PCL, posterior cruciate ligament; PLC, posterolateral corner; PTS, posterior tibial slope.

and cartilage status, and systematic examination under anesthesia with side-to-side comparison.[76] Particular attention should also be directed toward identifying iatrogenic medial meniscus posterior root injury, which has been reported as a potential but underrecognized cause of early onset medial compartment arthritis, persistent instability and graft overload following PCLR.[29]

Tunnel malposition—particularly anterior femoral tunnel placement and nonanatomic tibial tunnel positioning—remains the most common identifiable technical failure mechanism in published revision series.[15] When tunnel malposition is suspected, accurate assessment should include CT-based evaluation of tunnel orientation, footprint restoration, tunnel widening, and convergence before revision planning.

Revision PCLR is best conceptualized as a biomechanical correction procedure rather than simply a graft replacement operation. Unless the underlying biomechanical causes of failure—including associated instability, sagittal malalignment, tunnel malposition, and rehabilitation-related overload—are systematically corrected, repeat graft failure remains highly likely. A staged approach is generally recommended for revisions with enlarged tunnels (>12 mm), with bone grafting followed by a minimum 4- to 6-month interval before definitive ligament reconstruction.

PRACTICAL RISK MANAGEMENT FRAMEWORK

Current evidence collectively suggests that successful PCLR depends less on identification of a universally superior isolated technique and more on matching the surgical strategy to the individual patient's biomechanical risk profile. The following framework is proposed to guide individualized decision-making (Table 2).

FUTURE DIRECTIONS

Future progress will require less invention of new techniques and more systematic improvement of the infrastructure surrounding PCL surgery. Five priorities stand out as most critical for advancing the field.

First, the field must adopt standardized operational definitions for reconstruction failure, residual laxity, and graft rupture as universal reporting requirements in all prospective PCL studies. Without these, pooled analyses will continue to produce conclusions that are artifacts of definitional heterogeneity rather than true biological or technical differences.

Second, standardized objective instability assessment—particularly through validated stress radiography protocols such as kneeling or Telos-assisted posterior stress radiographs—must be more widely adopted as a minimum reporting standard. Subjective outcome scores alone are insufficient to characterize the biomechanically meaningful differences between reconstruction approaches.

Third, long-term comparative studies with a minimum 10-year follow-up are needed to evaluate graft durability and articular cartilage preservation, as the most clinically consequential differences between techniques are not detectable at the short- and midterm follow-up intervals that dominate the current literature.

Fourth, prospective investigation of slope-correcting osteotomy and SA in appropriately selected high-risk populations is needed, with biomechanical and patient-reported coprimary endpoints.

Fifth, criterion-based individualized rehabilitation pathways—incorporating objective neuromuscular benchmarks and validated return-to-sport clearance protocols specific to PCLR—must replace the current patchwork of time-based protocols. Until rehabilitation is standardized alongside surgical technique, it will remain impossible to determine whether observed outcome differences reflect surgical variables or postoperative management.

CONCLUSION

PCLR remains characterized by persistent biomechanical and biological uncertainty that has resisted resolution despite decades of technical refinement. Residual posterior laxity and reconstruction failure occur at rates substantially exceeding those observed after ACLR and are unlikely to be fully explained by any single technical variable.

The available evidence consistently indicates that successful outcomes depend less on the selection of a single universally superior technique and more on the systematic identification and individualized management of specific biomechanical risk factors present in each patient: graft forces during ligamentization, PLC deficiency, PTS abnormalities, tunnel positioning, and rehabilitation-related graft stress.

The field should transition away from simplified binary debates toward more nuanced, patient-specific risk stratification models that integrate biomechanical analysis, objective instability assessment, sagittal alignment evaluation, and individualized rehabilitation programming. Future progress will depend not on isolated technical innovation alone, but on broader integration of these principles alongside standardized outcome definitions across the field.

ORCID iDs

Tunay Erden https://orcid.org/0000-0002-0926-5879
Luke V. Tollefson https://orcid.org/0009-0004-6650-3935
Taylor J. Freetly https://orcid.org/0000-0001-9687-7701
Robert F. LaPrade https://orcid.org/0000-0002-9823-2306

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