Review Article

Graft Tensioning During Knee Ligament Reconstruction: Principles and Practice

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Abstract

Failure to correctly tension grafts may overconstrain or underconstrain the knee, potentially predisposing the patient to deteriorating clinical and/or radiographic results over time. Knee ligament reconstruction requires a fundamental understanding of native anatomy, ligament biomechanics, and principles of graft tensioning. A successful strategy for graft tensioning takes into account the specific biomechanics of the ligament or ligaments in question, the mechanical properties of the graft selected, the chosen fixation method, the selected tensioning method (ie, manual or mechanical), and the overall goal of the reconstruction (ie, isometry versus anisometry).

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Knee ligament reconstructions are among the most commonly performed orthopaedic surgeries.[1] Despite the widespread utility of these procedures, variation exists regarding appropriate intraoperative graft tensioning.[2-9] Although clinical evidence is largely equivocal or lacking,[5,8] the theoretic implications of improper graft tensioning are substantial, potentially leading to suboptimal clinical and radiographic results over time. Graft undertensioning could lead to residual laxity, with a graft that behaves biomechanically similar to a ligamentously deficient knee.[7] Conversely, graft overtensioning can lead to flexion contracture, increased ligamentous stress, graft breakdown, subluxation of the tibia, and increased articular contact pressures.[2,10-15]

To optimize graft tensioning for knee ligament reconstruction, the surgeon must have a thorough appreciation for native knee anatomy, biomechanics, and kinematics. It is critical to understand the specific mechanical properties of the selected graft and fixation method and to determine the biomechanical goals of the reconstruction.

Biomechanical Basis of Graft Tensioning

Anatomy

A well-executed knee ligament reconstruction should restore the patient's native anatomy. Although the details of footprint and bundle anatomy are beyond the scope of this review, it must be understood that graft tensioning is immaterial if primary fixation points are nonanatomic. For example, nonanatomic vertical anterior cruciate ligament (ACL) grafts placed superior or proximal to the femoral footprint fail more frequently, predisposing the knee to greater anterior laxity and loss of flexion.[16] The surgeon must first choose the anatomic target structure to restore. Subsequent graft tensioning is dependent on replicating the specific biomechanical function of that ligament or bundle to best recreate native knee kinematics.

Isometry and Anisometry

To develop a rationale for appropriate graft tensioning, the surgeon must understand several key biomechanical concepts. Knee ligaments are divided into isometric and anisometric structures. Isometric ligaments are of equal length and tension regardless of the angle of knee flexion because the distance between their origin and insertion sites does not change with knee flexion. Assuming anatomic positioning in an isometric graft, the angle of knee flexion at the time of tensioning should not affect the kinematics of the reconstruction.

In anisometric structures, such as the ACL and its bundles,[11,17] the posterior cruciate ligament (PCL) and its bundles,[3] and the posterolateral corner of the knee (PLC),[18-20] the length and tension of the construct changes with knee flexion. For instance, placement of the femoral footprint at the roof of the notch is not only nonanatomic, but it also results in anisometric reconstruction.[21] This can be easily demonstrated during ACL reconstruction (ACLR) by flexing and extending the knee after femoral fixation; graft recession in the tibial tunnel is noticeable during extension. Therefore, the angle of flexion at the time of ligamentous tensioning is extremely important and will affect the biomechanical behavior of the reconstruction. For example, the posterolateral bundle of the ACL is physiologically tense in extension and lax in flexion.[22] If this ligament is tensioned in extension, when the origin and insertion sites are farther apart, then relative ligamentous laxity will be experienced when the knee is brought into flexion, as occurs with native kinematics. However, if this ligament is tensioned in flexion, when the native ligament is less tense and shorter, then graft tension when the knee is brought to extension will exceed native ligament tension, which may lead to stiffness, flexion contracture, or graft attenuation. We generally recommend tensioning at the position of maximum physiologic tension to recreate native laxity. Understanding anisometry allows the surgeon to choose the appropriate tension angle, thus preserving range of motion while maximizing knee stability.

Biomechanical Considerations in Graft Selection

A variety of grafts has been used for knee ligament reconstruction. These graft choices are differentiated by their biomechanical properties, most notably their stiffness and viscoelastic activity. With tensile forces, stiffness is defined as force per unit area of lengthening. A graft with a higher stiffness value requires more force to create the same degree of lengthening. Of the commonly used grafts, bone–patellar tendon–bone (BPTB) grafts have the greatest stiffness (Figure 1). Because BPTB grafts are stiffer, less tension is required to recreate normal kinematics. With a less stiff graft, more stretch is experienced with regular knee motion. This may be perceived by the patient as increased laxity. To avoid this problem, greater tension must be applied at the time of initial fixation. For example, in cadaver knees, the tension requisite to recreate anatomic knee ACL tension is 16 N for BPTB constructs and 38 N for the doubled, non–pre-tensioned semitendinosus tendons.[29] In clinical study, a recent meta-analysis demonstrated postoperative laxity, defined as a KT-1000 arthrometer (Medmetric, San Diego, CA) side-to-side difference of >3 mm, to be less prevalent in patients who receive BPTB compared with those who receive hamstring grafts.[1] This less prevalent laxity may be because of the combination of stiffness and stress relaxation phenomena. These results have led several authors to suggest that hamstring grafts should be more highly tensioned than BPTB grafts to avoid postoperative excess laxity.[5,30]

Viscoelastic activity is another critical concept in graft selection. Vis-

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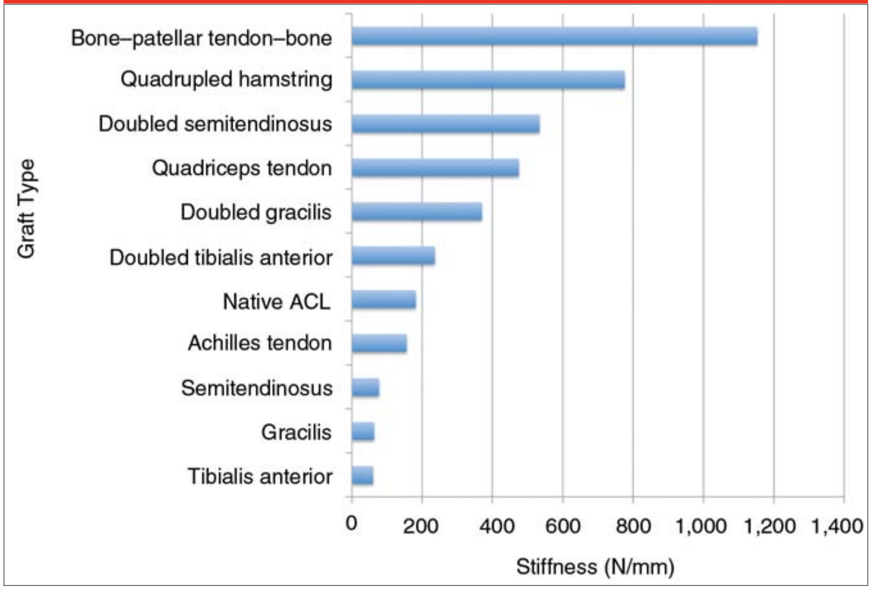
coelastic activity is defined as the nonlinear, time-dependent change in strain (ie, change in length over unit length) in response to a constant stress (ie, force per unit area). Creep and stress relaxation are important types of viscoelastic behavior. These refer, respectively, to the permanent and nonpermanent lengthening of a ligament in response to axial tension. Because of a ligament's viscoelasticity, the tension in a ligament at the time of intraoperative tensioning may differ substantially from the tension on that structure during physiologic load after equilibration. For example, hamstring grafts exhibit viscoelastic behavior and postoperative graft stretching. Semitendinosus and gracilis grafts loaded at 65 N for 15 minutes lose up to 50% of their original tension, whereas primate patellar tendons loaded at an average of 50 N for 10 minutes lost only a maximum 30% of their original tension.[28,31] In a cadaver ACLR study of doubled hamstring tendons, more than half of the tendon tension was lost, and KT-1000 translation notably increased in response to intraoperative knee cycling, with KT-1000 values of 5.8 mm for the intact knee, 8.1 mm for the reconstructed knee, and 10.5 mm for the post-cycled knee.[32]

Pre-tensioning the graft may prevent ligament lengthening, loss of tension, and development of postoperative laxity. An in vivo study of quadrupled semitendinosus/gracilis grafts showed that pre-tensioning with 50 intraoperative flexion/extension cycles from zero degrees to 110° decreased lengthening by 7.7 mm.[33] In vivo lengthening of >0.5 mm has been demonstrated in BPTB grafts intraoperatively with similar cycling.[34] These findings suggest that pre-tensioning may help reduce the development of postoperative laxity, especially in hamstring grafts. Clinical trials are lacking, however.

The literature supports pre-tensioning of soft-tissue allografts and autografts. Our practice is to use a graft tensioning board, tensioning the graft with maximum one-hand pull. The graft remains on this board for the portion of the operation between harvest and graft passage. The rate of tension loss is lower in BPTB grafts, obviating the need for pre-tensioning. Alternatively, fixing the femoral side and manually overtensioning the tibial side with repetitive cycling of the knee through a complete range of motion can dynamically pre-tension a graft.[4,5,7,8,11,25,32,33]

Figure 1



Stiffness for various grafts used in anterior cruciate ligament (ACL) reconstruction. Data sources: bone–patellar tendon–bone,[23] quadrupled hamstring,[24] doubled semitendinosus,[24] quadriceps tendon,[25] doubled gracilis,[24] doubled tibialis anterior,[26] native ACL,[23] Achilles tendon,[27] semitendinosus,[28] gracilis,[28] and tibialis anterior.[26]

Biomechanical Considerations in Fixation Method

Graft fixation strength varies substantially between fixation types (Table 1). Differences in fixation stiffness can reach an order of magnitude: 18 N/mm for the EndoButton (Smith & Nephew, Memphis, TN)/suture post combination to 269 N/mm for the interference screw/WasherLoc (Biomet, Warsaw, IN) combination.[14] In clinical practice, these variations may manifest as differences in postoperative laxity. In one series of 60 nonrandomized (ie, by order of appointments instead of by prepared, sealed, opaque envelopes) patients who underwent ACLR with hamstring grafts, there was a difference in objective radiographic outcomes depending on fixation with interference screw versus transcondylar cross-pins.[33] The use of aperture fixation (ie, BPTB with intra-articular screw fixation) versus suspensory fixation (ie, cortical button for quadrupled hamstring grafts) may increase overall construct stiffness, may allow for earlier and aggressive range of motion, and may contribute to decreases in postoperative laxity.[35] Suspensory fixation also may subject grafts to the so-called windshield wiper effect: because of greater distance between the fixation

Table 1

Fixation-type Stiffness in Anterior Cruciate Ligament Reconstruction (in N/mm)

Femoral Fixation	No. 5 Sutures Tied to Post at 70 N/mm	Double Staples at 174 N/mm	One 20-mm Washer at 192 N/mm	Two Tandem Washers at 318 N/mm	Metal Interference Screw at 340 N/mm	WasherLoc[a] at 506 N/mm
EndoButton[b] at 24 N/mm	18	21	21	22	22	23
Mitek[c] anchor at 26 N/mm	19	23	23	24	24	25
Bone mulch screw with bone compaction at 575 N/mm	62	134	144	205	214	269

[a] Biomet, Warsaw, IN
[b] Smith & Nephew, Memphis, TN
[c] DePuy Mitek, Raynham, MA
Adapted with permission from Karchin A, Hull ML, Howell SM: Initial tension and anterior load-displacement behavior of high-stiffness anterior cruciate ligament graft constructs. *J Bone Joint Surg Am* 2004;86(8):1675-1683.

point and the joint, the graft can move back and forth within the tunnels during motion cycles, potentially increasing laxity over time. As a rule, aperture fixation methods avoid problems related to the windshield wiper effect from micromotion by providing secure intra-articular fixation at the anatomic origin and insertion of the graft.[36]

An important caveat of tibial aperture fixation is the difficulty of hardware removal in a revision situation. If a surgeon chooses to use a construct with less stiff fixation, then supraphysiologic tension may be required to reproduce physiologic laxity. Use of high-stiffness graft and fixation methods requires lower intraoperative tension to reach the desired native knee ligament tension.[14] In general, time zero graft fixation parameters with most available fixation devices exceed physiologic loads in the early postoperative period, leading to a very low incidence of reported early clinical failures.

Method of Tensioning

Several devices have been developed to aid surgeons in the application and measurement of graft tension at the time of fixation. These include the Tension Isometer (Medmetric) Graft Tensioner (Arthrotek, Warsaw, IN), and the Intrafix device (DePuy Mitek, Norwood, MA). The maximum tension applied with a single hand pull by a sports medicine surgeon is 99 N.[37] In a cadaver study, hand tensioning versus device tensioning to 110 N did not affect postfixation laxity.[38] Clinical studies that compare these devices with hand tensioning are lacking. If a surgeon desires to tension to >100 N, a device may be recommended. In addition, if the surgeon wishes to reproducibly tension to a submaximal single hand pull—which may be difficult to reliably reproduce—a tensioner may be recommended. Although these devices may improve the reproducibility of tension applied, no biomechanical or clinical evidence indicates that there is clinical benefit to the use of a tensioning device. We prefer using a single hand-pull in the place of a tensioning device, even though clinical evidence to support this preference is lacking.

Biologic Response to Graft Tension

Several studies have examined the biologic effects of tension on the graft itself.[15,39,40] In a canine model, increasing tension within the native ACL from baseline tension to >20 N baseline tension led to focal degeneration, increased vacuolization, more coarse and less oriented collagen fibers, and a significant decrease in tensile strength at 12 weeks compared with native tendons.[15] In a canine BPTB ACLR model comparing 1 N to 39 N of tension, increased tension caused myxoid degeneration, poor vascularity, and nonstatistically significant decreases in load-to-failure strength at 3 months.[40] Conversely, in a rabbit BPTB ACLR model comparing tensions of 1 N, 7.5 N, and 17.5 N, increased tension caused no difference in cellularity, cell nucleus volume, or vascularity after 32 weeks.[39] These results suggest that supraphysiologic tendon tension may lead to detrimental biologic tendon changes, whereas tendon tension within normal range likely does not have similar effects. The clinical correlation of these findings in humans is unknown. Surgeons should be aware that overtensioning may have a biologic consequence that is currently poorly understood.

Clinical Approach to Graft Tensioning

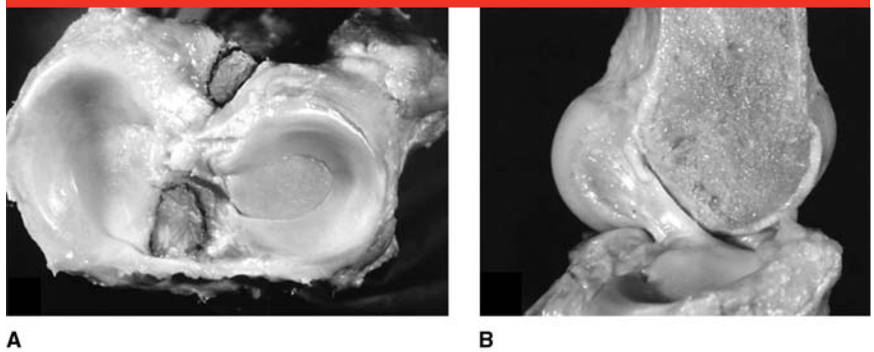
Anterior Cruciate Ligament

Native Kinematics

Understanding the biomechanical properties of the native ACL helps guide reconstruction. The native ACL has a stiffness of 182 N/mm and a load-to-failure of 1,725 N.[23] In cadaver models, considering both bundles as a single unit, the ACL is physiologically lax at 10° to 40° of flexion and physiologically tense (36 to 56 N) at full extension because the femoral origin lies posterior to the femoral center of rotation.[11,17] Thus, tensioning at midflexion could overconstrain the knee in extension, whereas tensioning at extension could theoretically result in laxity at midflexion.

The anatomic origin/insertion of the ACL is depicted in Figure 2. The ACL is an anisometric structure. The ligament is functionally divided into anteromedial and posterolateral bundles. Tension within the anteromedial bundle varies significantly less than does tension in the posterolateral bundle, reflecting its more isometric origin; but the anteromedial bundle is slightly more lax in extension and tense in flexion, with highest tension at 60°.[22] The posterolateral bundle exhibits notably greater variation in tension with knee flexion, reflecting its less isometric origin, with laxity in flexion and tension in extension greatest at zero degrees to 15°.[22]

Figure 2



Cadaver specimens demonstrating anterior cruciate ligament (ACL) anatomy. **A,** Axial view. The area outlined in black at the top is the posterior cruciate ligament footprint. The area outlined at the bottom is the ACL footprint. **B,** Sagittal view demonstrating the origin and insertion of the ACL. (Reproduced with permission from Amis AA, Jakob RP: Anterior cruciate ligament graft positioning, tensioning and twisting. *Knee Surg Sports Traumatol Arthrosc* 1998;6[suppl 1]:S2-S12.)

Single-bundle Repair

Numerous cadaver biomechanical studies have examined single-bundle ACLR with various tensioning protocols. These studies have shown that tensioning at 30° of flexion leads to increased risk of flexion contracture,[10] supraphysiologic graft tensions in extension,[30] and high tibiofemoral contact pressures.[11] Several randomized clinical trials have compared the effects of tensioning regimes on clinical outcomes (Table 2). These results suggest that, if tensioning is performed at 30°, hamstring tendons may require 80 N of tension but do not benefit from further tension.[5] BPTB grafts fixed at 30° of flexion are unlikely to require >20 N of tension, but if fixed at full extension, tensioning to 90 N may decrease postoperative excess laxity.[7,8] Surgeons should be careful about applying high tension in flexion because of the risk of flexion contracture and overconstraint.[10] Cadaver models have also revealed extensive stress relaxation for hamstring grafts,[30] suggesting that without extensive pre-tensioning, higher initial tension must be applied to these grafts to predictably achieve similar final laxity to BPTB grafts.

Although unequivocal high-quality evidence is lacking to make strongly supported recommendations, we prefer to perform autograft BPTB ACLR with interference screw aperture fixation, tensioned at full extension, with a maximal single hand pull (~99 N).[7,8,10,37] Maximum tensioning in full extension or using submaximal loading at 30° of flexion helps avoid overconstraint.[10,30] If soft-tissue grafts are used, we prefer to use autograft quadrupled hamstring tendons[24] with suspensory fixation on the femur, and cortical screw and back-up staple/anchor fixation on the tibia,[14,35,36] tensioned at full extension with a maximum single hand pull,[5,37] after first pre-tensioning on a graft preparation board to minimize stress relaxation.[30] Tensioning patterns do not differ for BPTB or soft-tissue allograft.[42]

Double-bundle Repairs

Notably fewer cadaver studies, and no clinical studies, have been performed to examine tensioning protocols for double-bundle repairs. Biomechanical evidence suggests that tensioning bundles separately at their individual positions of laxity, in order to maximally constrain the knee, leads to high individual graft tensions and poor "reciprocity," whereas tensioning both grafts at 20° of flexion may ameliorate these problems.[12,13,43] Three-dimensional model data based on dual orthogo-

Table 2

Randomized Clinical Trials Comparing the Effect of Tensioning on Outcomes Following Anterior Cruciate Ligament Reconstruction

Study	No. of Pts	Minimum Follow-up	Tensions Compared (Degrees of Flexion)	Graft Type/ Fixation	Pre-tensioning	Results
van Kampen et al[8]	38	1 yr	20 vs 40 N (20°)	BPTB, interference screw	Three cycles at final tension	No significant difference in patient-reported Lysholm, KT-1000,[a] IKDC, or rates of contracture between groups
Kim et al[5]	48	1 yr	79, 118, and 147 N (30°)	Pentupled hamstring, staple fixation	Three cycles at final tension	No significant difference in average patient-reported visual analogue scale of knee laxity, KT-2000[a] side-to-side difference
Yasuda et al[41]	70	2 yr	20, 40, 80 N (30°)	Doubled hamstring, staple fixation	Flexion cycling × 1 min at final tension	Significantly greater KT-1000[a] side-to-side difference in the lower tension group (2.2 vs 0.6 mm) Graft augmentation with the Leeds-Keio prosthesis was used
Nicholas et al[7]	49	20 mo	45 vs 90 N (full extension)	BPTB, interference screw	Ten cycles at final tension	Significantly greater tibial displacement and significantly more patients with “abnormal” tibial displacement in the low tension group No significant difference in patient-reported modified Knee Outcome Survey scores

BPTB = bone–patellar tendon–bone, IKDC = International Knee Documentation Committee
[a] KT-1000, KT-2000 arthrometer (Medmetrics, San Diego, CA)

nal fluoroscopic imaging suggests that tensioning both bundles at a low flexion angle may prevent overconstraint.[44] No clinical studies comparing tensioning protocols have been performed, but excellent clinical outcomes have been obtained by tensioning the anteromedial bundle at 60° of flexion and the posterolateral bundle at zero degrees to 15° of flexion.[45] Given their physiologic loads, tensioning the posterolateral bundle in extension and the anteromedial bundle in midflexion replicates physiologic stability patterns while minimizing overconstraint.[22,45]

Posterior Cruciate Ligament

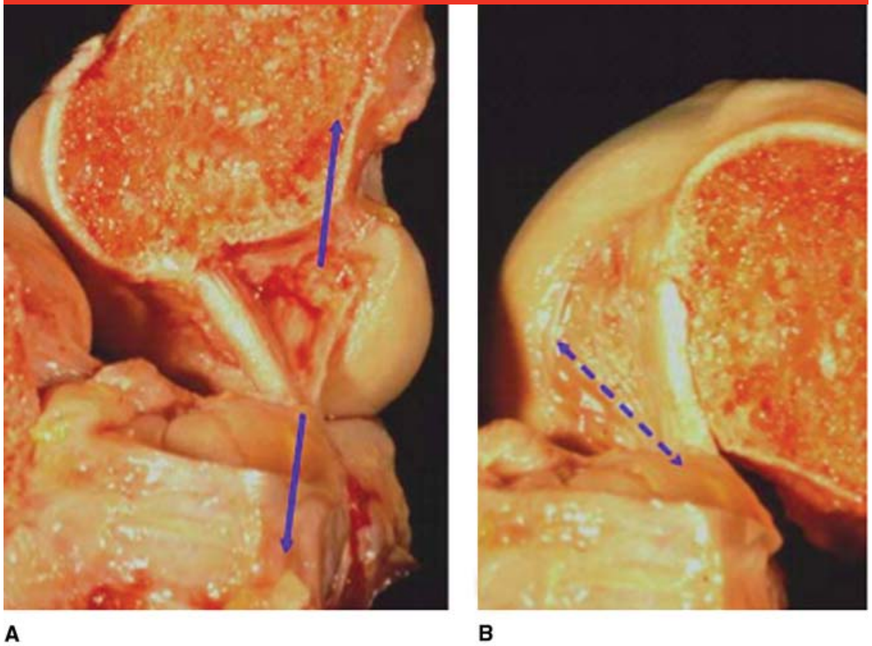
Native Kinematics

The anatomic origin and insertion of the PCL are shown in Figures 2 and 3. The PCL is an anisometric structure. Viewed as a single structure, the PCL is physiologically lax at full extension and tense (112 N) at 90° of flexion because the central femoral footprint lies anterior to the femoral center of rotation. The PCL is functionally divided into the anterolateral and posteromedial bundles. The anterolateral bundle comprises 65% of the substance of the PCL, has maximal tension in 90° of flexion, and is the main stabilizer to posterior stress.[3,46] The posteromedial bundle tightens in extension and early flexion.[3] Sectioning studies demonstrate that the posteromedial bundle produces small but statistically significant increases in mean laxity at zero degrees (+1.06 mm) and 10° (+0.83 mm) of flexion, but plays a minimal role at higher flexion angles.[46]

Single-bundle Repair

Several cadaver biomechanical studies of single-bundle PCL repairs have

Figure 3



Photographs of a sagittally sectioned cadaveric femur with a retained medial femoral condyle demonstrating posterior cruciate ligament (PCL) anatomy. **A,** The arrows indicate tension within the proximodistally oriented posteromedial bundle of the PCL with the knee in extension. **B,** With flexion, the posteromedial bundle, indicated by the arrow, is oriented anteroposteriorly. (Adapted with permission from Amis AA, Gupte CM, Bull AMJ, Edwards A: Anatomy of the posterior cruciate ligament and the meniscofemoral ligaments. *Knee Surg Sports Traumatol Arthrosc* 2006;14[3]:257-263.)

been performed, many of which were intended to reconstruct the anterolateral bundle. These studies suggest that tensioning at 90° of flexion, with an anterior tibial force of 134 to 156 N, replicates native knee kinematics and hence decreases the risk of overconstraint and extension loss.[3] When using the transtibial technique, tensioning in flexion allows force propagation to the intra-articular portion of the graft around the so-called killer turn. This turn is created by the sharp angulation of the graft exiting the tibial tunnel headed toward the femoral insertion, thus creating an area of abrasion. Tensioning a graft at full extension may propagate force only to the tunnel portion of the graft, resulting in residual laxity.[4,6,47]

To date, no clinical trials comparing various tensioning regimes in PCL reconstruction have been conducted. Given the biomechanical and clinical evidence, the authors prefer single-bundle PCL reconstruction with Achilles tendon allograft, tensioned in 90° of flexion,[4,6,47] bone plug fixation with an interference screw, and a long biologic interference screw and supplementary cortical staple fixation for the soft-tissue component.[14,35,36]

Double-bundle Repair

Few cadaver or clinical studies comparing tensioning regimes in double-bundle PCL repairs have been performed.[48] Markolf et al[48] demonstrated that a single anterolateral graft best reproduced the normal PCL force profiles; however, laxities were greater than normal between zero degrees and 30° of knee flexion. The addition of a second posteromedial graft tensioned to 10 N at 30° of flexion reduced laxity in early flexion, but it did so at the expense of higher-than-normal forces in the posteromedial graft.[48] In performing a double-bundle reconstruction, the surgeon should take care to avoid overconstraint and decreased knee motion when adding the posteromedial bundle tensioned at a low flexion angle.[48]

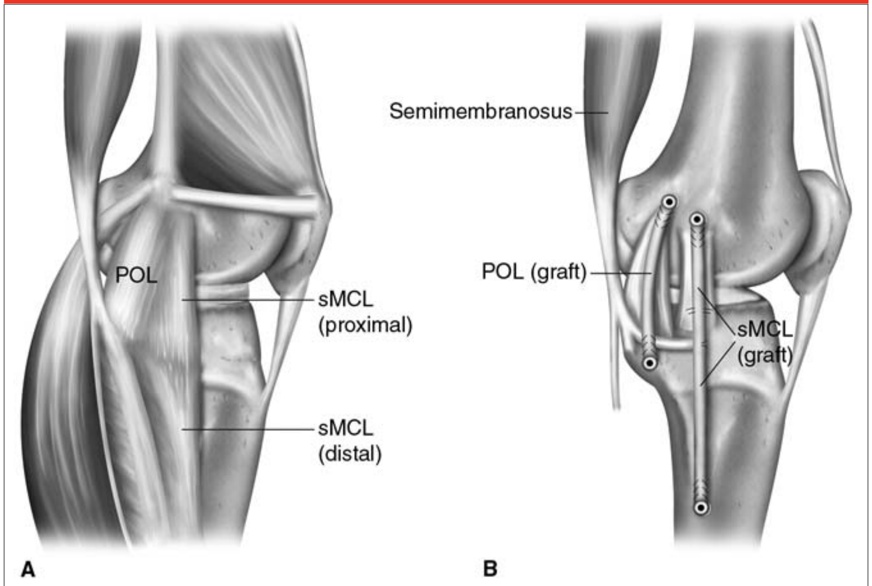
Medial Ligament Complex

The anatomy of the medial aspect of the knee is depicted in Figure 4. Major structures that undergo graft reconstruction to stabilize the medial side of the knee are the superficial medial collateral ligament (sMCL) and the posterior oblique ligament (POL).

Functional Kinematics

Reconstruction of the sMCL is important because sectioning studies demonstrate it to be the primary static stabilizer of the knee to valgus stress.[20,49] The medial collateral ligament (MCL) was traditionally thought to be an isometric structure because its proximal origin lies near the femoral center of rotation.[20] In vivo,[50] ex vivo,[9] and modeling[51] studies have confirmed isometry for the central third of the sMCL. However, the sMCL/POL complex is relatively wide, and when one divides these structures into anterior and posterior halves, their function is best understood as anisometric. The anterior portion (sMCL) elongates slightly and tightens maximally in flexion (1 to 2 mm at 90°); the posterior segment (POL) elongates and tightens in extension (2 to 4 mm at zero degrees), with an average change of 2.8 mm. Warren et al[20] demonstrated that the sMCL was maximally elon-

Figure 4



A, Illustration of the anatomy of the medial collateral ligament (MCL) complex. **B,** Illustration of the reconstruction of the MCL complex. POL = posterior oblique ligament, sMCL = superficial medial collateral ligament. (Adapted with permission from Coobs BR, Wijdicks CA, Armitage BM, et al: An in vitro analysis of an anatomical medial knee reconstruction. *Am J Sports Med* 2010;38[2]:339-347.)

gated at 45° degrees of flexion and was 1 mm shorter at 30°. The POL is tighter in extension and has most of its effect at zero degrees and 30° of flexion.[52] The POL shares only 10% of valgus load and helps to stabilize against internal rotation at all flexion angles.[53]

Single-bundle Reconstruction

The goal of most surgeons when performing single-bundle reconstruction is an isometric reconstruction of the sMCL, which requires surgical precision (Figure 4). In a computer navigation model, Feeley et al[54] demonstrated that 4 mm of deviation in any direction from the center of the sMCL footprint causes a significant decrease in isometry. Most authors locate an isometric point with a suture looped over Kirschner wires at the origin and the insertion of the sMCL, looking for length change of <3 to 4 mm through a motion cycle.[55]

In theory, the angle of tension for an isometric structure such as the central sMCL should not influence kinematic outcome. However, most studies report tensioning of the graft between 30° and 60°, corresponding to the ligament's maximum length and highest resistance to valgus force. Subtle variations mentioned in the literature include tensioning the MCL at 30° to allow for 1 mm of creep at 45°,[56] tensioning at 30° or 45° with 50 N of force,[55] and tensioning with a varus moment.[57]

For sMCL reconstruction, we prefer an isometric reconstruction at the center of the femoral and tibial sMCL footprints, as judged by the Kirschner wire/suture technique.[55] We use an Achilles tendon allograft, with maximum manual tension at 30°, with a slight varus force.[57] The proximal bone block is fixed with interference screw fixation, and the graft is stapled distally.[14,35,36]

Double-bundle Reconstruction

Double-bundle constructs restore both the sMCL and the POL. Some authors suggest tensioning the POL component at 60° of flexion,[56] whereas others describe equivalent results with tensioning at zero degrees or 30°.[58] Feeley et al[54] compared the ability to restore valgus stability in a cadaver model using both single- and double-bundle reconstruction techniques. Grafts were tensioned to 44 N and fixed at 30° of flexion. Although the single-bundle reconstruction decreased opening with valgus force, only double-bundle repairs were able to restore the knee's ability to respond to both valgus and internal rotation forces.

In our practice, we prefer a double-bundle reconstruction with an isometric central sMCL, as described above, and an anisometric reconstruction of the POL, with hand tensioning near full extension.[58] There is no evidence to recommend for or against varus or internal rotation during the tensioning process.

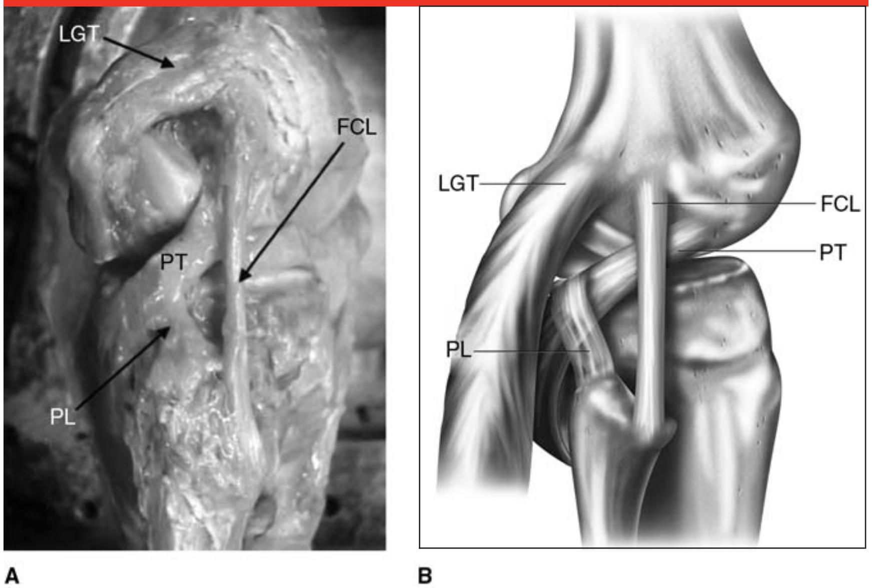
Lateral Collateral Ligament and Posterolateral Corner

The anatomy of the PLC is shown in Figure 5. The major stabilizers of the PLC that are surgically reconstructed include the lateral collateral ligament (LCL), popliteus, and popliteofibular ligament (Figure 6). There are few biomechanical and clinical studies with regard to graft tensioning for PLC reconstruction.

Functional Kinematics

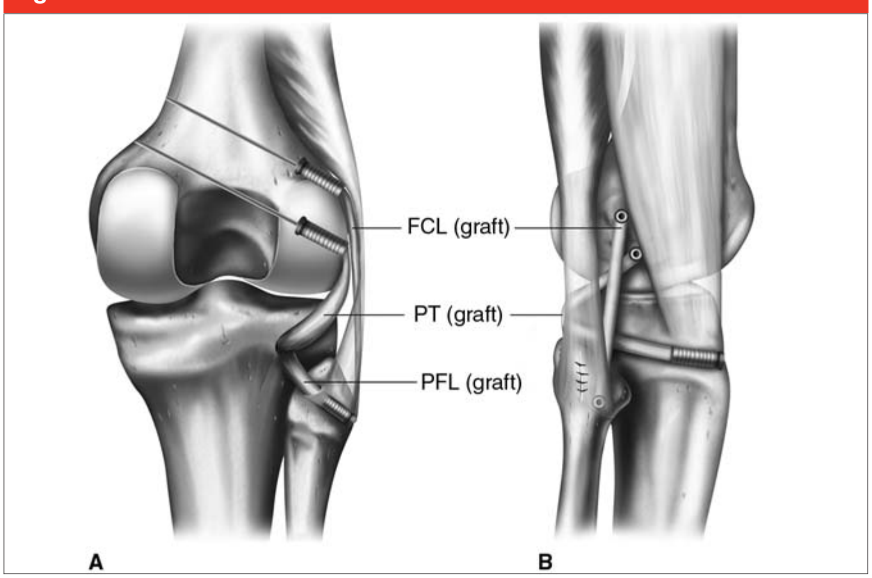
The LCL, popliteus, and popliteofibular ligament confer stability to the knee in response to varus, external rotation, and posterior forces.[18,19] With isolated insufficiency of all PLC structures, the largest increase to external rotation is at 30° of flexion.[19] The LCL is an isometric ligament that is the primary restraint to varus

Figure 5



Photograph of a cadaver specimen (**A**) and illustration (**B**) demonstrating the anatomy of the posterolateral corner. FCL = fibular collateral ligament, LGT = lateral gastrocnemius tendon, PL = popliteofibular ligament, PT = popliteus tendon. (Adapted with permission from LaPrade RF, Ly TV, Wentorf FA, Engebretsen L: The posterolateral attachments of the knee: A qualitative and quantitative morphologic analysis of the fibular collateral ligament, popliteus tendon, popliteofibular ligament, and lateral gastrocnemius tendon. *Am J Sports Med* 2003;31[6]:854-860.)

Figure 6



PA (**A**) and lateral (**B**) illustrations demonstrating reconstruction of the posterolateral corner. FCL = fibular collateral ligament, PFL = popliteofibular ligament, PT = popliteus tendon. (Reproduced with permission from McCarthy M, Camarda L, Wijdicks CA, Johansen S, Engebretsen L, LaPrade RF: Anatomic posterolateral knee reconstructions require a popliteofibular ligament reconstruction through a tibial tunnel. *Am J Sports Med* 2010;38[8]:1674-1681.)

force, especially at low flexion angles.[19,59] Direct force measurements of the LCL during an applied varus moment demonstrate loading responses at all angles of knee flexion, with the response at 30° of flexion significantly higher than that at 90° of flexion.[60] The popliteus is anisometric, made up of tendon and muscle, thus allowing for dynamic control and balance of tibial neutral rotation.[61] Sectioning of the popliteus alone elucidates its importance in preventing external rotation at 90° to 120° of flexion without contributions to varus rotation or posterior translation.[19,59] The popliteofibular ligament is anisometric, takes up maximal tension during an external rotation force at 60° to 90°, and is lax with internal tibial rotation.[61] Isolated sectioning does not cause increased varus, rotational, or translational changes.[59] However, the popliteofibular ligament assists maximally with varus force at 45° of flexion.[62]

LCL and PLC Reconstruction

The goal of LCL reconstruction is an isometric reconstruction. Most authors recommend hand tensioning of the LCL component at 20° to 30° of knee flexion, with mild valgus to prevent lateral gapping.[63-65] Tensioning for the popliteus and popliteofibular ligament component is more variable and differs by author and construct type. Comparisons of fibula-based popliteal reconstructions indicate that most were tensioned at 30° of knee flexion.[64,66,67] Tibia-based reconstructions of the popliteus were also tensioned by hand at 30° to 90° of flexion.[63,65,67] Controversy exists regarding the use of an internal rotation force, with conflicting data for and against its use secondary to concerns for overconstraint.[65]

There are many different methods for PLC reconstruction. In general, these are fibula-based with one or

Table 3

Ex Vivo Cadaver Studies of Posterolateral Corner Reconstructions

Study	No. of Bundles	Femoral Tunnels	Distal Fixation	Tensioning
Ho et al[66]	2	2	TF	Manual
	2	1	TF	Manual
Rauh et al[64]	2	1	TF	Manual
	3	2	TF and T	Manual
McCarthy et al[65]	2	2	TF, T, and PFL	Manual
	2	2	TF and T	Manual
Kim et al[67]	2	2	T, CF, and AFL	57 N
	2	1	PF and T	57 N
	2	1	TF	57 N
Feeley et al[68]	2	1	TF AP	30 N
	2	1	TF Obl	30 N
	2	2	TF AP	30 N
	2	2	TF Obl	30 N
Apsingi et al[63]	2	1	TF	[a]
	3	2	TF and T	[a]

AFL = anterior popliteofibular ligament, AP = straight anterior-posterior transfibular tunnels, CF = central fibular, IR = internal rotation, LCL = lateral collateral ligament, Obl = 40° transfibular tunnels, PF = posterior fibula, PFL = posterior popliteofibular ligament, T = tibia, TF = transfibular, Val = valgus

[a] Authors tensioned until forces were within intact specimen

two femoral tunnels and may include a tibia-based component.[67] Cadaver studies of fibula-based techniques have demonstrated no significant difference between the intact and reconstructed knee to varus load or to external torque at any flexion angle.[62,68] However, two recent biomechanical studies in which all three functional components were anatomically reconstructed separately documented overconstraint of internal and varus rotation, respectively.[63,64] To date, no randomized clinical studies have investigated the different procedures. However, most clinical case series report reasonable outcomes regardless of technique used.[69] A summary of pertinent biomechanical studies for PLC reconstruction is given in Table 3. If reconstructing the LCL alone, we prefer hand tensioning at 30° of knee flexion.[63-65] For PLC reconstruction, we prefer a fibula-based technique with a soft-tissue allograft, usually semitendinosus.[69] We prefer either a single isometric tunnel on the femur or a double femoral tunnel recreating the insertion of both the popliteus and the LCL.[64,66,67] For the single femoral tunnel, we fix the graft with a soft-tissue biointerference screw under hand tension at 30°, with a slight valgus and internal rotation force.[64,66,67] For the double femoral tunnel, we differentially tension and fix the LCL and popliteus at 30° and 90°, respectively.[64,66,67]

Summary

Graft tensioning for knee ligament reconstruction relies on a thorough appreciation of native knee anatomy and kinematics. Many other factors should also be taken into account, including the mechanical properties of the selected graft, the fixation method, and the specific biomechanical goal of the reconstruction. Although extensive biomechanical cadaver evidence can guide graft tensioning, few clinical trials with patient-oriented functional clinical outcomes are available to strongly support one method of tensioning over another. Future investigators are encouraged to perform high-quality trials in order to accurately direct graft tensioning protocols.

References

Evidence-based Medicine: Levels of evidence are described in the table of contents. In this article, reference 35 is a level I study. References 1, 5, 7,

Table 3 (continued)

Ex Vivo Cadaver Studies of Posterolateral Corner Reconstructions

LCL Flexion (degrees)	Posterior Fibula Flexion (degrees)	Tibia-based Flexion (degrees)	Force During Fixation	Results
30	30	—	IR, Val	Same as intact
30	30	—	IR, Val	
30	30	—	IR, Val	Tighter than intact except tibia-based at 30°
30	30	30	Val (LCL), IR (T)	
30	—	60	Val	Improved IR kinematics with PFL
30	—	60	Val	
30	—	30	—	Same as intact
—	30	30	—	
30	30	—	—	
30	30	—	—	Both same as intact for varus, but Obl improved for rotation
30	30	—	—	
30	30	—	—	
30	30	—	—	
20	—	90	—	Same as intact
20	90	90	—	

AFL = anterior popliteofibular ligament, AP = straight anterior-posterior transfibular tunnels, CF = central fibular, IR = internal rotation, LCL = lateral collateral ligament, Obl = 40° transfibular tunnels, PF = posterior fibula, PFL = posterior popliteofibular ligament, T = tibia, TF = transfibular, Val = valgus

[a] Authors tensioned until forces were within intact specimen

8, 33, and 41 are level II studies. Reference 16 is a level III study. References 45, 50, 51, and 69 are level IV studies. References 36, 37, 55, and 56 are level V expert opinion.

References printed in **bold type** indicate those published within the past 5 years.

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