Systematic Review

Biomechanical Results of Lateral Extra-articular Tenodesis Procedures of the Knee: A Systematic Review

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Purpose: To systematically review and compare biomechanical results of lateral extra-articular tenodesis (LET) procedures. **Methods:** A systematic review was performed using the PubMed, Medline, Embase, and Cochrane databases. The search terms included the following: extraarticular, anterolateral, iliotibial, tenodesis, plasty, augmentation, procedure, reconstruction, technique, biomechanics, kinematic, robot, cadaver, knee, lateral tenodesis, ACL, Marcacci, Lemaire, Losee, Macintosh, Ellison, Andrews, Hughston, and Muller. The inclusion criteria were nonanatomic, in vitro biomechanical studies, defined as in vitro investigations of joint motion resulting from controlled, applied forces. **Results:** Of the 10 included studies, 7 analyzed anterior tibial translation and reported that isolated LET procedures did not restore normal anterior stability to the anterior cruciate ligament (ACL)−deficient knee. Seven of the 8 studies analyzing tibial rotation reported a reduction in internal tibial rotation across various flexion angles in the ACL-deficient knee when compared with the native state. Five studies reported a reduction in intra-articular graft force with the addition of an LET. Two studies evaluated length change patterns, graft course, and total strain range and found that reconstruction techniques in which the graft attached proximal to the lateral epicondyle and coursed deep to the fibular collateral ligament were most isometric. **Conclusions:** In the ACL-deficient knee, LET procedures overconstrained the knee and restricted internal tibial rotation when compared with the native state. In addition, isolated LET procedures did not return normal anterior stability to the ACL-deficient knee but did significantly reduce anterior tibial translation and intra-articular graft forces during anteriorly directed loading. **Clinical Relevance:** Combined injury to the ACL and anterolateral structures has been reported to exhibit greater anterolateral rotatory instability when compared with isolated ACL injuries. Despite the reported risk of joint overconstraint, consideration should be given to reconstructing the anterolateral structures and the ACL concurrently to maximally restore both anterior tibial translation and rotatory stability.

The anterolateral soft-tissue structures of the knee have received increased attention because of the recent "rediscovery" of the anterolateral ligament.[1] Starting more than 4 decades ago, the anterolateral structures were considered secondary stabilizers to the anterior cruciate ligament (ACL)[2] for controlling anterolateral rotatory movement.[3] ACL tears, which occur in 100,000 to 200,000 patients per year in the United States, are commonly associated with concomitant damage to the anterolateral structures.[4-6] In a clinical study of 82 consecutive knees, Terry et al.[7] showed concurrent anterolateral capsular injury in 93% of patients with an ACL tear. Combined injury to the ACL and anterolateral structures has been reported to exhibit greater anterolateral rotatory instability relative to isolated ACL injuries.[3,8] Recognition of the synergistic relation between the anterolateral structures and the ACL in controlling anterolateral rotatory stability has led to renewed interest in otherwise largely discontinued lateral extra-articular tenodesis (LET) procedures.[9]

Historically, ACL tears were often treated with ACL reconstructions combined with LET procedures, or LET

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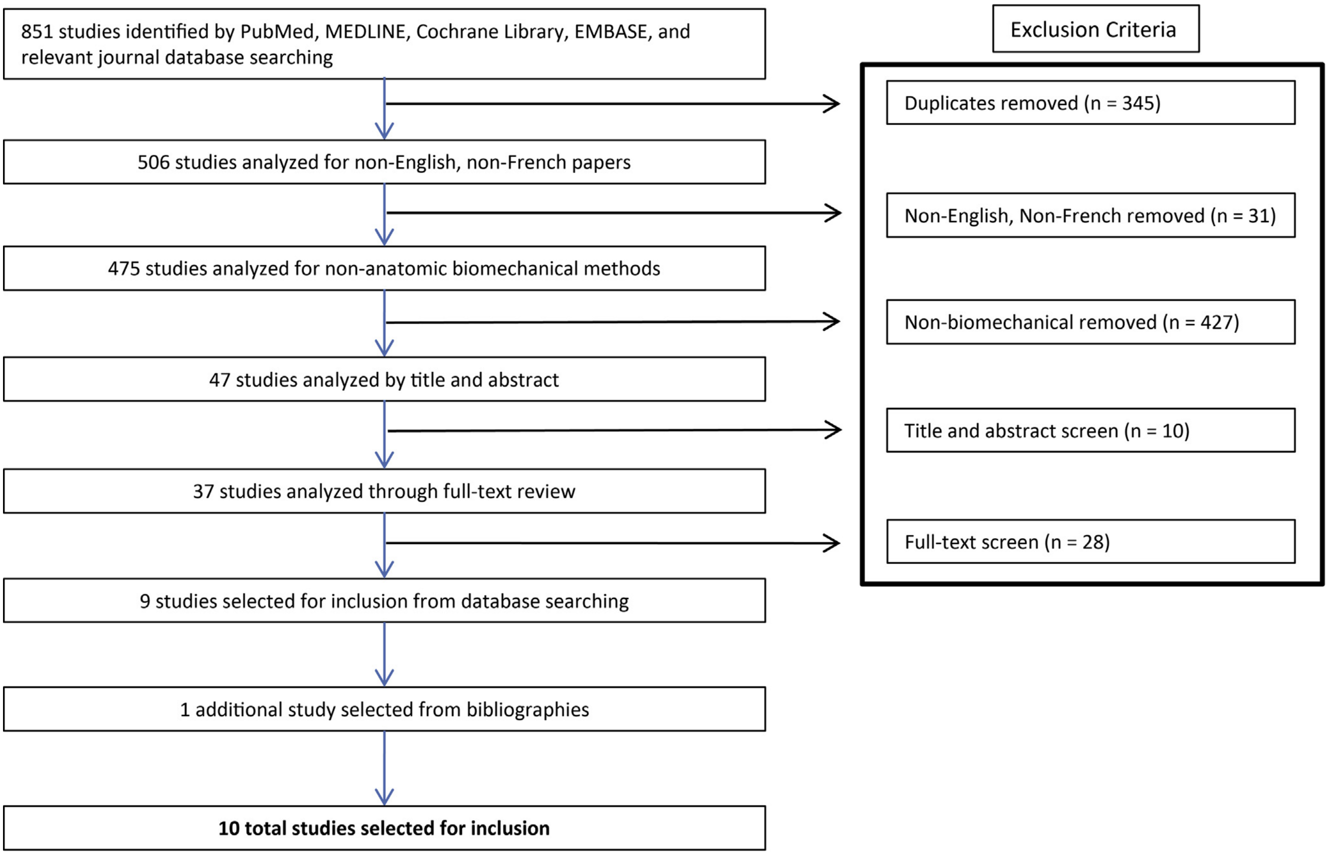

Fig 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart of literature search.

procedures alone, which were initially proposed to eliminate anterolateral rotatory instability and anterior tibial translation.[10] Since the advent of the LET procedure, variant reconstructions have been proposed, implemented, and subsequently modified to treat anterolateral rotatory instability; however, poor long-term outcomes, including graft failure, residual instability, and joint over-constraint, discouraged many surgeons from performing extra-articular reconstructions.[11-14] The reported high failure rate of these procedures led some authors to suggest that the nonanatomic nature of these techniques may have contributed to poor long-term outcomes.[11,14]

Numerous in vitro biomechanical studies have attempted to quantify the efficacy of variant LET procedures. However, given the variability of each surgical technique regarding graft choice and fixation, it is challenging to reach objective conclusions concerning the durability and kinematic superiority of a certain technique. Thus, the purpose of this study was to systematically review the literature to compare the biomechanical outcomes of variant lateral knee extra-articular procedures.

Methods

Article Identification and Selection

This study was conducted in accordance with the 2015 PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement and the PRISMA checklist.[15] A systematic review of the literature from 1980 to 2015 on extra-articular procedures was performed across a 4-database−wide search including PubMed, Medline, Embase, and Cochrane. The queries were performed in August 2015 with the following search terms: extraarticular, anterolateral, iliotibial, tenodesis, plasty, augmentation, procedure, reconstruction, technique, biomechanics, kinematic, robot, cadaver, knee, lateral tenodesis, ACL, Marcacci, Lemaire, Losee, Macintosh, Ellison, Andrews, Hughston, and Muller. The literature was gathered using the following searches:

- Search 1: (extra-articular or extraarticular or extra articular or anterolateral or antero-lateral or iliotibial or IT band or IT tract) and (tenodesis or plasty or augmentation or procedure or reconstruction or technique) and (biomechanics or kinematic or robot or cadaver) and (knee)

Table 1. Chronologic Summaries of Lateral Extra-articular Tenodesis Techniques

Year	Surgical Technique	Summary
1967	Lemaire[27]	A strip of iliotibial band was detached proximally and passed deep to the FCL, through a femoral tunnel at the attachment point of the head of the lateral gastrocnemius. The graft was then passed deep to the FCL a second time and fixed with sutures to the iliotibial band with the knee flexed to 30° and held in external rotation (Fig 2).
1976	MacIntosh[28]	A strip of iliotibial band was detached proximally and passed deep to the FCL, through an osteoperiosteal tunnel posterior to the FCL femoral attachment. The graft was then looped through the lateral intermuscular septum and sutured back onto itself at the Gerdy tubercle with the knee flexed to 90° and held in external rotation (Fig 3).
1978	Losee[29]	A strip of iliotibial band was detached proximally and passed through a femoral tunnel that originated at the attachment point of the lateral gastrocnemius and ended anterodistal to the FCL femoral insertion site. The graft was then sutured at the Gerdy tubercle with the knee flexed to 30° and held in external rotation (Fig 4).
1979	Arnold and Coker[36]	A strip of iliotibial band was detached proximally, passed beneath the FCL and popliteus tendon, and sutured to the Gerdy tubercle with the knee flexed to 90°-100° and held in external rotation (Fig 5).
1979	Ellison[31]	A distally detached strip of iliotibial band with a bone flake was passed deep to the FCL and anchored in a bone trough slightly anterior to its original harvest site at the Gerdy tubercle with the knee flexed to 90° and held in external rotation. The capsular structures were reefed deep to the FCL (Fig 6).
1979	Wilson and Scranton[32*]	A strip of iliotibial band was detached proximally, passed deep to the FCL and lateral gastrocnemius tendon, and sutured back onto itself with the knee flexed to 60° and held in external rotation. This extra-articular reconstruction was used in conjunction with an intra-articular ACL semitendinosus graft reconstruction (Fig 7).
1980	Zarins and Rowe[35*]	The semitendinosus tendon was detached proximally and passed through an obliquely oriented tibial tunnel, across the knee joint, and over the lateral femoral condyle. After passing over the lateral femoral condyle, the graft was passed deep to the FCL and sutured onto the iliotibial band. Similarly, the iliotibial band was passed deep to the FCL and over the superior aspect of the lateral femoral condyle. After passing over the lateral femoral condyle, the graft was passed across the knee joint, through the same obliquely oriented tibial tunnel as the semitendinosus tendon, and fixed with sutures to the semitendinosus tendon with the knee flexed to 60° and held in external rotation (Fig 8).
1982	Andrews[26]	Two strips of iliotibial band were detached proximally and sutured at their proximal ends. Then, the sutures were passed through 2 parallel tunnels, which originated at the lateral femoral condyle and exited at the medial femoral condyle. After passing through the tunnels in the lateral-to-medial direction, the sutures were tied together over the adductor tubercle. The grafts were fixed with the knee flexed to 90° and held in external rotation. In addition, the grafts were fixed to ensure that the anterior bundle was taut in flexion and the posterior bundle was taut in extension (Fig 9).
1982	Benum[30]	The lateral one-third of the patellar tendon was harvested proximally with a patellar bone block, passed deep to the FCL, and fixed with a staple within a bony groove deep to the femoral origin of the FCL with the knee flexed to 45° and held in external rotation (Fig 10).
1983	Müller[34]	A strip of iliotibial band was detached proximally and fixed with 2 cancellous screws to a point anterior to the junction of the femoral shaft and lateral femoral condyle with the knee held in external rotation (Fig 11).
1990	Modified Andrews[20]	The iliotibial band was divided, and a 20-mm-wide portion of the band was detached proximally. The strip of iliotibial band was fixed with a soft-tissue fixation screw and washer at the distal insertion of the lateral muscular septum on the linea aspera, just anterior to the posterior femoral cortex (Fig 12).
1998	Marcacci and Zaffagnini[33,*]	Semitendinosus and gracilis tendons were harvested proximally, sutured together, and passed through a tibial ACL reconstruction tunnel. The graft exited the tibial tunnel intra-articularly and was passed through the posterior aspect of the femoral notch and over the top of the lateral femoral condyle. The graft was then passed deep to the iliotibial band and over the FCL and was fixed distal to the Gerdy tubercle with the knee flexed to 90° and held in external rotation (Fig 13).

ACL, anterior cruciate ligament; FCL, fibular collateral ligament.
*Combined intra-articular and extra-articular reconstruction.

- Search 2: lateral and (plasty or tenodesis or augmentation) and (ACL or knee) and (biomechanics or kinematic or robot or cadaver)
- Search 3: (Marcacci or Lemaire or Losee or Macintosh or Ellison or Andrews or Müller) and (surgery or tenodesis or plasty or augmentation or procedure or reconstruction or technique) and (biomechanics or kinematic or robot or cadaver) and (ACL or knee)

The inclusion criteria were in vitro biomechanical, kinematic, or robotic studies. For the purpose of this review, a biomechanical or kinematic analysis was defined as an in vitro investigation of joint or ligament motion resulting from controlled, applied forces. Therefore, the studies that met the inclusion criteria investigated the impact that LET procedures have on knee joint kinematics. The exclusion criteria were studies in languages other than English or French, nonsurgical treatment, case reports, clinical studies, and concurrent fracture or dislocation. Four investigators (E.L.S., J.D.M., J.M.S., D.C.M.) reviewed

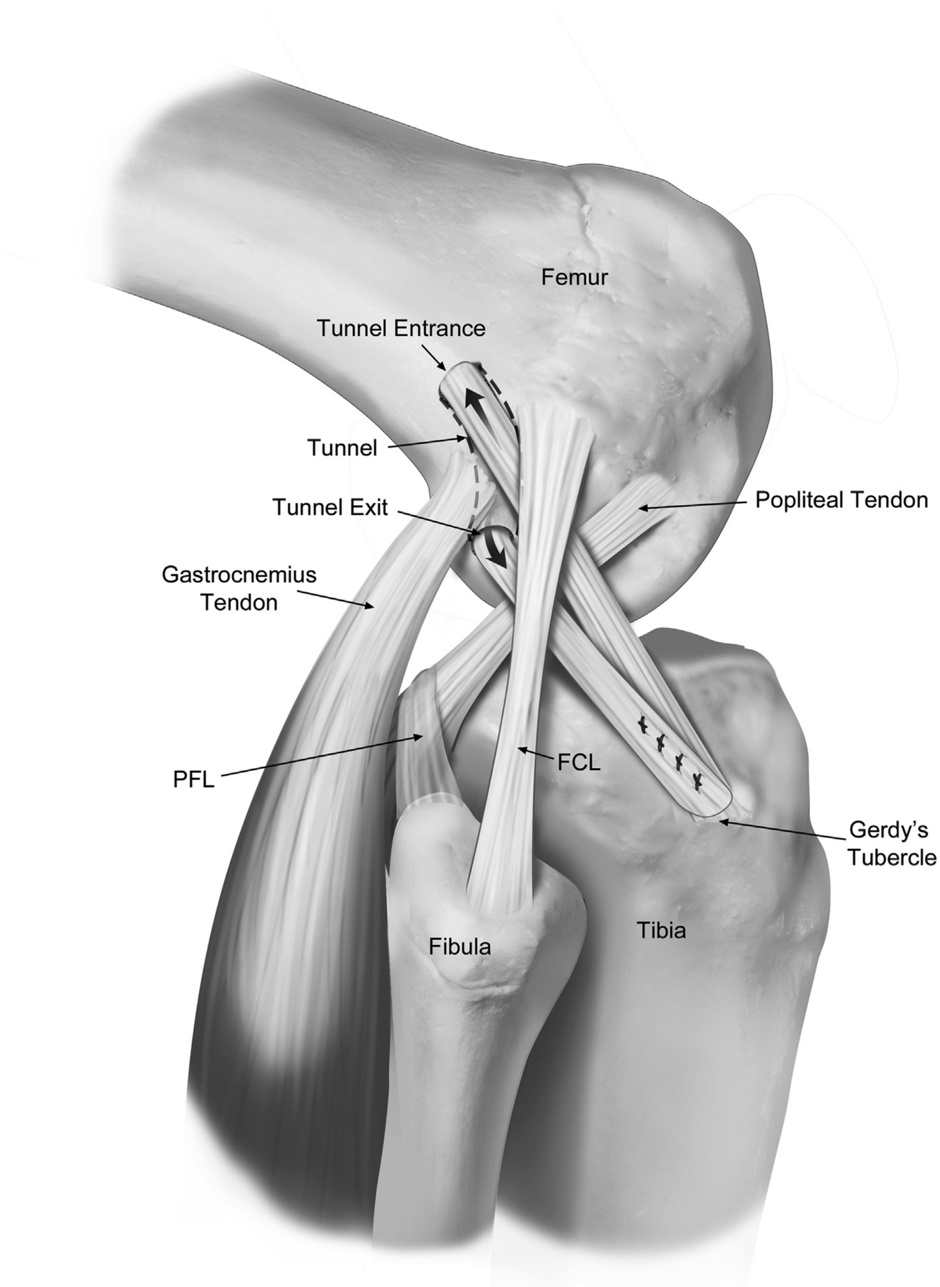

Fig 2. Lemaire technique.[27] (FCL, fibular collateral ligament; PFL, popliteofibular ligament.)

the titles and abstracts of all articles that met the inclusion and exclusion criteria, and full-text articles were obtained to verify that the criteria were met.

Results

A flow diagram documenting the method of article identification and selection is shown in Figure 1. After the elimination of duplicate articles, 506 remained. The investigators independently reviewed the titles and abstracts, identifying 37 full-text articles for review. Application of the inclusion and exclusion criteria yielded 10 full-text articles for inclusion in the review.[16-25]

Surgical Techniques

The surgical approach for addressing anterolateral rotatory instability in ACL-deficient patients varied between studies. Over time, LET techniques evolved by altering graft choice and tibiofemoral positioning. However, several LET techniques exhibited a significant degree of uniformity, with the extra-articular graft generally attaching distally at the Gerdy tubercle and traveling proximally and posterolaterally toward the lateral femoral condyle.[20,26-35] Table 1 and Figures 2-13 summarize the 12 LET techniques in this review.

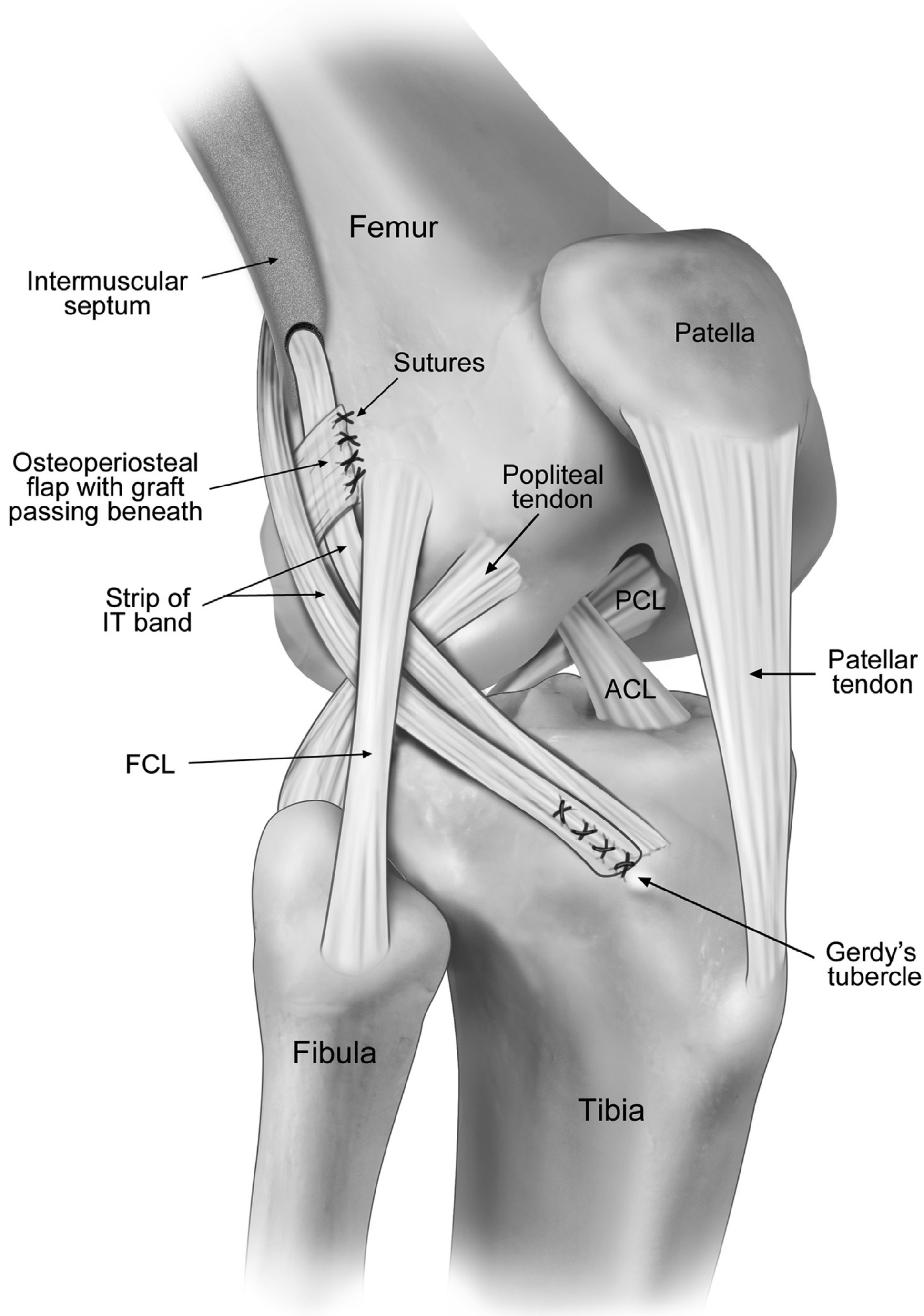

Fig 3. MacIntosh technique.[28] (ACL, anterior cruciate ligament; FCL, fibular collateral ligament; IT, iliotibial; PCL, posterior cruciate ligament.)

Biomechanical Results

Anterior Tibial Translation, Internal-External Rotation, and Varus-Valgus Rotation. Anterior tibial translation, internal-external rotation, and varus-valgus rotation for the different lateral extra-articular procedures are documented in Table 2. Graft force, strain, and/or length change patterns were reported in 6 studies.[18-23]

Graft Force and Graft Strain. Engebretsen et al.[20] compared the total graft force experienced by the ACL reconstruction when a modified Andrews iliotibial band tenodesis was added both before and after an intra-articular ACL reconstruction. When the LET was added to the intra-articular reconstruction, the total graft force experienced by the ACL graft was significantly reduced ($P \leq .01$) by

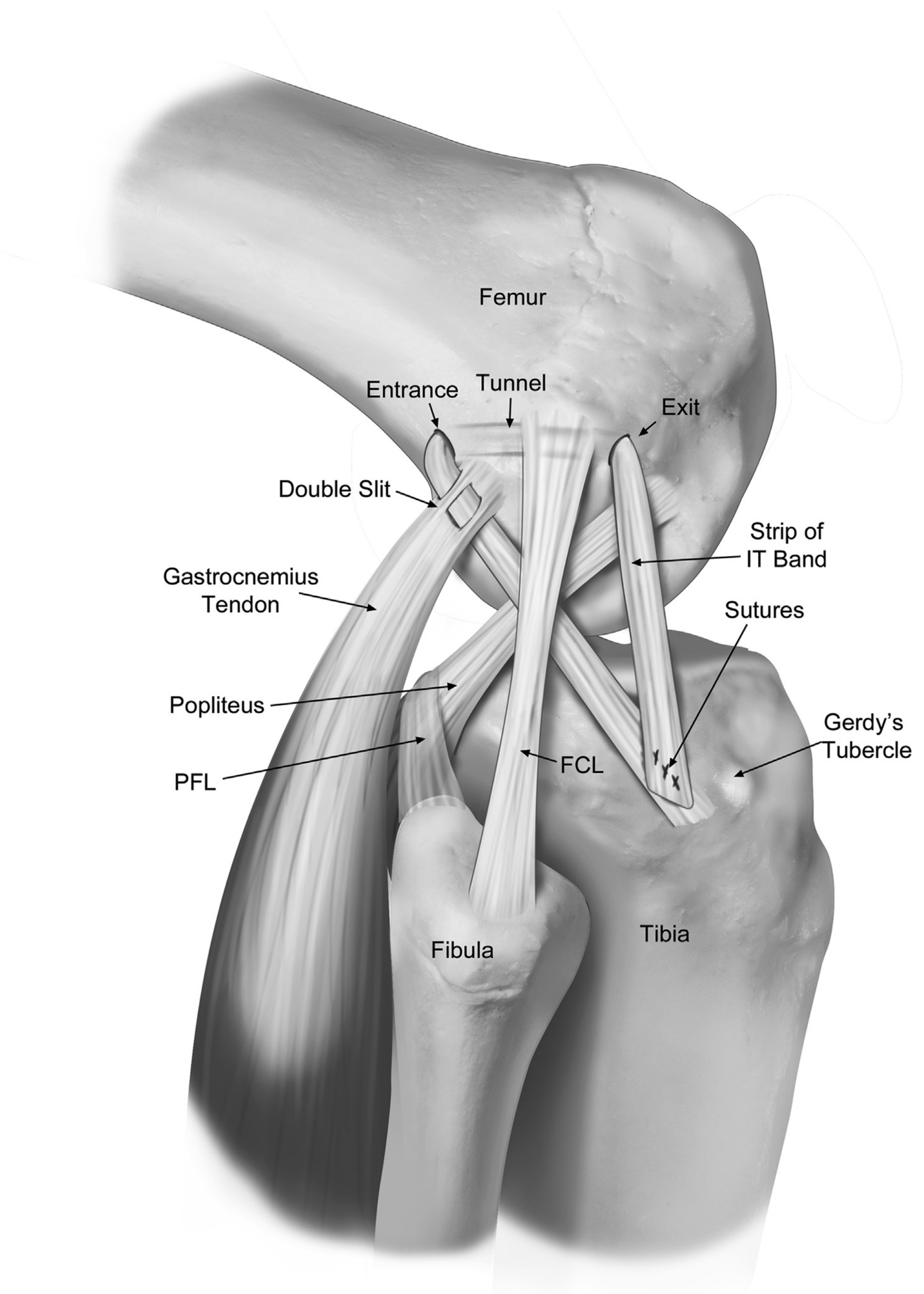

Fig 4. Losee technique.[29] (FCL, fibular collateral ligament; IT, iliotibial; PFL, popliteofibular ligament.)

an average of 43% over all 4 tested flexion angles (0°, 30°, 60°, and 90°). In contrast, when an ACL reconstruction was added to the LET, the total graft force decreased by an average of 15% over all 4 tested flexion angles; however, this reduction was not significant at each angle or over all 4 flexion angles combined.

In an additional study, Engebretsen et al.[21] analyzed the force patterns exhibited by a transposed patellar tendon graft (using the Benum LET procedure,[30] as described in Table 1) in loaded and unloaded states at 4 flexion angles (0°, 30°, 60°, and 90°). Forces experienced by the LET patellar tendon graft showed an isotonic pattern through the 4 flexion angles. Average forces experienced by the LET patellar tendon graft for each specimen across all flexion angles were one-third less force than the intact ACL at extension; however, the graft experienced 49% greater force than the intact ACL from 30° to 90°. Furthermore, there were increased forces on the patellar tendon graft during the unloaded state across all 4 flexion angles when compared with the intact ACL. When an

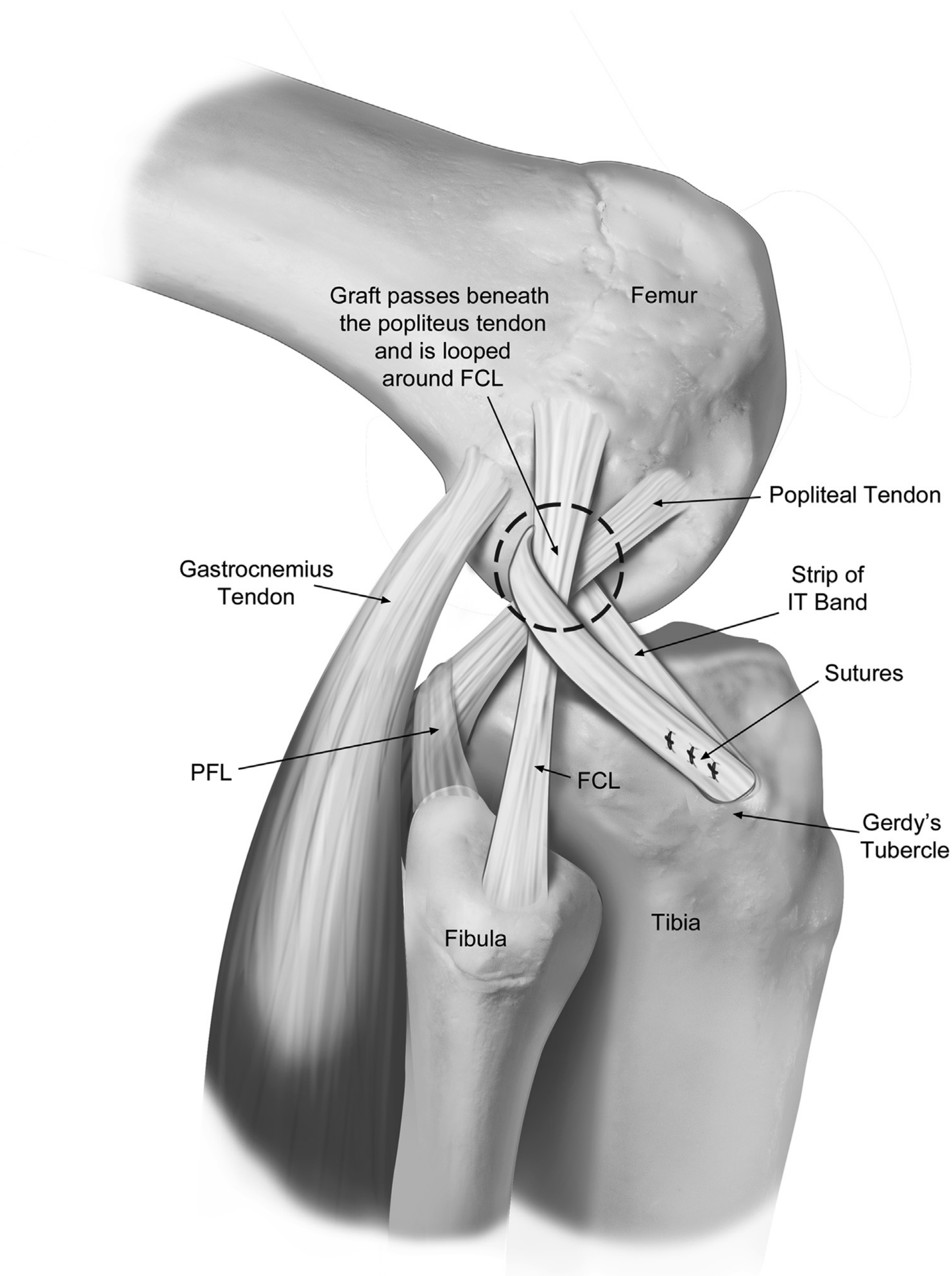

Fig 5. Arnold and Coker technique.[36] (FCL, fibular collateral ligament; IT, iliotibial; PFL, popliteofibular ligament.)

anteriorly directed load was applied, average forces on the patellar tendon graft were 3 times higher than the native, intact ACL.

Draganich et al.[19] used a strain gauge to deduce the strain patterns exhibited by the Müller anterolateral femorotibial ligament tenodesis[34] across 8 knee flexion angles at 15° increments from 0° to 90°. With a 50-N anteriorly applied force, the strain exhibited by the tenodesis was approximately 1.4% at 0° of flexion and 1.9% at 15° of flexion. The graft strain increased to approximately 3.6% at 30°. Strain patterns remained relatively constant between 30° and 90°. With a 3-Nm internal rotation torque, the strain exhibited by the tenodesis was approximately 3.7% at flexion angles of 0° and 15°. Strain patterns remained relatively constant between 30° and 90°, with magnitudes ranging from 4.6% (60°) to 5.8% (45°). The results of this study showed that, although the LET procedure did not restore knee stability to the level of an intact ACL, it significantly improved anterior stability and reduced internal rotation between 30° and 90° of flexion for the ACL-deficient knee ($P < .05$).

In a subsequent study, Draganich et al.[18] analyzed force patterns using 3 surgical techniques: isolated extra-articular reconstruction (Müller), isolated intra-articular reconstruction, and a combined extra-articular and

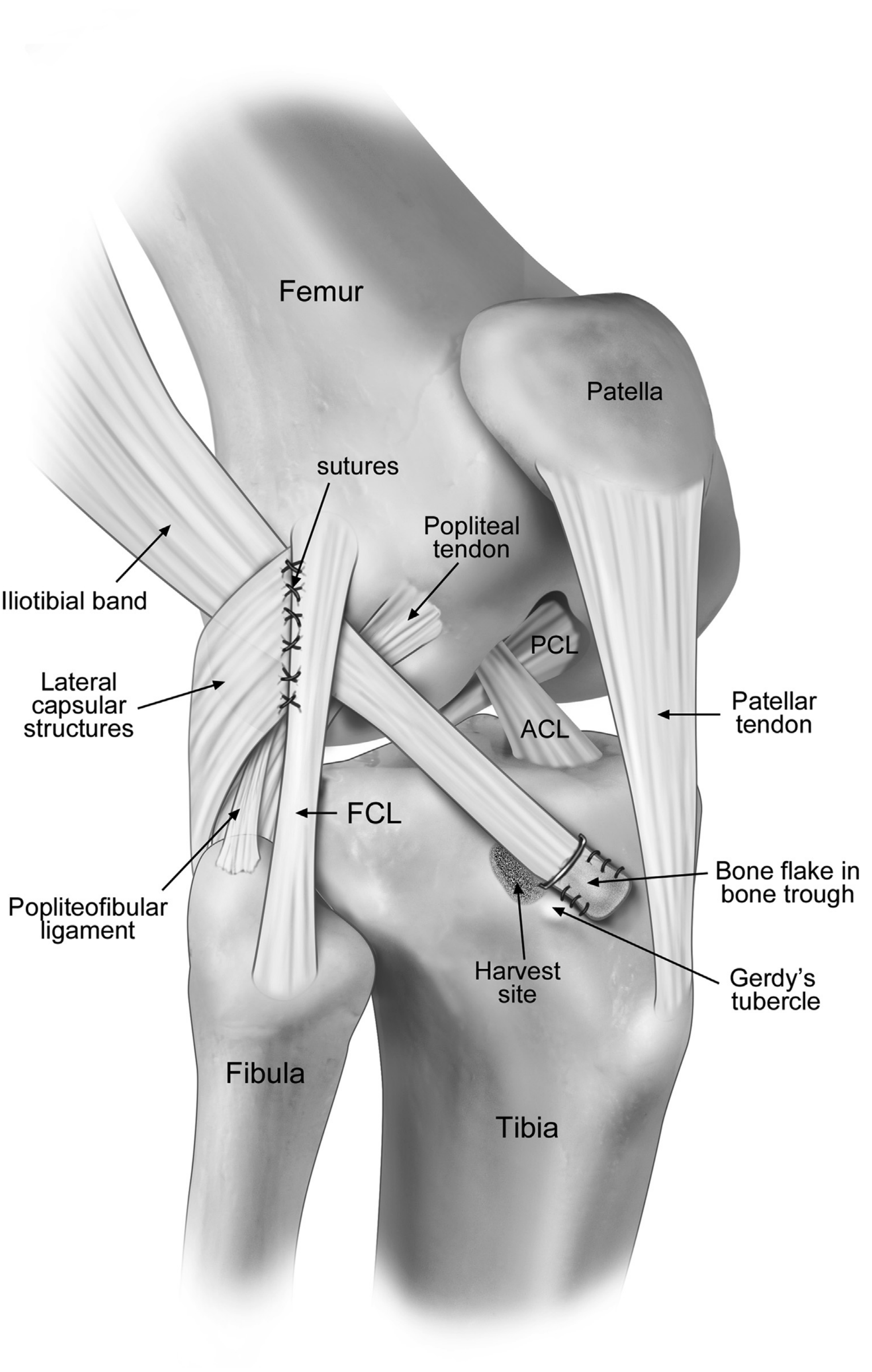

Fig 6. Ellison technique.[31] (ACL, anterior cruciate ligament; FCL, fibular collateral ligament; PCL, posterior cruciate ligament.)

intra-articular reconstruction. Force patterns for the extra-articular reconstruction technique were obtained from the previous study by Draganich et al.[19] In the combined reconstruction, the strain exhibited by the tenodesis during a 50-N anteriorly applied force was not significantly different ($P > .05$) from the strain shown when the extra-articular reconstruction was performed alone. In addition, the strain exhibited by the intra-articular graft in the combined reconstruction was not significantly different ($P > .05$) from that when an intra-articular graft was used alone (5.9% [maximum] at 30° and 4.2% [minimum] at 60°). For a 3-Nm internal

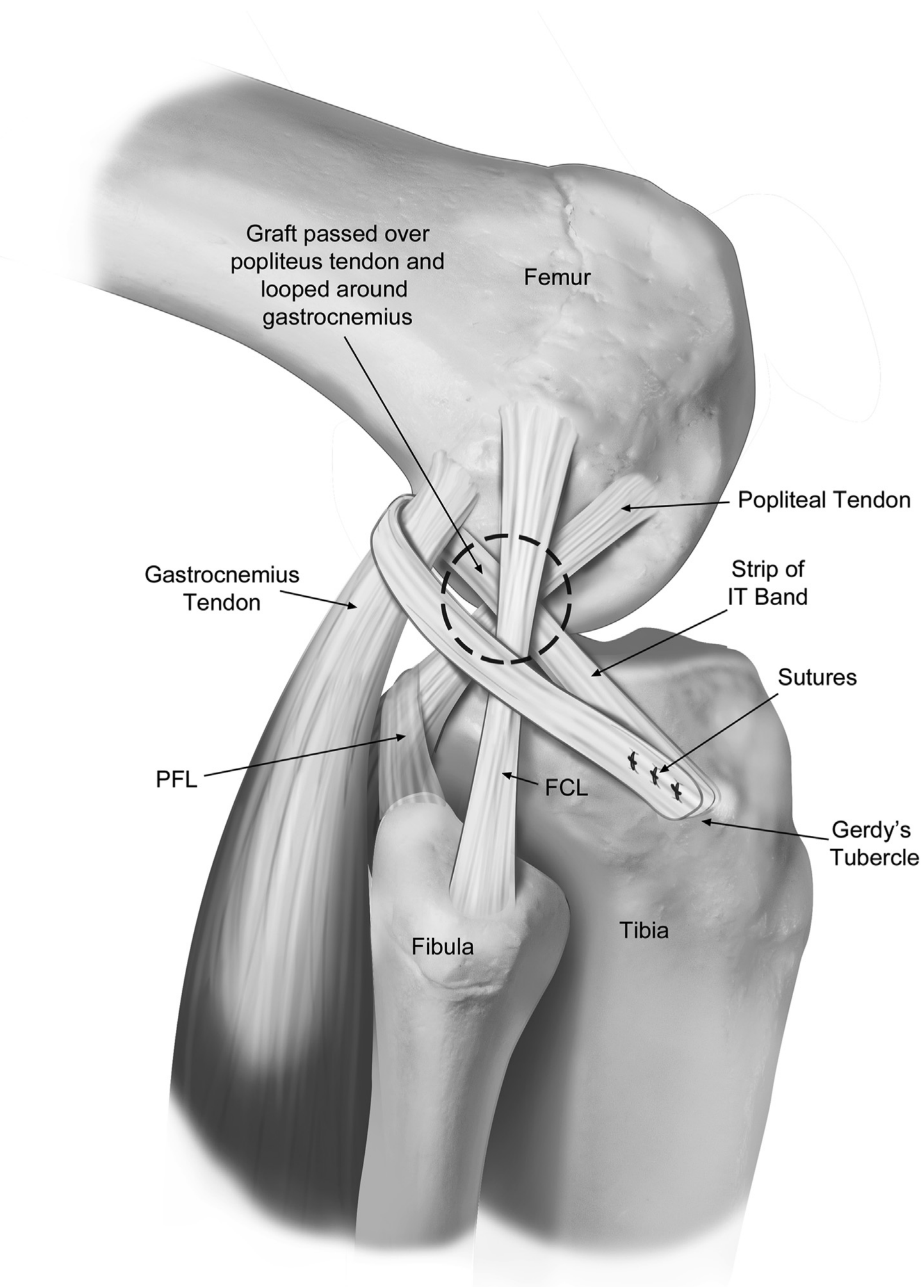

Fig 7. Wilson and Scranton technique.[32] (FCL, fibular collateral ligament; IT, iliotibial; PFL, popliteofibular ligament.)

rotation torque, the strain experienced by the extra-articular graft in the combined reconstruction was not significantly different ($P > .05$) from the strain experienced by the extra-articular graft when it was applied individually. Similarly, the strain in the intra-articular graft of the combined reconstruction was not significantly different ($P > .05$) from the strain shown by the intra-articular graft when used alone (5.4% [maximum] at 15°, 2.9% [minimum] at 60°, and 3.9% at 90°). It was reported that the strain in the intra-articular graft during rotation, both when used alone and when used in combination, was greatest at 15° of knee flexion and least between 45° and 90°. In contrast, the strain in the extra-articular graft during rotation was lowest at 0° and greatest between 30° and 90°. These results suggested that the Müller tenodesis technique may provide a load-sharing role when used in combination with an intra-articular reconstruction.[18,19]

Length Change Patterns and Graft Course. Kittl et al.[22] evaluated length change pattern, graft course, and total strain range (Maximum strain − Minimum strain) indices exhibited by various extra-articular reconstruction techniques in cadaveric models. Figure 14 shows the femoral eyelet position and corresponding tibiofemoral point combinations used to

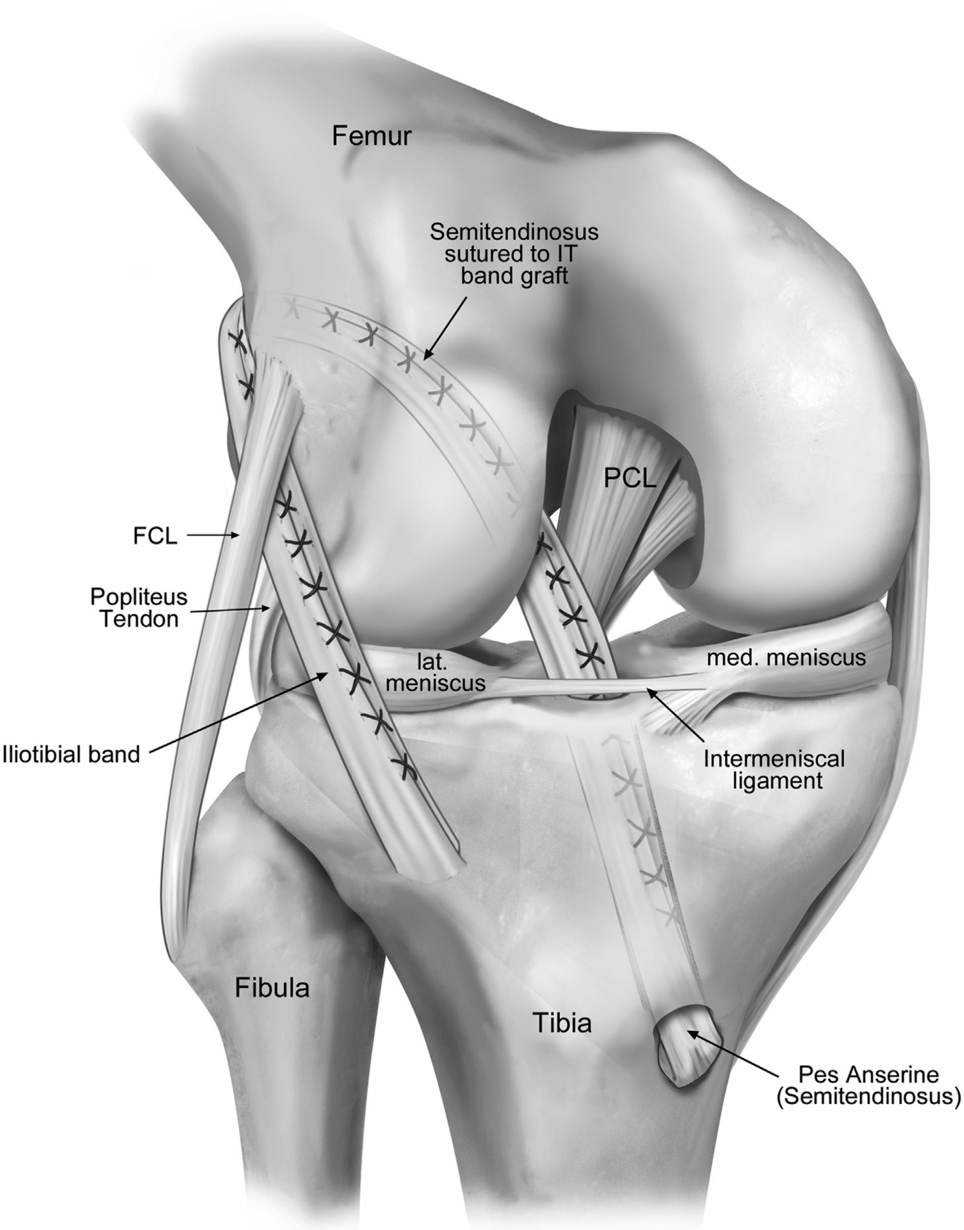

Fig 8. Zarins and Rowe technique.[35] (FCL, fibular collateral ligament; IT, iliotibial; lat, lateral; med, medial; PCL, posterior cruciate ligament.)

re-create the various extra-articular reconstructions. Table 3 indicates the LET procedure corresponding to the different tibial and femoral eyelet points shown in Figure 14.

Kittl et al.[22] noted significant differences in graft length change patterns when the graft coursed superficial or deep to the fibular collateral ligament (FCL). Grafts passing over (lateral to) the FCL had a tendency to lengthen during early knee flexion, whereas grafts coursing deep (medial) to the FCL tended to decrease in length. Kittl et al. concluded that grafts that ran deep to the FCL had “desirable” length change patterns, such that their length remained relatively constant during knee flexion-extension. Length change patterns for various extra-articular reconstruction techniques are presented in Figure 15.[22]

Krackow and Brooks[23] examined length change patterns of grafts between the femur and tibia over 7 flexion angles. When the Gerdy tubercle was used as the tibial attachment point and the lateral epicondyle was used as the femoral attachment point, tension increased with increasing knee flexion. In addition, they noted that changes in the femoral attachment resulted in relatively greater separation distances throughout the complete range of motion (0° to 125°) than were shown by varying the tibial graft attachment points.

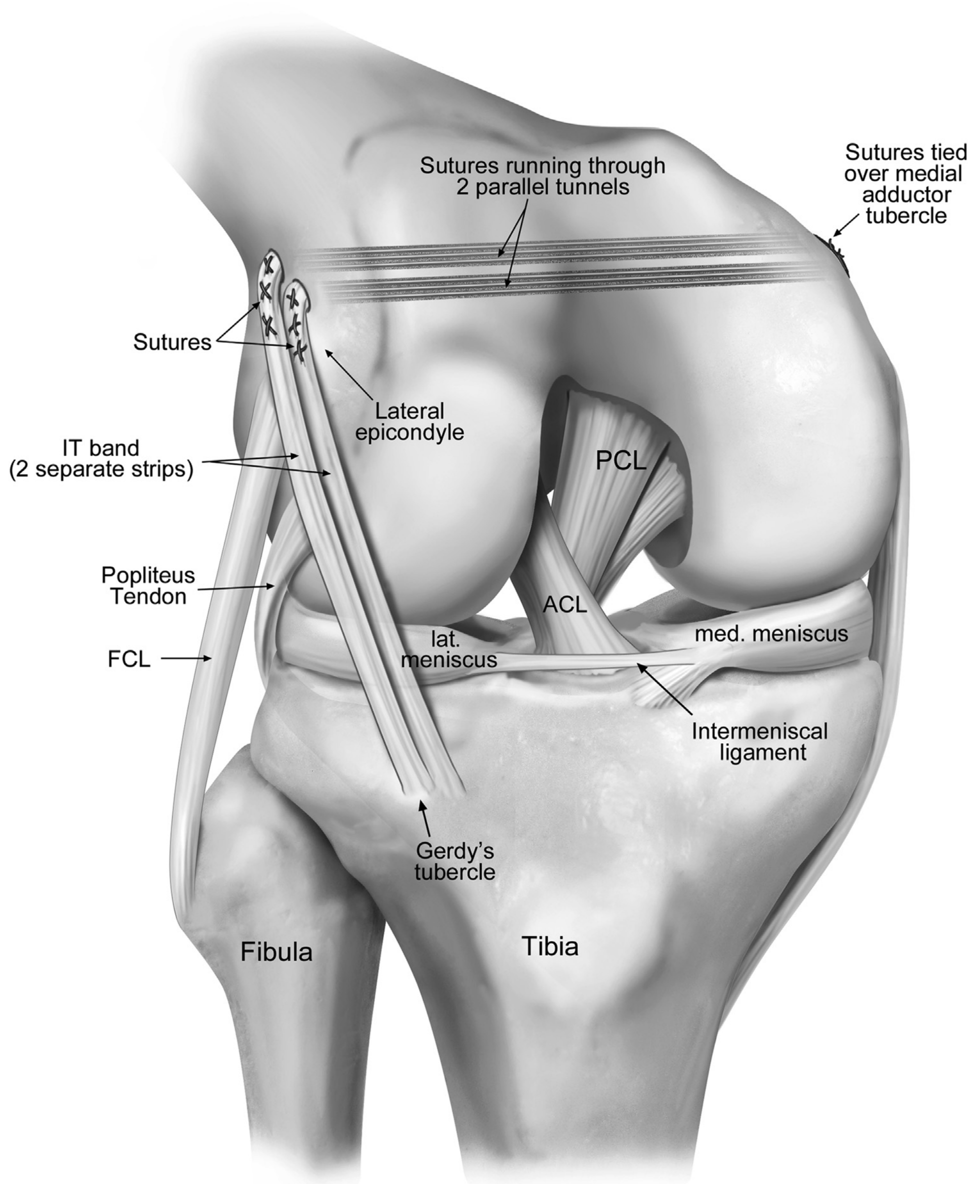

Fig 9. Andrews technique.[26] (ACL, anterior cruciate ligament; FCL, fibular collateral ligament; IT, iliotibial; lat, lateral; med, medial; PCL, posterior cruciate ligament.)

Discussion

The most important finding of this systematic review was that isolated LET procedures significantly reduced (overconstrained) internal rotation of the tibia to levels less than normal across various flexion angles from 0° to 90° in the ACL-deficient knee, as shown in 7 of 8 studies analyzing rotatory movement.[17-21,24,25] In addition, whereas isolated LET procedures did not return normal anterior stability to the ACL-deficient knee, they did significantly reduce anterior tibial translation and the forces on an intra-articular graft during the application of an anteriorly directed load. These findings verify the conclusions of previous studies that asserted that the ACL and anterolateral structures collectively inhibit anterolateral rotatory instability in the intact knee.[2,3,8,9]

Many variants of LET procedures have been proposed, implemented, and modified to address residual anterolateral rotatory instability. The 10 studies included in this systematic review showed significant variability with respect to the surgical technique used for the LET procedure.[16-25] Despite variability in the surgical approaches, most studies exhibited similar biomechanical results, bringing previous concerns about the efficacy of LET procedures to the forefront. Previous studies documenting LET procedures recommended fixing the graft with the tibia maintained in an externally rotated position.[20,26-28,30-33,35,36] However,

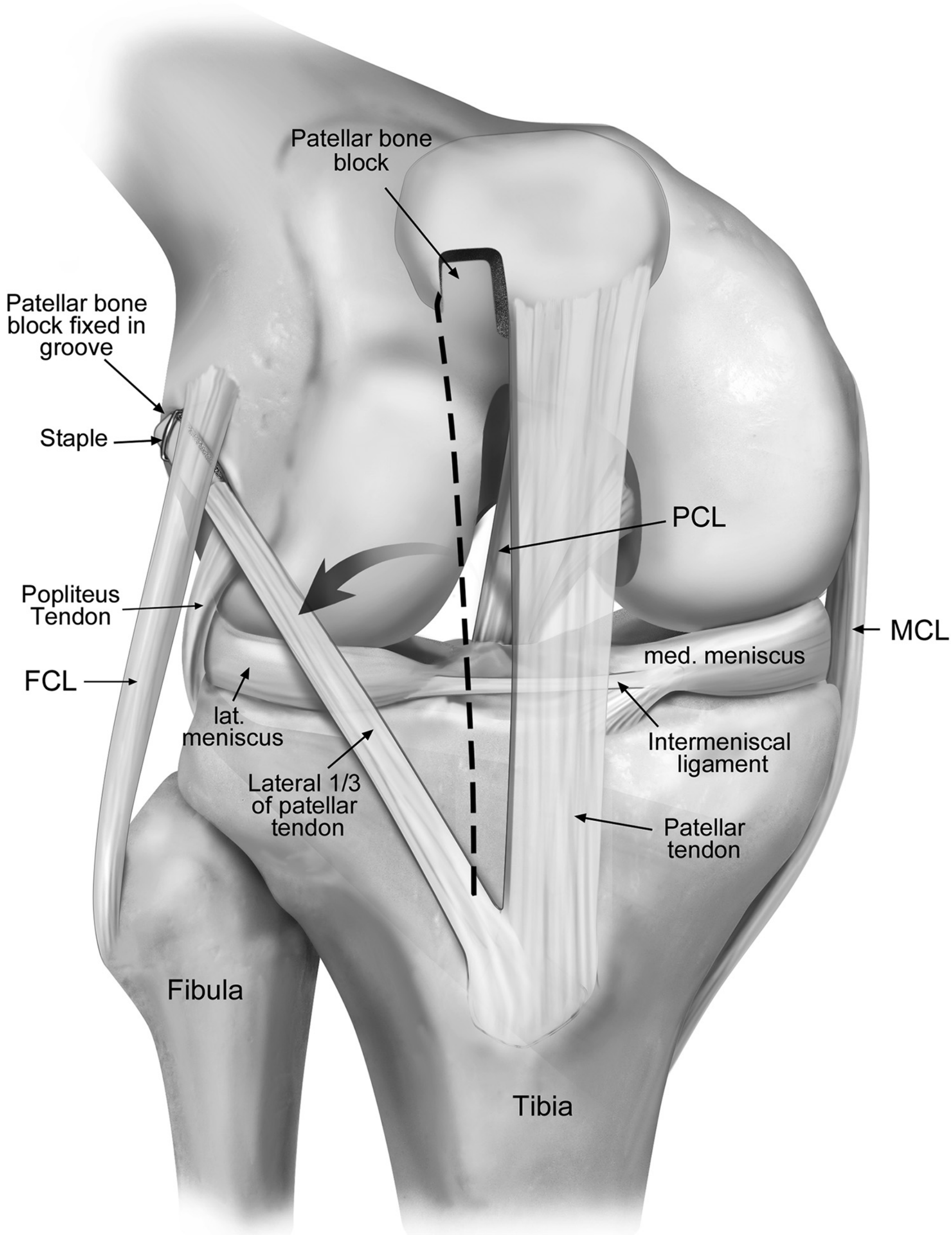

Fig 10. Benum technique.[30] (FCL, fibular collateral ligament; lat, lateral; MCL, medial collateral ligament; med, medial; PCL, posterior cruciate ligament.)

non-neutral positioning of the tibia interferes with the "screw home" mechanism because the externally fixed graft effectively inhibits physiological rotation of the tibia about its central axis.[21] Of the 8 studies in this review that analyzed rotatory movement, 7 showed joint over-constraint, indicated by a significant reduction in internal rotatory movement relative to that of the native knee joint.[17-21,24,25] Previous studies have reported that over-constraint of the knee may cause abnormal joint kinematics, leading to the development of premature osteoarthritis.[18,20,21,24,25] In addition, joint over-constraint has been theorized to result in graft elongation and eventual graft failure.[21]

As discussed previously, the studies included in this systematic review reported significant variability in the anatomic attachment points and course of the LET graft used. However, a common theme among the studies included in this review was the nonanatomic nature of their graft placement. Krackow and Brooks[23] discussed the importance of anatomic tunnel placement during extra-articular reconstructions, stating that satisfactory ligamentous reconstructions required the femoral and tibial attachments to be oriented such that the vector of restraint was appropriate to prevent the instability being experienced. Although the LET procedures described in this review reduced

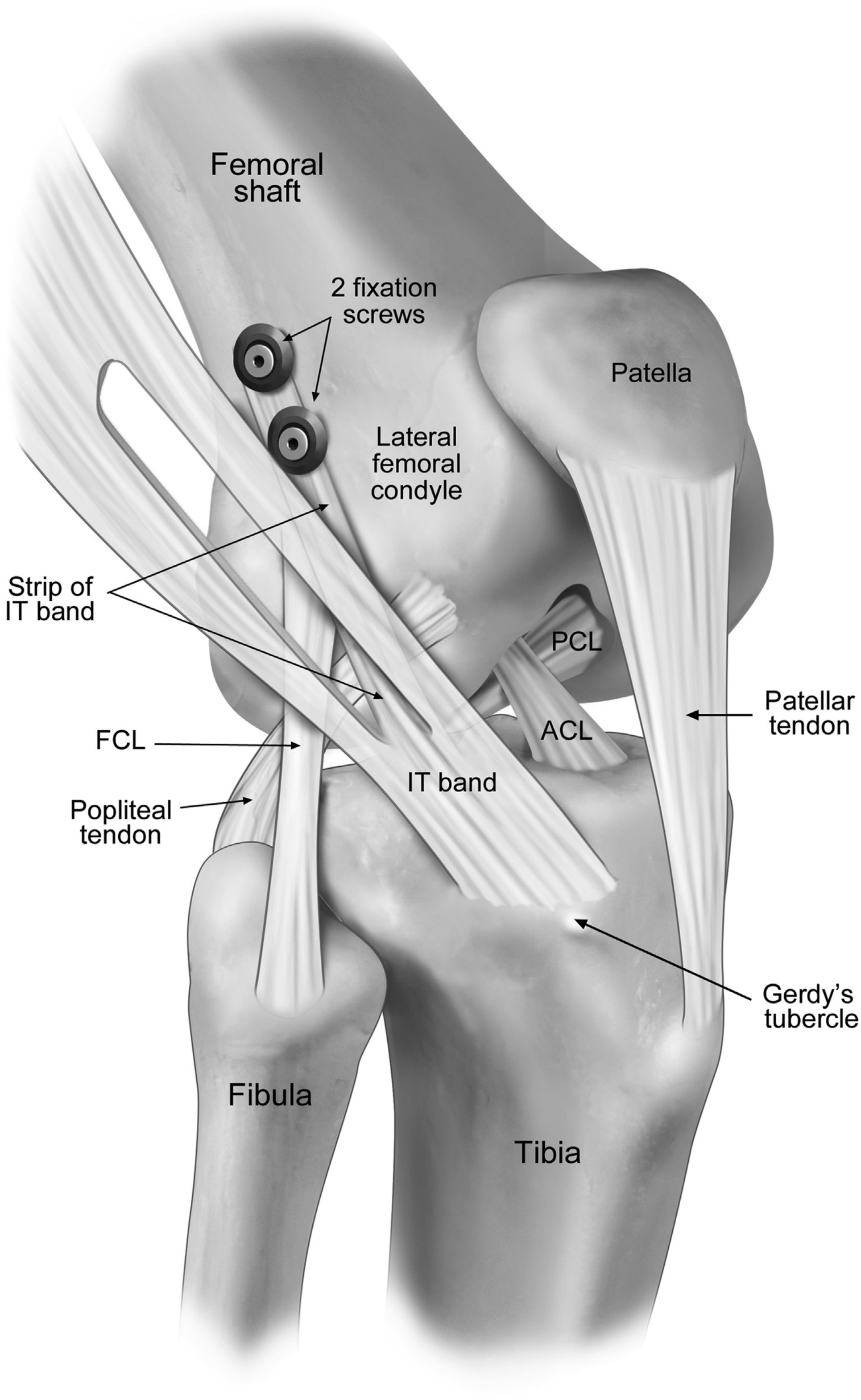

Fig 11. Müller technique.[34] (ACL, anterior cruciate ligament; FCL, fibular collateral ligament; IT, iliotibial; PCL, posterior cruciate ligament.)

anterolateral rotatory instability and anterior tibial translation, they did not restore the native kinematic state of the knee. We theorize that this could be because of the nonanatomic reconstruction of the anterolateral structures of the knee; however, further research is needed to support this claim.

Various LET procedures have exhibited good short-term clinical outcomes.[39,40] However, after a period of

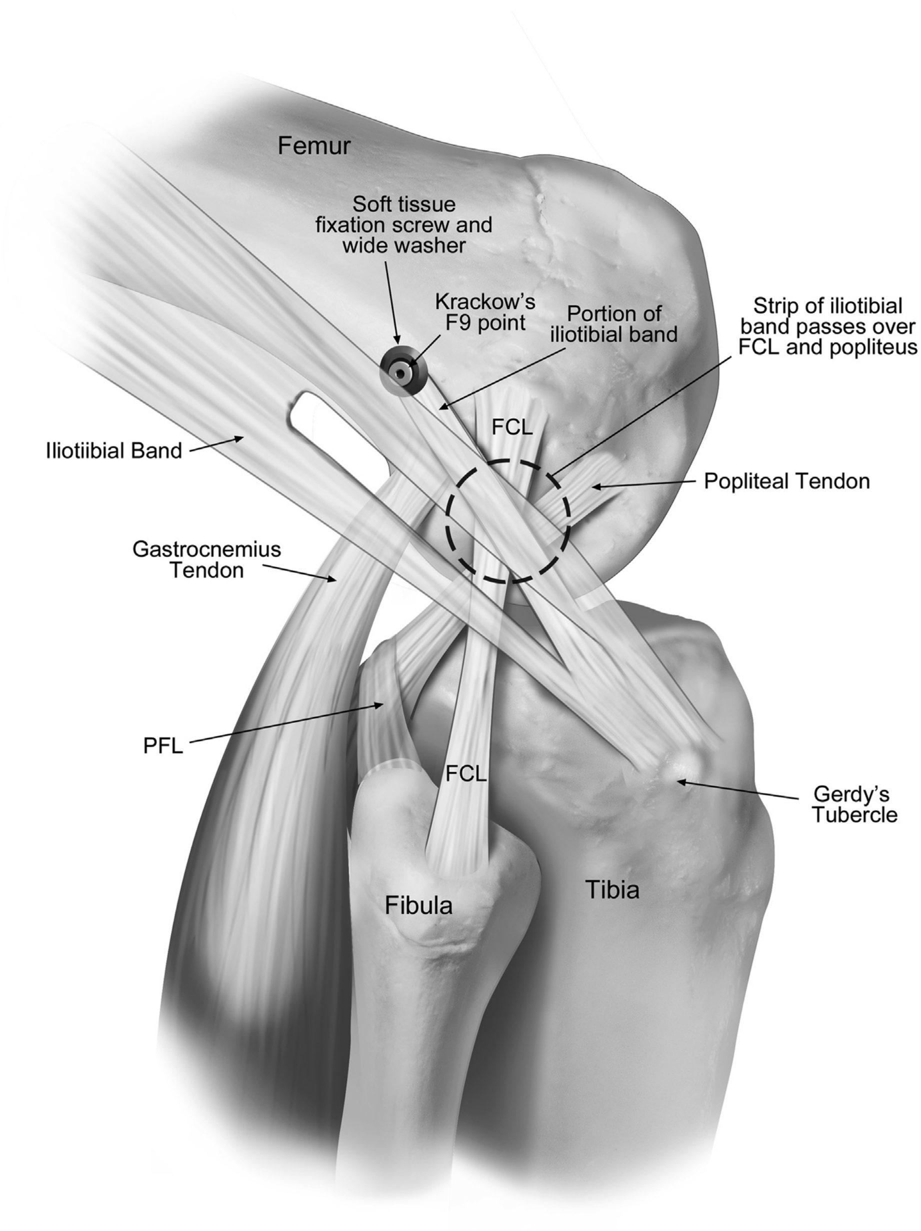

Fig 12. Modified Andrews technique.[20] (FCL, fibular collateral ligament; PFL, popliteofibular ligament.)

initial stability, LET reconstructions have often shown a tendency to elongate, with return of anterolateral rotatory instability in the ACL-deficient knee.[11,41-43] It has been suggested that this may be due to the fact that the procedures analyzed in this systematic review were considered nonanatomic relative to the orientation of extra-articular grafts. Isometry, which was a principle reviewed across all studies, indicates a constant distance between 2 moving points on opposite sides of the joint.[22] Sidles et al.[37] asserted that an entirely isometric LET procedure does not exist. However, it has been suggested that the increased extent of isometry of a ligament reconstruction reduces the propensity of graft lengthening and failure. It has been reported that an increase in separation distance between the insertion points of a ligament reconstruction of 6% could lead to permanent graft elongation; therefore, appropriate graft positioning and tensioning of LET procedures are paramount.[44] In a recent study, Kittl et al.[22] reported that any tibiofemoral reconstruction combination that inserted proximal to the lateral epicondyle and coursed deep to the FCL was nearly isometric between 0° and 90°. As the knee extended, only a slight increase in length was shown, implying an ability to inhibit anterior subluxation of the lateral tibial plateau. Among the LET procedures analyzed, the MacIntosh procedure was reported to display the most isometric pattern from 0° to 90° of flexion.[22]

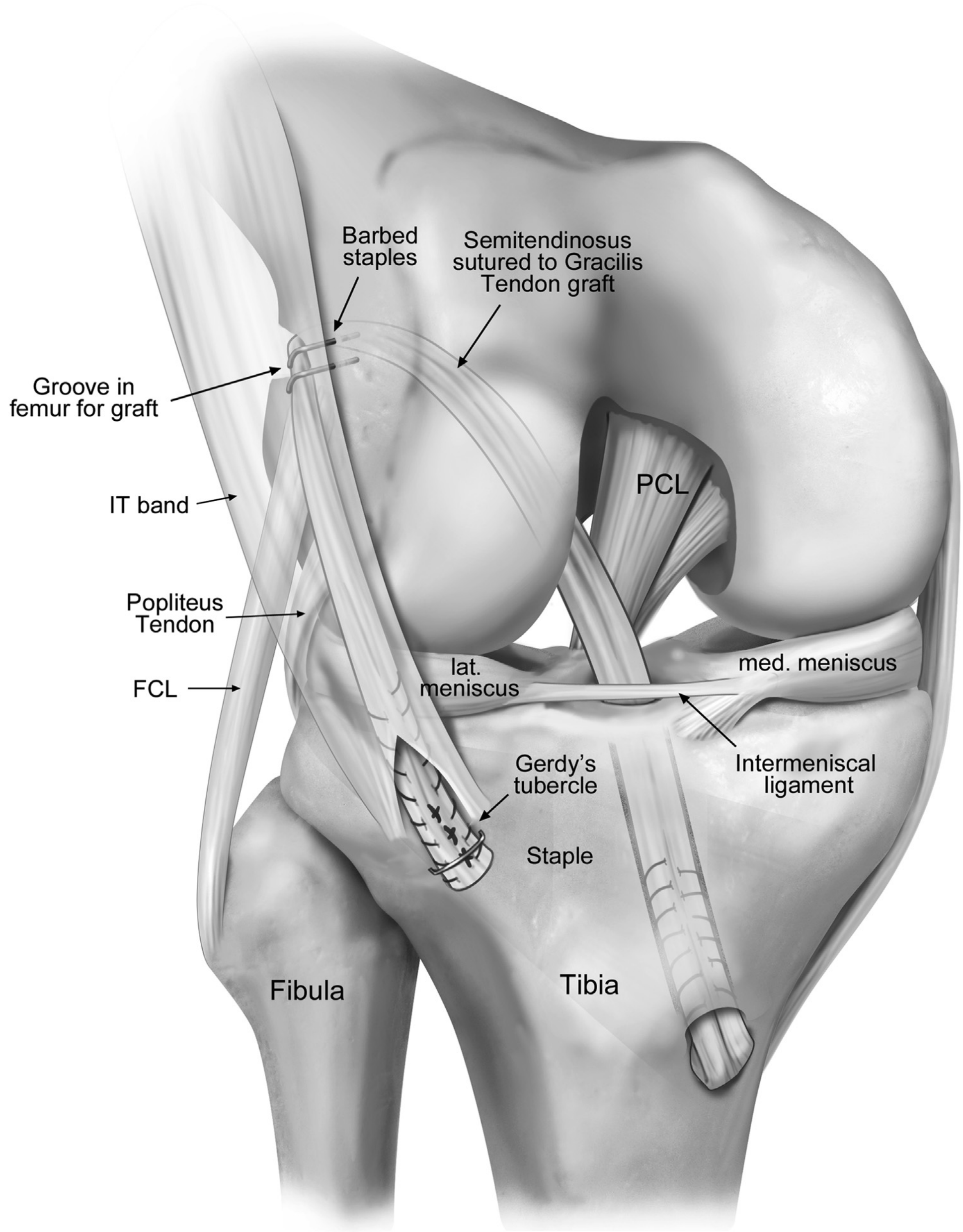

Fig 13. Marcacci and Zaffagnini technique.[33] (FCL, fibular collateral ligament; IT, iliotibial; lat, lateral; med, medial; PCL, posterior cruciate ligament.)

Although clinical outcome studies have reported evidence of long-term LET graft failure,[11,41-43] some authors have advocated for the use of LET procedures to augment ACL reconstruction because they have been proposed to provide secondary restraint and decrease forces experienced by intra-articular reconstruction grafts.[18-20] Therefore, the addition of an LET to an ACL reconstruction may be practical in patients in whom the intra-articular graft may require additional protection, such as patients who are obese, patients who are highly active, or patients in whom the anterolateral structures are severely compromised.[18] We believe that further comparative clinical studies investigating the ability of an LET to improve outcomes after ACL reconstructions are necessary.

Limitations

We recognize that this systematic review has limitations that should be considered when interpreting its results. First, this review contains limitations inherent to the reviewed in vitro studies. Namely, the time-zero, biomechanical results would reflect only the initial stability achieved immediately postoperatively and not the final results experienced after the in vivo

Table 2. Biomechanical Data From 8 Studies Investigating Anterior Translation, Internal-External Rotatory Movement, and Varus-Valgus Rotation

Authors	Year	Reconstruction	Flexion	Anterior Translation: Displacement	Internal-External Rotation	Varus-Valgus Rotation	
						Flexion	Rotation
Amis and Scammel[16]	1993	IA	20° 90°	No significant difference from intact knee	No significant difference from intact knee	20°	No significant difference from intact knee
		IA + EA (MacIntosh)	20° 90°			20°	
		EA	20° 90°			20°	
Butler et al.[17]	2013	Single bundle + EA (Losee)	30° 90°	2.3 mm > normal 0.3 mm > normal	Internal: 2.5° < normal Internal: 4.8° < normal	Not reported	Not reported
		Double bundle + EA	30° 90°	2.1 mm < normal 1.3 mm < normal	Internal: 3.2° < normal Internal: 5.4° < normal	Not reported	Not reported
Draganich et al.[19]	1989	EA (Müller)	15° increments from 0°-90°	0°: 3.2 mm > normal 15°, 30°: 3.7 mm > normal 90°: 2 mm > normal	External: 15°: 2.2° > normal 30°: 4.6° > normal Internal: 45°: 5.5° < normal 60°: 6.9° < normal 90°: 7.5° < normal	Not reported	Not reported
Draganich et al.[18]	1990	IA	15° increments from 0°-90°	No significant difference from intact knee	No significant difference from intact knee	Not reported	Not reported
		IA + EA (Müller)	15° increments from 0°-90°			Not reported	Not reported
		EA	15° increments from 0°-90°	0°: 3.2 mm > normal 15°, 30°: 3.7 mm > normal 30°-90°: significant reduction ($P < .05$) 90°: 2 mm > normal	External: 15°: 2.2° > normal 30°: 4.6° > normal Internal: 45°: 5.5° < normal 60°: 6.9° < normal 90°: 7.5° < normal	Not reported	Not reported
Engebretsen et al.[21]	1990	EA (Benum)	30° increments from 0°-90°	No significant difference from intact knee	External: significantly different from intact knee ($P \leq .001$)	Not reported	Not reported
Engebretsen et al.[20]	1990	IA	30° increments from 0°-90°	No significant difference from intact knee	No significant difference from intact knee	Not reported	Not reported
		IA + EA (modified Andrews)	30° increments from 0°-90°		External: significantly different from intact knee ($P \leq .05$)	Not reported	Not reported
		EA + IA	30° increments from 0°-90°			Not reported	Not reported
Matsumoto and Seedhom[24]	1994	IA	5° increments from 0°-90°	Not reported	3.5-Nm external rotation: no significant difference from intact knee 3.5-Nm internal rotation: less than or equal to intact knee	5° increments from 0°-90°	12.5-Nm valgus torque (clinical pivot shift test): negative test

(continued)

Table 2. Continued

Authors	Year	Reconstruction	Flexion	Anterior Translation: Displacement	Internal-External Rotation	Varus-Valgus Rotation	
						Flexion	Rotation
		IA + EA (Zarins-Rowe)	5° increments from 0°-90°	Not reported	3.5-Nm external rotation: no significant difference from intact knee 3.5-Nm internal rotation: less rotation than intact knee	5° increments from 0°-90°	
		EA	5° increments from 0°-90°			5° increments from 0°-90°	
Samuelson et al.[25]	1996	IA (ACL-deficient knee)	30° increments from 0°-90°	No significant difference from intact knee	Internal: significantly different from intact knee ($P < .01$)	Not reported	Not reported
		IA (combined injury)	30° increments from 0°-90°	0°: 2 mm > normal Otherwise, no significant difference from intact knee	Internal: significantly different from intact knee ($P < .002$)	Not reported	Not reported
		IA + EA (Müller) with 0 N of tension (combined injury)	30° increments from 0°-90°	90°: 2 mm < intact knee	Internal: 60°, 90°: 7.5° less rotation than intact knee	Not reported	Not reported
		IA + EA with 22 N of tension (combined injury)	30° increments from 0°-90°	60°, 90°: 3 mm < intact knee	Internal: 30°-90°: 10°-15° less rotation than intact knee	Not reported	Not reported

ACL, anterior cruciate ligament; EA, extra-articular; IA, intra-articular.

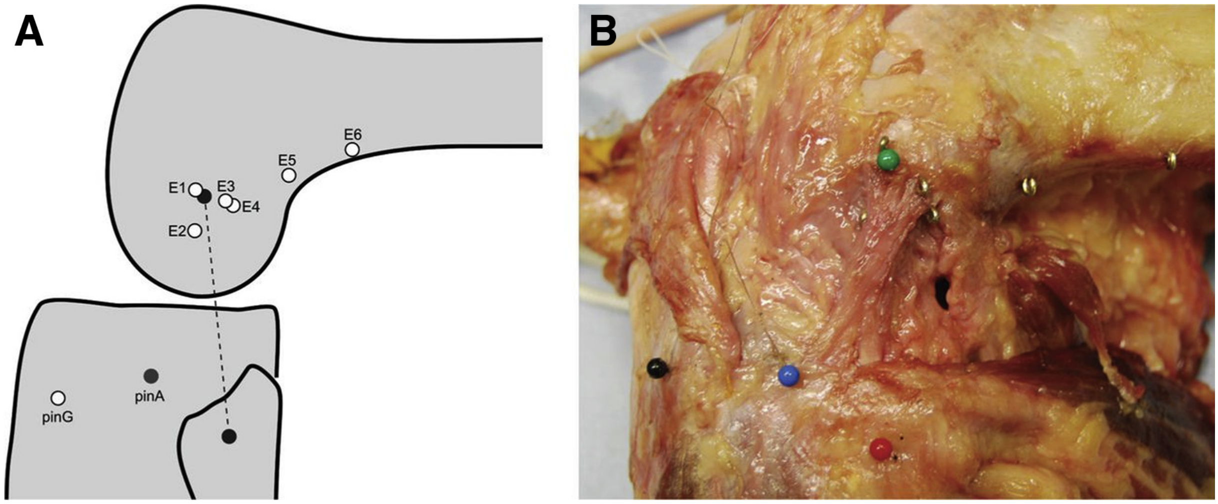

Fig 14. Femoral eyelet positioning. Tibiofemoral point combinations represent structures on the lateral side, extra-articular soft-tissue reconstructions, and femoral isometric points. (A) Pin G indicates the Gerdy tubercle; pin A, area of Segond avulsion; and dashed line, fibular collateral ligament. (B) The black pin indicates the Gerdy tubercle; blue pin, area of Segond avulsion; red pin, fibular head; and green pin, lateral epicondyle. Reproduced with permission from Kittl et al.[22]

Table 3. Femoral Eyelet Positioning and Corresponding Tibiofemoral Point Combinations for Lateral Extra-articular Tenodesis Procedures

		Tibial Pin	
Femoral Eyelet	Position (From Lateral Femoral Epicondyle)	Pin G	Pin A
E1	2 mm anterior, 2 mm distal	Anterior part of Losee[29] reconstruction	Mid-third lateral capsular ligament ALL defined by Claes et al.[1]
E2	10 mm posterior, 4 mm distal	Isometric point of Draganich et al.[18,19]	
E3	4 mm posterior, 8 mm proximal	Lemaire[27] reconstruction*	ALL defined by Dodds et al.[38]
E4	6 mm posterior, 10 mm proximal	Isometric point of Sidles et al.[37]	
E5	Over-the-top position	Zarins-Rowe[35] reconstruction* Isometric point F9 of Krackow and Brooks[23] Posterior part of Losee[29] reconstruction*	
E6	Posterior femoral cortex at distal termination of intermuscular septum	Anterior fibers of ITT MacIntosh[28] reconstruction*	Posterior fibers of ITT

NOTE. Reproduced with permission from Kittl et al.[22] There were 4 native tissue structures, 4 reconstructions, and 3 femoral isometric points.
ALL, anterolateral ligament; ITT, iliotibial tract; Pin A, area of Segond avulsion; Pin G, Gerdy tubercle.
*Course deep to lateral collateral ligament.

healing process. Second, there was variability in the surgical techniques used and the means through which the biomechanical results were quantified. Finally, a limitation that is inherent in any systematic review is the possibility that relevant articles were not identified through the literature search and that studies published after the performed search were not included. We believe that the biomechanical results of the techniques examined in this review will influence the further refinement of anterolateral ligament reconstruction techniques, thus making the comprehensive nature of this review significant and externally valid.

Conclusions

In the ACL-deficient knee, LET procedures overconstrained the knee and restricted internal tibial rotation when compared with the native state. In addition, isolated LET procedures did not return normal anterior stability to the ACL-deficient knee but did significantly

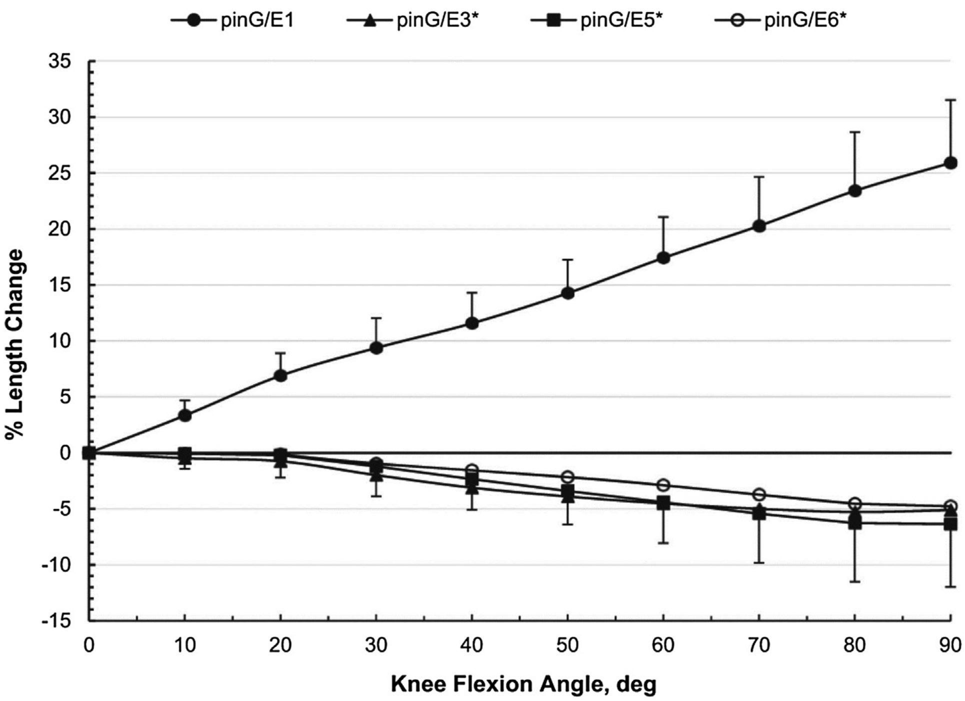

Fig 15. Length change patterns exhibited by MacIntosh (pin G/E6), Zarins and Rowe (pin G/E5), Losee (pin G/E1), and Lemaire (pin G/E3) lateral extra-articular procedures between 0° and 90° with pooled 95% confidence intervals. One should note that femoral insertion points proximal to the lateral epicondyle displayed similar length change patterns. An asterisk indicates the graft passed deep to the fibular collateral ligament. Reproduced with permission from Kittl et al.[22]

reduce anterior tibial translation and intra-articular graft forces during anteriorly directed loading.

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