secondary stabilizers and combined injury in anterior cruciate ligament reconstruction

wybren a. van der wal

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W.A. van der Wal

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Secondary Stabilizers and Combined Injury in Anterior Cruciate Ligament Reconstruction

Secundaire stabilisatoren en gecombineerd letsel bij voorste kruisbandreconstructie

(met een samenvatting in het Nederlands)

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Voor mijn Ouders

chapter 1

Introduction, Aims, and Questions Addressed

Anterior cruciate ligament (ACL) reconstruction (ACLR) is widely performed worldwide in ACL-injured patients to restore knee stability and enable return to sport.[1,2] Although current surgical techniques and rehabilitation protocols have improved outcomes, a considerable proportion of patients continue to experience residual instability[3,4], do not return to their pre-injury level of activity[5–7], or sustain graft failure.[8–10] These observations reflect that outcomes after ACLR are influenced by a range of factors, and that ACL-related knee stability is not solely determined by the ACL itself, but is also affected by the contribution of secondary stabilizing structures and concomitant pathology.[11,12] In particular, concomitant injuries to structures such as the menisci and anterolateral corner complex, as well as variations in lower- limb alignment, may influence knee kinematics and increase forces on the reconstructed ACL.[13–15] Despite growing biomechanical evidence supporting the role of these factors, their integration into clinical decision-making remains inconsistent. Therefore, a more comprehensive understanding of the biomechanical contribution of secondary stabilizers and concomitant pathology, and their translation to clinical practice, is required to optimize treatment strategies and reduce the risk of ACLR failure.

The central aim of this thesis is to improve understanding of how concomitant injuries, secondary stabilizing structures, and osseous alignment influence ACL biomechanics and knee kinematics. This knowledge is translated into clinical practice to optimize surgical decision-making and perioperative management, and ultimately improve patient outcomes. Specifically, this thesis addresses the following aims:

1. To systematically evaluate the biomechanical influence of concomitant intra- and extra-articular injuries and lower-limb alignment in the coronal and sagittal planes on ACL (graft) force and ACL-related knee kinematics;
2. To evaluate the biomechanical role of the iliotibial tract (ITB) and the anterolateral ligament (ALL) in anterolateral rotatory instability in ACL-injured knees, and to compare the effects of lateral extra-articular tenodesis (LET) versus ALL-reconstruction in ACL-reconstructed knees;
3. To determine the individual and combined biomechanical effects of lateral meniscus posterior root (LMPR) and Kaplan fiber tears in the ACL-deficient knee and to assess the impact of LMPR repair, modified Lemaire lateral extra-articular tenodesis (LET), or both, in the ACL-reconstructed knee;
4. To evaluate whether the addition of an anterolateral corner (ALC) reconstruction to ACLR is associated with improved joint awareness, other patient-reported outcomes, and lower graft re-rupture rates in young high-risk patients;
5. To interpret biomechanical findings on the ALL within the ALC and to clarify its implications for surgical decision-making in ACLR;
6. To determine the prevalence of increased posterior tibial slope (PTS) in a young high-risk primary ACLR population and to evaluate whether ALC reconstruction is associated with lower revision rates in this subgroup;

7. To determine whether the addition of an anterolateral genicular nerve block to an adductor canal block improves postoperative pain control and reduces analgesic consumption after combined ACLR and ALC reconstruction.

The anterior cruciate ligament

The knee is a complex weightbearing hinge joint that allows flexion, extension, and limited rotation while transmitting large loads during standing and motion. Anatomically, it consists of the tibiofemoral and patellofemoral articulations between the femur, tibia, and patella, with motion and stability governed by bones, articular cartilage, menisci, ligaments, joint capsule, muscles, and tendons.[16–18] Key stabilizing ligaments include the medial and lateral collateral ligaments on the sides, and the anterior and posterior cruciate ligaments centrally, along with the menisci and surrounding capsuloligamentous structures.[16–18] Together these structures balance mobility with stability so the knee can bear body weight and contribute to efficient gait while minimizing joint wear.[17,19] Within this system, the ACL is a primary stabilizer located in the center of the knee (Figure 1).

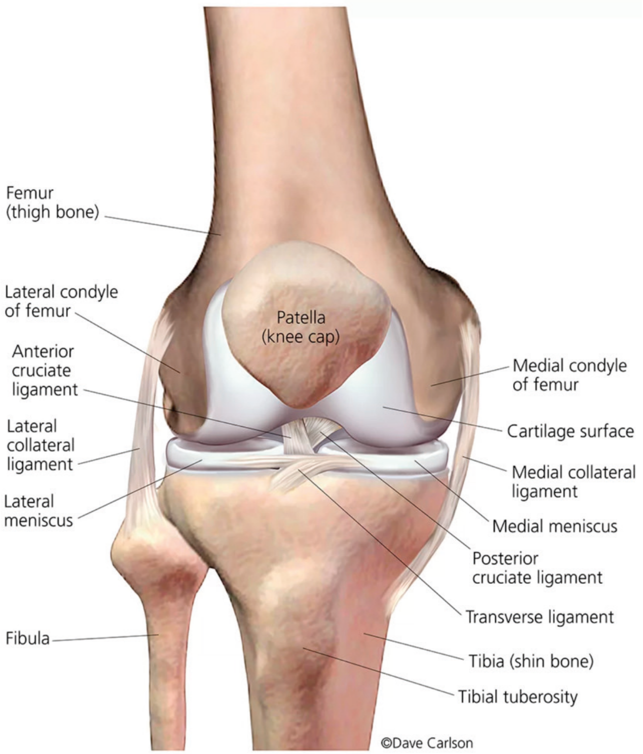

Figure 1. Illustration of the bones, ligaments, cartilage, and menisci of the human right knee (anterior view). © Dave Carlson/CarlsonStockArt.com. Used with permission.[20]

The ACL is an intracapsular, but extra-synovial structure in the knee.[21,22] The ACL is a band of dense connective tissue that is ensheathed by synovium, which separates it from intra-articular fluid while providing a route for vascular and neural supply.[21,22] Within this sheath, the ACL runs from the posteromedial aspect of the lateral femoral condyle to the anterior intercondylar area of the tibia, with a mean length of about 32 mm and width of 7-12mm in extension.[21,23,24] Microscopically, it consists mainly of type 1 collagen organized into longitudinal fascicles, embedded in a matrix rich in proteoglycans and an elastic fiber system that allows the ligament to tolerate multiaxial loading.[21,25] Classic and highly cited anatomical work describes the ACL as comprising two major fiber bundles, the anteromedial (AM) and posterolateral (PL) bundles, sometimes with an intermediate component.[21,23,24,26] The bundle nomenclature is based on its tibial insertion: the AM bundle inserts more anteromedial within the ACL tibial footprint, while the PL bundle inserts more posterolateral.[21,23,27,28]

Functionally, the two bundles are non-isometric. The PL bundle is tight in near-extension and slackens with early flexion; the AM bundle tightens progressively with flexion and becomes the main restraint to anterior tibial translation at higher flexion angles.[21,23,24,26] Smigielski et al. re-examined the ACL and found that at approximately 2-3 mm from the femoral insertion the ligament consistently forms a flat ribbon (≈11–16 mm wide, 2.5–3.4 mm thick) in exact continuity with the posterior femoral cortex, without a clear macroscopic separation between AM and PL bundles (Figure 2).[29] The "double-bundle effect" described by Amis and Dawkins is explained as an optical result of the twisted flat ribbon, which gives the impression of two or three separate bundles when the knee flexes.[26,29] In this view, AM and PL bundles are best regarded as functional regions within a single multifascicular ribbon, distinguished by their insertion areas and tension patterns rather than by robust internal partitions.[21,24,27,29] Therefore, classic AM / PL morphometric data remain directly useful for anatomic reconstruction, while the ribbon concept emphasizes reproducing each patient's broad, flat femoral and tibial footprints rather than assuming round, cord-like bundles.[24,28–31]

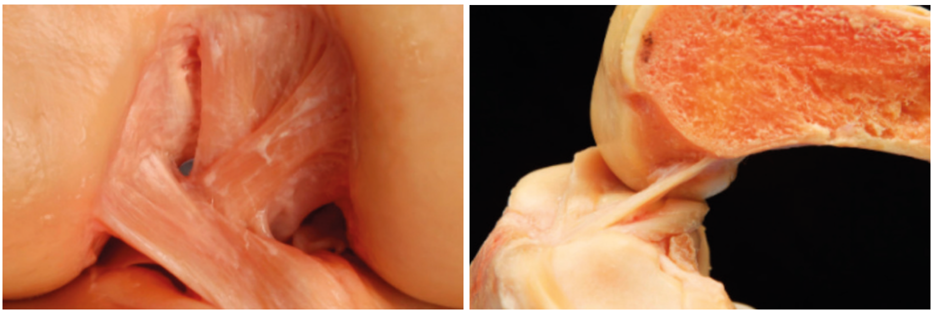

Figure 2. The ribbon shape of the ACL after removal of the synovial tissue in a right knee.[29]

Vascularization of the ACL is provided mainly by branches of the middle genicular artery, which penetrate the posterior capsule and travel within the synovial sheath to form a periligamentous plexus that sends transverse branches into a longitudinal intra-ligamentous network.[32,33]

The ACL contains abundant mechanoreceptors: Ruffini endings, Pacinian corpuscles, Golgi-like receptors, and free nerve endings, supplied by posterior articular branches of the tibial nerve.[21] These receptors deform with ligament strain and joint motion, converting mechanical loading into neural signals about knee position and movement.[21] ACL rupture leads to loss of mechanoreceptor input, associated with quadriceps weakness, reduced maximal voluntary contraction, and impaired joint position sense; proprioceptive deficits correlate with the number of intact mechanoreceptors.[21]

Anterior cruciate ligament biomechanics

The primary biomechanical function of the ACL is to resist anterior tibial translation, acting as the main stabilizer that prevents the tibia from moving forward relative to the femur across all knee flexion angles.[15,34,35] The ACL also serves as a secondary stabilizer against tibial internal rotation, particularly near full knee extension, contributing to rotational stability but with decreasing influence as the knee flexes beyond 30-35 degrees.[15,36] The ACL also provides secondary restraint to varus and valgus rotations of the knee, helping to limit excessive side-to-side angulation under load.[37] The tensile properties of the ACL and its oblique orientation in the knee enable it to withstand complex loading conditions including anterior shear, rotational, and varus-valgus moments, which are common during dynamic activities.[37,38]

Anterior cruciate ligament injury

ACL injuries occur at an estimated global incidence of about 68.6 per 100,000 person-years, with higher rates in males (81.7 per 100,000) than females (55.3 per 100,000), and with a peak incidence in young adults aged 14 to 25 years.[2] Annually, hundreds of thousands of ACL tears are reported worldwide, with a significant and increasing number undergoing surgical reconstruction as patients seek to return to high levels of activity.[1,2] It is thought that approximately 12,000 ACL reconstructions are performed annually in The Netherlands. The incidence of ACL injuries is increasing, particularly among female athletes, largely due to their growing participation in high-risk pivoting sports such as soccer and basketball.[39,40] Female athletes experience ACL injury rates up to eight times higher than males in similar sports, driven by a combination of anatomical, hormonal, neuromuscular, and biomechanical factors that increase vulnerability during pivoting moments.[39,40] The pivoting moment that is the primary trauma mechanism causing ACL rupture involves a combination of valgus stress and tibial internal rotation, with the knee in flexed position. This commonly occurs during non-contact, rapid deceleration, cutting maneuvers, or awkward landings with the foot planted; this biomechanical loading causes excessive strain on the

ACL fibers leading to rupture.[41,42] While non-contact mechanisms are the most common cause of ACL ruptures, direct contact to the knee and gear-induced injuries such as in alpine skiing also play significant roles depending on the sport. Direct contact injuries, such as tackles or collisions, occur in combat and aggressive sports like American Football and rugby, involving a direct blow to the knee.[41,43,44]

Isolated ACL ruptures occur in only about 24-40% of cases, while concomitant injuries are present in the majority (60-79%).[45–47] Concomitant meniscal injuries are highly prevalent with ACL injuries, with reported incidences ranging from approximately 41% to 79%, depending on the chronicity of the injury and the patient population.[47,48] LMPR tears occur in about 6.6 – 16% of ACL ruptures[46,49–51], while medial meniscus ramp lesions are reported in approximately 20- 30% of ACL cases, and they often co-exist.[46,52] Cartilage injuries are common in conjunction with ACL ruptures, with studies showing that all patients with acute, isolated ACL ruptures sustain some degree of chondral damage at the time of injury, which progressively worsens over time, particularly in the lateral femoral condyle and patella.[53,54] Medial collateral ligament (MCL) complex injuries are the most common concomitant ligamentous injury occurring with ACL ruptures, with studies reporting an incidence of 41% to 67% in patients with ACL ruptures; these injuries frequently involve the superficial MCL, deep MCL, and posterior oblique ligament.[15,55,56] Other but less frequent concomitant ligamentous injuries that can occur are posterolateral corner and posterior cruciate ligament injuries.[57] ALC injuries frequently accompany ACL ruptures. The ALC is a complex region of the knee, the main components including the superficial and deep (Kaplan fiber) layers of the ITB, the capsulo-osseous layer and the anterolateral capsule including the ALL (Figure 3).[58,59] There is conflicting evidence on the incidence of associated injury to the ALL and Kaplan fibers. While some magnetic resonance imaging (MRI) studies reported a higher incidence of (partial) Kaplan fiber injury,[60,61] other MRI studies reported a higher incidence of (partial) ALL injury.[62–65] The reported incidences of injury are 21% to 60% for the Kaplan fibers and 21 to 71% for the ALL.[60– 65]

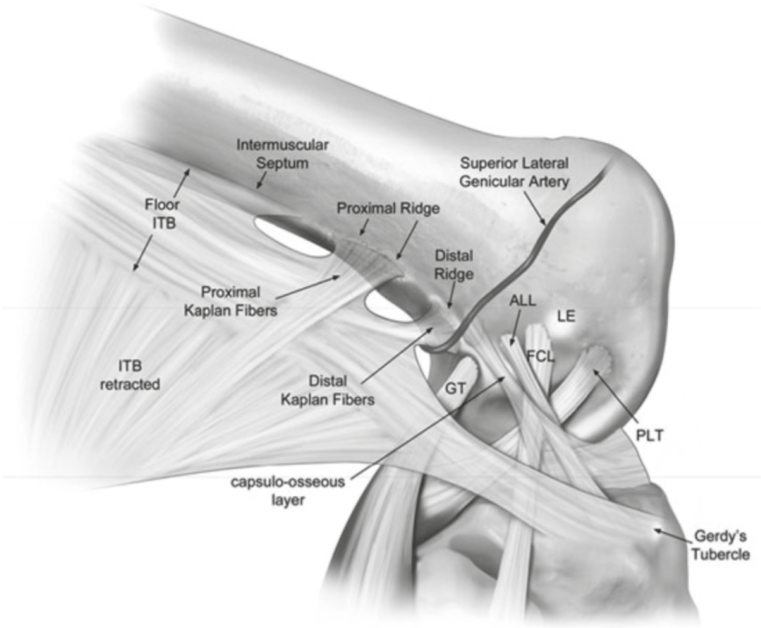

Figure 3. Illustration depicting structures of the ALC of the knee. ALL, anterolateral ligament; FCL, fibular collateral ligament; GT, lateral gastrocnemius tendon; iliotibial band; LE, lateral epicondyle; PLT, popliteus tendon.[58]

Anterior cruciate ligament concomitant injury biomechanics

The ACL acts as secondary stabilizer to tibial internal, varus- and valgus rotation, thereby contributing to the biomechanical function of multiple other structures in the knee.[15,36,37] Conversely, the menisci, posterolateral corner, MCL/posteromedial/anteromedial corner, and ALC function as secondary stabilizers on ACL graft force and ACL-related knee kinematics.[66,67] In addition, osseous morphology, sagittal plane alignment (posterior tibial slope (PTS)) and coronal plain alignment (varus and valgus), play a significant role in ACL biomechanics.[67]

Biomechanical cadaveric studies consistently show the medial meniscus, especially the posterior horn, as a major secondary restraint to anterior tibial translation and ACL graft loading.[68–74] Total lateral meniscectomy does not consistently change ACL graft forces under anterior tibial translation, but increases anterior tibial translation during a (simulated) pivot-shift in both the ACL-deficient and ACL-reconstructed knee, emphasizing its role in rotatory stability rather than as a static anterior restraint.[75,76] LMPR tears have been shown to cause a significant increase in tibial internal rotation and anterior tibial translation during the pivot-shift in ACL-deficient knees compared with ACL-deficient knees with an intact LMPR.[77–79] Sectioning the posterolateral corner structures (lateral collateral ligament, popliteus tendon, popliteofibular ligament, lateral capsule) in biomechanical cadaveric studies has shown to increase varus and external rotation, and to elevate forces in the native ACL and in ACL grafts.[80–82] Multiple studies reported a significant increase of ACL graft force after superficial medial collateral ligament sectioning with or without a deep MCL tear.[83–85] The ALC complex acts as a secondary stabilizer to the ACL and helps to resist both tibial internal rotation and internal rotation during the pivot shift. However, its individual components do not act uniformly, as each structure provides a distinct degree of restraint to this stabilizing function.[15,86–88] PTS modifying osteotomy biomechanical studies show a near-linear relationship between increasing PTS and higher ACL graft forces under axial load; decreasing slope correspondingly reduces graft force and anterior tibial translation.[89,90] Finally, cadaveric studies have shown a direct relationship between varus- and valgus alignment and ACL force.[91–93]

Anterior cruciate ligament treatment

Management of ACL ruptures has shifted from "one-size-fits-all" surgery, aiming for anatomic graft placement, appropriate graft choice, and criterion-based rehabilitation to restore knee kinematics and allow safe return to sport.[94] ACLR is the current standard for restoring biomechanical stability in the knee joint in symptomatic, active patients, particularly athletes in cutting and pivoting sports. In ACLR, the remnants of the native ACL are debrided when necessary but left *in situ* when reasonably possible, leaving a sheath of natural ligament tissue with a blood supply to surround the ACL graft, which may speed up revascularization of the graft[95] , and preserve mechanoreceptors. After the femoral and tibial tunnels have been drilled, the graft is passed into the knee joint and secured with the selected method of fixation. Autografts are generally favored over allografts, with most commonly used options including a hamstring tendon-, a bone-patellar-tendon-bone-, or a quadriceps tendon graft. Over the past decade, increasing evidence has demonstrated that injuries to the ALC accompanying ACL rupture contribute to anterolateral rotatory instability.[96,97] Clinical studies have reported that isolated ACLR in young, high-risk athletes without addressing the ruptured ALC may lead to residual rotational instability and higher ACL graft re-rupture rates and that the addition of an ALC reconstruction improves rotatory stability and reduces graft failure.[96–98]

Furthermore, it is crucial to systematically identify and treat concomitant pathologies in ACL-injured knees, because when undiagnosed or left untreated, these specific pathologies could lead to graft overload in ACL-reconstructed knees.[67]

Adding an ALC reconstruction and the treatment of concomitant pathologies impacts the levels of the perceived postoperative pain and warrants effective pain management protocols to ensure patient comfort and facilitate early mobilization. Rehabilitation is central to outcome and re-injury risk and has evolved from rigid timelines to criterion-based, individual protocols.[94,99,100]

Although ACLR has proven to be an effective treatment, young athletes undergoing ACLR face a substantial risk of graft rupture, with reported secondary injury rates up to 10% in patients younger than 25 years.[8–10] Furthermore, about a fifth of athletes do not return to sports, about a third do not return to their preinjury level, and about half do not return to competitive sport.[5–7]

Central aim of this thesis

The central aim of this thesis is to improve understanding of how concomitant injuries, secondary stabilizing structures, and osseous alignment influence ACL biomechanics and knee kinematics. This knowledge is translated into clinical practice to optimize surgical decision-making and perioperative management, and ultimately improve patient outcomes.

Specific aims of this thesis

1. Secondary Stabilizers of the ACL

ACLR restores stability in most patients; however, residual instability and graft failure remain relevant clinical problems. Knee stability is not solely determined by the ACL, but by the interaction between the ACL, secondary stabilizing structures, and lower-limb alignment in the coronal and sagittal planes. Failure to recognize these factors may result in persistent abnormal knee kinematics and overloading of the reconstructed ACL graft. Therefore, a structured evaluation of concomitant pathology and its biomechanical consequences is necessary to guide surgical indications and treatment strategies in ACL-injured patients.

The first part of this thesis focuses on the biomechanical influence of concomitant pathology and secondary restraints in ACL-related knee kinematics and graft loading.

Chapter 2 presents a systematic review of biomechanical cadaveric studies investigating the influence of concomitant intra- and extra-articular injuries and lower-limb alignment in the coronal and sagittal planes on ACL (graft) force and ACL-related knee kinematics. The purpose of this study was to provide a comprehensive overview of pathology associated with increased ACL graft force and abnormal knee kinematics and to obtain a comprehensive overview of pathologies that should be evaluated in primary and revision ACLR.

Questions addressed:

- *Which concomitant injuries and coronal and sagittal alignment conditions affect in situ forces or strain in the native or reconstructed ACL?*

- *How do these injuries and conditions influence anterior tibial translation and tibial rotation in ACL-intact, ACL-deficient, and ACL-reconstructed knees?*
- *Which concomitant injuries and coronal and sagittal alignment conditions are associated with abnormal knee kinematics during simulated clinical stability tests (e.g., Lachman or pivot-shift test)?*

Chapter 3 presents a systematic review of comparative biomechanical cadaveric studies investigating the influence of the ALC structures on ACL-related knee kinematics. The purpose of this study was to provide a comprehensive overview of the effect of the ITB and the ALL on anterolateral rotatory instability in ACL-injured knees, and the effect of lateral LET versus ALL-reconstruction in ACL-reconstructed knees.

Questions addressed:

- *How does sectioning of the ITB and/or ALL influence anterior tibial translation and tibial rotation?*
- *How do LET and ALL-reconstruction affect ACL-related knee kinematics?*
- *How do LET and ALL-reconstruction compare in their ability to restore knee kinematics in ACL-reconstructed knees?*

2. Combined Pathology and ACL Biomechanics

In the first part of this thesis, the influence of individual secondary stabilizing structures and concomitant pathology on ACL-related knee kinematics were evaluated. However, ACL injury is frequently accompanied by multiple concomitant injuries. LMPR tears and ALC injuries are commonly present in ACL-injured knees. Both injuries have been shown to influence tibial internal rotation and ACL-related knee kinematics during pivot-shift loading. When these injuries present simultaneously in the ACL-injured knee, their effects may be additive. Therefore, evaluation of these commonly combined injuries is necessary to better understand their influence on ACL-related knee kinematics.

Chapter 4 presents a biomechanical cadaveric study investigating the role of LMPR and Kaplan fiber injury in ACL-related knee kinematics, and the effect of their treatment in the ACL-reconstructed knee. The purpose of this study was to determine the individual and combined biomechanical effects of LMPR and Kaplan fiber tears in the ACL-deficient knee and to assess the impact of LMPR repair, modified Lemaire LET, or both, in the ACL-reconstructed knee.

Questions addressed:

- *Do the LMPR and the Kaplan fibers act as secondary stabilizers to tibial internal rotation and pivot-shift loading in the ACL-deficient knee?*
- *Does combined LMPR and Kaplan fiber injury have additive biomechanical effects regarding tibial internal rotation, and anterior tibial translation-, tibial internal rotation, and valgus rotation during a simulated pivot shift?*

- *Are both LMPR repair and modified Lemaire LET necessary to restore knee kinematics in the ACL-reconstructed knee compared to the intact state?*

3. Patient Outcomes after Isolated ACL Reconstruction versus ACL Reconstruction with Anterolateral Corner Reconstruction

After establishing the biomechanical role of the secondary stabilizers and the effect of combined pathology to ACL-related knee kinematics, the clinical relevance of adding an ALC reconstruction to ACLR requires further evaluation. Although ALC reconstructions have been associated with improved rotatory stability and reduced graft failure rates in high-risk patients, it remains unclear whether these differences are reflected in patient-perceived knee joint awareness.

Clinical outcomes after ACLR have traditionally been assessed using established patient-reported outcome measures (PROMs) such as the International Knee Documentation Committee (IKDC) and Lysholm scores. However, these instruments may demonstrate ceiling effects in young, high-functioning athletes and may not detect subtle differences in knee perception. The Forgotten Joint Score-12 (FJS-12) evaluates joint awareness during daily activities and, owing to its low ceiling effect, may be a suitable questionnaire to use in this population. Although validated for ACLR, data on FJS-12 after ACLR are limited, and comparative results between isolated ACLR and ACLR combined with ALC reconstruction are lacking.

Furthermore, interpretation of clinical outcomes after combined ACLR and ALC reconstruction requires a clear understanding of the underlying pathology. As highlighted in the systematic review in part 1, the ALC consists of multiple structures, including the ITB Kaplan fibers and the ALL. A comprehensive understanding of the ALC structures is essential when considering surgical treatment and when interpreting both biomechanical and clinical outcome data.

Chapter 5 presents a clinical comparative cohort study evaluating PROMs in a young, high-demand patient population after isolated ACLR with hamstring tendon autograft and ACLR with hamstring tendon autograft combined with ALC reconstruction.

The purpose of this study was to compare FJS-12 at 2-year follow-up in patients younger than 25 years, with a preoperative Tegner score ≥ 7 and intent to return to competitive sports, undergoing either isolated single-bundle hamstring autograft ACLR or hamstring autograft ACLR with modified Lemaire LET.

Questions addressed:

- *Do patients treated with ACLR combined with ALC reconstruction report higher FJS-12 and other PROMs compared with patients treated with isolated ACLR?*

- *Do patients treated with ACLR combined with ALC reconstruction have a lower ACL-graft re-rupture rate compared to patients treated with isolated ACLR?*

Chapter 6 presents an editorial commentary addressing the biomechanical relevance of the ALL as part of the different anatomical structures of the ALC and discusses its implications for surgical strategy in ACLR.

The purpose of this commentary was to interpret biomechanical findings on the ALL within the ALC complex as a whole and to clarify how these findings should guide indications for ALC reconstruction during ACLR.

Question addressed:
- *How should the findings of a systematic review on the biomechanical role of the ALL be interpreted when considering adding ALC reconstruction to ACLR?*

4. Anterolateral Corner Reconstruction and Revision Risk after Primary ACL Reconstruction in Patients with Increased Posterior Tibial Slope

Following the biomechanical study investigating combined injury patterns in part II, this part of the thesis investigates combined conditions in the clinical setting. Increased PTS and ALC injury influence ACL graft loading through distinct mechanisms. Increased PTS increases anterior tibial translation and ACL graft forces, whereas ALC injury primarily affects anterolateral rotatory instability. When both conditions are present, their combined effect may contribute to persistent instability and subsequent graft failure after ACLR.

Increased PTS has consistently been associated with higher revision rates after ACLR, particularly in young high-risk patients returning to pivoting sports. In addition, the clinical study presented in Part III demonstrated a substantially lower ACL graft re-rupture rate in patients who underwent ACLR with ALC reconstruction compared to patients who underwent isolated ACLR. However, it remains unclear whether ALC reconstruction mitigates the increased revision risk associated with elevated PTS in the primary ACLR setting. Further clinical data are needed to clarify the relationship between increased PTS, ALC reconstruction, and graft survival.

Chapter 7 presents a multicenter comparative cohort study in a young high-risk primary ACLR population, examining the clinical relevance of increased PTS and the potential role of concomitant ALC reconstruction in reducing revision rates after ACL reconstruction.

The purpose of this study was to determine the prevalence of increased PTS in a young high-risk primary ACLR population and to evaluate whether ALC reconstruction is associated with lower revision rates in patients with increased PTS.

Questions addressed:

- *What is the prevalence of increased PTS in a young, high-risk primary ACLR population?*
- *Within the subgroup with increased PTS, is ALC reconstruction independently associated with a lower risk of revision after primary ACLR compared to isolated ACLR?*

5. Perioperative Pain Management after Combined ACL Reconstruction and Anterolateral Corner Reconstruction

In this thesis, the indications and clinical outcomes of adding an ALC reconstruction to ACLR were evaluated. Although the addition of an ALC reconstruction may improve rotatory stability and reduce graft failure, the procedure requires an additional lateral incision at the distal femur. This may influence postoperative pain perception and early recovery. Effective postoperative pain control is particularly important since adequate analgesia facilitates early mobilization and rehabilitation.

Current multimodal analgesia protocols for ACLR typically include systemic analgesics and peripheral nerve blocks. However, an adductor canal block mainly anesthetizes the anteromedial aspect of the knee and lower leg and does not cover the distal lateral femoral region involved in ALC reconstruction. Consequently, patients undergoing combined ACLR and ALC reconstruction may experience persistent lateral knee pain. Optimizing perioperative pain management strategies for this specific patient population is therefore warranted.

Chapter 8 presents a multicenter, double-blind randomized controlled trial protocol comparing postoperative analgesia after combined ACLR and ALC reconstruction using an adductor canal block alone versus an adductor canal block combined with an anterolateral genicular nerve block.

The purpose of this study was to determine whether the addition of an anterolateral genicular nerve block to an adductor canal block improves postoperative pain control after ACLR combined with ALC reconstruction.

Questions addressed:

- *Does the addition of an anterolateral genicular nerve block to an adductor canal block reduce early postoperative pain after combined ACLR and ALC reconstruction?*
- *Does the addition of an anterolateral genicular nerve block reduce postoperative opioid consumption and use of non-opioid rescue analgesics after combined ACLR and ALC reconstruction?*

REFERENCES

1. Moses B, Orchard J, Orchard J. **Systematic Review: Annual Incidence of ACL Injury and Surgery in Various Populations**. *Res Sports Med*. 2012;20(3-4):157-179. doi:10.1080/15438627.2012.680633
2. Sanders TL, Kremers HM, Bryan AJ, et al. **Incidence of Anterior Cruciate Ligament Tears and Reconstruction: A 21-Year Population-Based Study**. *Am J Sports Med*. 2016;44(6):1502- 1507. doi:10.1177/0363546516629944
3. Getgood AMJ, Bryant DM, Litchfield R, et al. **Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2-Year Outcomes From the STABILITY Study Randomized Clinical Trial**. *Am J Sports Med*. 2019;48(2):285-297. doi:10.1177/0363546519896333
4. Lindanger L, Strand T, Mølster AO, Solheim E, Inderhaug E. **Effect of Early Residual Laxity After Anterior Cruciate Ligament Reconstruction on Long-term Laxity, Graft Failure, Return to Sports, and Subjective Outcome at 25 Years: Response**. *Am J Sports Med*. 2021;49(14):NP73-NP74. doi:10.1177/03635465211049370
5. Ardern CL, Taylor NF, Feller JA, Webster KE. **Fifty-five per cent return to competitive sport following anterior cruciate ligament reconstruction surgery: an updated systematic review and meta-analysis including aspects of physical functioning and contextual factors**. *Br J Sports Med*. 2014;48(21):1543. doi:10.1136/bjsports-2013-093398
6. Ardern CL, Webster KE, Taylor NF, Feller JA. **Return to sport following anterior cruciate ligament reconstruction surgery: a systematic review and meta-analysis of the state of play**. *Br J Sports Med*. 2011;45(7):596. doi:10.1136/bjsm.2010.076364
7. Gokeler A, Dingenen B, Hewett TE. **Rehabilitation and Return to Sport Testing After Anterior Cruciate Ligament Reconstruction: Where Are We in 2022**? *Arthrosc, Sports Med, Rehabilitation*. 2022;4(1):e77-e82. doi:10.1016/j.asmr.2021.10.025
8. Grassi A, Kim C, Muccioli GMM, Zaffagnini S, Amendola A. **What Is the Mid-term Failure Rate of Revision ACL Reconstruction? A Systematic Review**. *Clin Orthop Relat R*. 2017;475(10):2484-2499. doi:10.1007/s11999-017-5379-5
9. Magnussen RA, Meschbach NT, Kaeding CC, Wright RW, Spindler KP. **ACL Graft and Contralateral ACL Tear Risk within Ten Years Following Reconstruction**. *JBJS Rev*. 2015;3(1):NA; doi:10.2106/jbjs.rvw.n.00052
10. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
11. Group TMK, Spindler KP, Huston LJ, et al. **Ten-Year Outcomes and Risk Factors After Anterior Cruciate Ligament Reconstruction: A MOON Longitudinal Prospective Cohort Study**. *Am J Sports Med*. 2018;46(4):815-825. doi:10.1177/0363546517749850
12. Senorski EH, Svantesson E, Baldari A, et al. **Factors that affect patient reported outcome after anterior cruciate ligament reconstruction–a systematic review of the Scandinavian knee ligament registers**. *Br J Sports Med*. 2019;53(7):410. doi:10.1136/bjsports-2017-098191
13. Kato J, Fukushima H, Kensaku A, et al. **Multiple secondary stabiliser injuries increase rotational instability in anterior cruciate ligament-deficient knees**. *Knee Surg, Sports Traumatol, Arthrosc*. 2025;33(9):3169-3178. doi:10.1002/ksa.12565
14. Tischer T, Paul J, Pape D, et al. **The Impact of Osseous Malalignment and Realignment Procedures in Knee Ligament Surgery: A Systematic Review of the Clinical Evidence**. *Orthop J Sports Med*. 2017;5(3):2325967117697287. doi:10.1177/2325967117697287

15. Willinger L, Athwal KK, Holthof S, Imhoff AB, Williams A, Amis AA. **Role of the Anterior Cruciate Ligament, Anterolateral Complex, and Lateral Meniscus Posterior Root in Anterolateral Rotatory Knee Instability: A Biomechanical Study**. *Am J Sports Med*. 2023;51(5):1136-1145. doi:10.1177/03635465231161071
16. Flandry F, Hommel G. **Normal Anatomy and Biomechanics of the Knee**. *Sports Med Arthrosc Rev*. 2011;19(2):82-92. doi:10.1097/jsa.0b013e318210c0aa
17. J PK, M AK, D V. **Healthy Gait: Review of Anatomy and Physiology of Knee Joint**. *Int J Curr Res Rev*. 2020;12(06):01-08. doi:10.31782/ijcrr.2020.12061
18. Yan M, Liang T, Zhao H, et al. **Model Properties and Clinical Application in the Finite Element Analysis of Knee Joint: A Review**. *Orthop Surg*. 2024;16(2):289-302. doi:10.1111/os.13980
19. Zhang L, Liu G, Han B, et al. **Knee Joint Biomechanics in Physiological Conditions and How Pathologies Can Affect It: A Systematic Review**. *Appl Bionics Biomech*. 2020;2020(1):7451683. doi:10.1155/2020/7451683
20. Carlson D. **Human Knee Joint – Anterior View 1a (Internet)**. *Carlson Stock Art*. Available from https://www.carlsonstockart.com/photo/human-anatomy-skeletal-system-knee-joint- front-view-right-1a
21. Duthon VB, Barea C, Abrassart S, Fasel JH, Fritschy D, Ménétrey J. **Anatomy of the anterior cruciate ligament**. *Knee Surg, Sports Traumatol, Arthrosc*. 2006;14(3):204-213. doi:10.1007/s00167-005-0679-9
22. Siegel L, Vandenakker-Albanese C, Siegel D. **Anterior cruciate ligament injuries: anatomy, physiology, biomechanics, and management**. *Clin J Sport Med : Off J Can Acad Sport Med*. 2012;22(4):349-355. doi:10.1097/jsm.0b013e3182580cd0
23. Petersen W, Zantop T. **Anatomy of the Anterior Cruciate Ligament with Regard to Its Two Bundles**. *Clin Orthop Relat Res*. 2007;454(NA;):35-47. doi:10.1097/blo.0b013e31802b4a59
24. Zantop T, Petersen W, Sekiya JK, Musahl V, Fu FH. **Anterior cruciate ligament anatomy and function relating to anatomical reconstruction**. *Knee Surg, Sports Traumatol, Arthrosc*. 2006;14(10):982-992. doi:10.1007/s00167-006-0076-z
25. Marieswaran M, Jain I, Garg B, Sharma V, Kalyanasundaram D. **A Review on Biomechanics of Anterior Cruciate Ligament and Materials for Reconstruction**. *Appl Bionics Biomech*. 2018;2018(1):4657824. doi:10.1155/2018/4657824
26. Amis AA, Dawkins GP. **Functional anatomy of the anterior cruciate ligament. Fibre bundle actions related to ligament replacements and injuries**. *J bone Jt Surg Br Vol*. 1991;73(2):260- 267. doi:10.1302/0301-620x.73b2.2005151
27. Chhabra A, Starman JS, Ferretti M, Vidal AF, Zantop T, Fu FH. **Anatomic, Radiographic, Biomechanical, and Kinematic Evaluation of the Anterior Cruciate Ligament and Its Two Functional Bundles**. *J Bone Jt Surg*. 2006;88(suppl_4):2-10. doi:10.2106/jbjs.f.00616
28. Zantop T, Wellmann M, Fu FH, Petersen W. **Tunnel Positioning of Anteromedial and Posterolateral Bundles in Anatomic Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2008;36(1):65-72. doi:10.1177/0363546507308361
29. Śmigielski R, Zdanowicz U, Drwięga M, Ciszek B, Ciszkowska-Łysoń B, Siebold R. **Ribbon like appearance of the midsubstance fibres of the anterior cruciate ligament close to its femoral insertion site: a cadaveric study including 111 knees**. *Knee Surg, Sports Traumatol, Arthrosc*. 2015;23(11):3143-3150. doi:10.1007/s00167-014-3146-7
30. Siebold R, Ellert T, Metz S, Metz J. **Tibial Insertions of the Anteromedial and Posterolateral Bundles of the Anterior Cruciate Ligament: Morphometry, Arthroscopic Landmarks, and Orientation Model for Bone Tunnel Placement**. *Arthrosc: J Arthrosc Relat Surg*. 2008;24(2):154-161. doi:10.1016/j.arthro.2007.08.006

31. Siebold R, Ellert T, Metz S, Metz J. **Femoral Insertions of the Anteromedial and Posterolateral Bundles of the Anterior Cruciate Ligament: Morphometry and Arthroscopic Orientation Models for Double-Bundle Bone Tunnel Placement—A Cadaver Study**. *Arthrosc: J Arthrosc Relat Surg*. 2008;24(5):585-592. doi:10.1016/j.arthro.2007.12.008
32. Bicer EK, Lustig S, Servien E, Selmi TAS, Neyret P. **Current knowledge in the anatomy of the human anterior cruciate ligament**. *Knee Surg, Sports Traumatol, Arthrosc*. 2010;18(8):1075-1084. doi:10.1007/s00167-009-0993-8
33. ARNOCZKY SP. **Anatomy of the Anterior Cruciate Ligament**. *Clin Orthop Relat Res*. 1983;172(NA;):19-25. doi:10.1097/00003086-198301000-00006
34. Dienst M, Burks RT, Greis PE. **Anatomy and biomechanics of the anterior cruciate ligament**. *Orthop Clin North Am*. 2002;33(4):605-620. doi:10.1016/s0030-5898(02)00010-x
35. Takeda Y, Xerogeanes JW, Livesay GA, Fu FH, Woo SLY. **Biomechanical function of the human anterior cruciate ligament**. *Arthrosc: J Arthrosc Relat Surg*. 1994;10(2):140-147. doi:10.1016/s0749-8063(05)80081-7
36. Parsons EM, Gee AO, Spiekerman C, Cavanagh PR. **The Biomechanical Function of the Anterolateral Ligament of the Knee**. *Am J Sports Med*. 2015;43(3):669-674. doi:10.1177/0363546514562751
37. Li G, Papannagari R, Defrate LE, Yoo JD, Park SE, Gill TJ. **The effects of ACL deficiency on mediolateral translation and varus–valgus rotation**. *Acta Orthop*. 2009;78(3):355-360. doi:10.1080/17453670710013924
38. Inoue M, McGurk-Burleson E, Hollis JM, Woo SLY. **Treatment of the medial collateral ligament injury**. *Am J Sports Med*. 1987;15(1):15-21. doi:10.1177/036354658701500103
39. Mancino F, Kayani B, Gabr A, Fontalis A, Plastow R, Haddad FS. **Anterior cruciate ligament injuries in female athletes: risk factors and strategies for prevention**. *Bone Jt Open*. 2024;5(2):94-100. doi:10.1302/2633-1462.52.bjo-2023-0166
40. Hewett TE, Myer GD, Ford KR, et al. **Biomechanical Measures of Neuromuscular Control and Valgus Loading of the Knee Predict Anterior Cruciate Ligament Injury Risk in Female Athletes: A Prospective Study**. *Am J Sports Med*. 2005;33(4):492-501. doi:10.1177/0363546504269591
41. Sundberg A, Högberg J, Tosarelli F, et al. **Sport-Specific Injury Mechanisms and Situational Patterns of ACL Injuries: A Comprehensive Systematic Review**. *Sports Med (Auckl, Nz)*. 2025;55(10):2489-2527. doi:10.1007/s40279-025-02271-w
42. Gopinatth V, Smith MV, Matava MJ, Brophy RH, Knapik DM. **Most Anterior Cruciate Ligament Injuries in Professional Athletes Occur Without Contact to the Injured Knee: A Systematic Review of Video Analysis Studies**. *Arthroscopy*. 2025;41(4):1155-1162.e1. doi:10.1016/j.arthro.2024.03.047
43. Villa FD, Tosarelli F, Ferrari R, et al. **Systematic Video Analysis of Anterior Cruciate Ligament Injuries in Professional Male Rugby Players: Pattern, Injury Mechanism, and Biomechanics in 57 Consecutive Cases**. *Orthop J Sports Med*. 2021;9(11):23259671211048182. doi:10.1177/23259671211048182
44. Johnston JT, Mandelbaum BR, Schub D, et al. **Video Analysis of Anterior Cruciate Ligament Tears in Professional American Football Athletes**. *Am J Sports Med*. 2018;46(4):862-868. doi:10.1177/0363546518756328
45. Gracia G, Cavaignac M, Marot V, Mouarbes D, Laumonerie P, Cavaignac E. **Epidemiology of Combined Injuries of the Secondary Stabilizers in ACL-Deficient Knees: Medial Meniscal Ramp Lesion, Lateral Meniscus Root Tear, and ALL Tear: A Prospective Case Series of 602 Patients With ACL Tears From the SANTI Study Group**. *Am J Sports Med*. 2022;50(7):1843- 1849. doi:10.1177/03635465221092767

46. Magosch A, Mouton C, Nührenbörger C, Seil R. **Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions**. *Knee Surg, Sports Traumatol, Arthrosc*. 2021;29(9):3059-3067. doi:10.1007/s00167-020-06352-3
47. Hagino T, Ochiai S, Senga S, et al. **Meniscal tears associated with anterior cruciate ligament injury**. *Arch Orthop Trauma Surg*. 2015;135(12):1701-1706. doi:10.1007/s00402-015-2309-4
48. Hardy A, Berard E, Freychet B, et al. **Epidemiology and Characteristics of Meniscal Tears in Patients With Combined ACL and Medial Collateral Ligament Injuries Versus Isolated ACL Tears: A Case-Control Study From the Francophone Arthroscopic Society**. *Am J Sports Med*. 2024;53(1):154-162. doi:10.1177/03635465241296879
49. Ciatti R, Gabrielli A, Iannella G, Mariani PP. **Arthroscopic incidence of lateral meniscal root avulsion in patients with anterior cruciate ligament injury**. *J Orthop Traumatol*. 2021;22(1):30. doi:10.1186/s10195-021-00591-x
50. Praz C, Vieira TD, Saithna A, et al. **Risk Factors for Lateral Meniscus Posterior Root Tears in the Anterior Cruciate Ligament–Injured Knee: An Epidemiological Analysis of 3956 Patients From the SANTI Study Group**. *Am J Sports Med*. 2019;47(3):598-605. doi:10.1177/0363546518818820
51. Lambrey PJ, Fayard JM, Graveleau N, et al. **Male sex, revision surgery, low volume of anterior cruciate ligament remnant, and significant instability are risk factors for Posterior Root Tear of the Lateral Meniscus in patients undergoing Anterior Cruciate Ligament Reconstruction**. *Arthrosc: J Arthrosc Relat Surg*. 2024;41(4):1030-1038. doi:10.1016/j.arthro.2024.05.028
52. Bernholt D, DePhillipo NN, Aman ZS, Samuelsen BT, Kennedy MI, LaPrade RF. **Increased posterior tibial slope results in increased incidence of posterior lateral meniscal root tears in ACL reconstruction patients**. *Knee Surg, Sports Traumatol, Arthrosc*. 2021;29(11):3883-3891. doi:10.1007/s00167-021-06456-4
53. Potter HG, Jain SK, Ma Y, Black BR, Fung S, Lyman S. **Cartilage Injury After Acute, Isolated Anterior Cruciate Ligament Tear**. *Am J Sports Med*. 2012;40(2):276-285. doi:10.1177/0363546511423380
54. Davidson EJ, Figgie C, Nguyen J, et al. **Chondral Injury Associated With ACL Injury: Assessing Progressive Chondral Degeneration With Morphologic and Quantitative MRI Techniques**. *Sports Heal*. 2024;16(5):722-734. doi:10.1177/19417381231205276
55. Cristiani R, Bunt F van de, Kvist J, Stålman A. **High Prevalence of Superficial and Deep Medial Collateral Ligament Injuries on Magnetic Resonance Imaging in Patients With Anterior Cruciate Ligament Tears**. *Arthroscopy*. 2024;40(1):103-110. doi:10.1016/j.arthro.2023.05.029
56. Rehlingen-Prinz FV, Leiderer M, Dehoust J, et al. **Association of medial collateral ligament complex injuries with anterior cruciate ligament ruptures based on posterolateral tibial plateau injuries**. *Sports Med - Open*. 2023;9(1):70. doi:10.1186/s40798-023-00611-6
57. Temponi EF, Júnior LH de C, Saithna A, Thaunat M, Sonnery-Cottet B. **Incidence and MRI characterization of the spectrum of posterolateral corner injuries occurring in association with ACL rupture**. *Skelet Radiol*. 2017;46(8):1063-1070. doi:10.1007/s00256-017-2649-y
58. Godin JA, Chahla J, Moatshe G, et al. **A Comprehensive Reanalysis of the Distal Iliotibial Band: Quantitative Anatomy, Radiographic Markers, and Biomechanical Properties**. *Am J Sports Med*. 2017;45(11):2595-2603. doi:10.1177/0363546517707961
59. Meena A, Attri M, Farinelli L, et al. **Anterolateral corner of knee: Current concepts**. *J Exp Orthop*. 2025;12(1):e70172. doi:10.1002/jeo2.70172

60. Balendra G, Willinger L, Pai V, et al. **Anterolateral complex injuries occur in the majority of 'isolated' anterior cruciate ligament ruptures**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(1):176-183. doi:10.1007/s00167-021-06543-6
61. Firoozabadi MA, Mortazavi SMJ, Shakiba M, et al. **Investigating Injuries to the Anterolateral Corner of the Knee: Imaging Insights Into Kaplan Fibers and the Anterolateral Ligament in Anterior Cruciate Ligament Tears**. *Orthop J Sports Med*. 2025;13(3):23259671251319504. doi:10.1177/23259671251319504
62. Leao RV, Helito PVP, Saithna A, Correa MF de P, Helito CP. **Anterolateral Ligament and Kaplan Fiber Injury Both Occur Frequently in Acute Anterior Cruciate Ligament-Injured Knees**. *J Clin Med*. 2024;13(4):946. doi:10.3390/jcm13040946
63. Dyck PV, Smet ED, Roelant E, Parizel PM, Heusdens CHW. **Assessment of Anterolateral Complex Injuries by Magnetic Resonance Imaging in Patients With Acute Rupture of the Anterior Cruciate Ligament**. *Arthrosc: J Arthrosc Relat Surg*. 2019;35(2):521-527. doi:10.1016/j.arthro.2018.08.032
64. Watanabe S, Nagai K, Hoshino Y, et al. **Influence of Injury to the Kaplan Fibers of the Iliotibial Band on Anterolateral Rotatory Knee Laxity in Anterior Cruciate Ligament Injury: A Retrospective Cohort Study**. *Am J Sports Med*. 2022;50(12):3265-3272. doi:10.1177/03635465221116097
65. Runer A, Dammerer D, Kranewitter C, et al. **Injuries to the anterolateral ligament are observed more frequently compared to lesions to the deep iliotibial tract (Kaplan fibers) in anterior cruciate ligament deficient knees using magnetic resonance imaging**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(1):309-318. doi:10.1007/s00167-021-06535-6
66. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction Can Restore Native Knee Kinematics in the Anterior Cruciate Ligament Reconstructed Knee: A Systematic Review of Biomechanical Cadaveric Studies**. *Arthrosc: J Arthrosc Relat Surg*. 2024;40(2):632-647.e1. doi:10.1016/j.arthro.2023.05.005
67. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **Meniscal Tears, Posterolateral and Posteromedial Corner Injuries, Increased Coronal Plane, and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament–Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**. *Arthrosc: J Arthrosc Relat Surg*. 2022;38(5):1664-1688.e1. doi:10.1016/j.arthro.2021.11.044
68. Naendrup JH, Pfeiffer TR, Chan C, et al. **Effect of Meniscal Ramp Lesion Repair on Knee Kinematics, Bony Contact Forces, and In Situ Forces in the Anterior Cruciate Ligament**. *Am J Sports Med*. 2019;47(13):3195-3202. doi:10.1177/0363546519872964
69. DePhillipo NN, Moatshe G, Brady A, et al. **Effect of Meniscocapsular and Meniscotibial Lesions in ACL-Deficient and ACL-Reconstructed Knees: A Biomechanical Study**. *Am J Sports Med*. 2018;46(10):2422-2431. doi:10.1177/0363546518774315
70. Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, Woo SL. **Importance of the medial meniscus in the anterior cruciate ligament-deficient knee**. *J Orthop Res*. 2000;18(1):109-115. doi:10.1002/jor.1100180116
71. Ahn JH, Bae TS, Kang KS, Kang SY, Lee SH. **Longitudinal Tear of the Medial Meniscus Posterior Horn in the Anterior Cruciate Ligament–Deficient Knee Significantly Influences Anterior Stability**. *Am J Sports Med*. 2011;39(10):2187-2193. doi:10.1177/0363546511416597

72. Stephen JM, Halewood C, Kittl C, Bollen SR, Williams A, Amis AA. **Posteromedial Meniscocapsular Lesions Increase Tibiofemoral Joint Laxity With Anterior Cruciate Ligament Deficiency, and Their Repair Reduces Laxity**. *Am J Sports Med*. 2016;44(2):400-408. doi:10.1177/0363546515617454
73. Seon JK, Gadikota HR, Kozanek M, Oh LS, Gill TJ, Li G. **The Effect of Anterior Cruciate Ligament Reconstruction on Kinematics of the Knee With Combined Anterior Cruciate Ligament Injury and Subtotal Medial Meniscectomy: An In Vitro Robotic Investigation**. *Arthrosc: J Arthrosc Relat Surg*. 2009;25(2):123-130. doi:10.1016/j.arthro.2008.09.020
74. Lorbach O, Kieb M, Herbort M, Weyers I, Raschke M, Engelhardt M. **The influence of the medial meniscus in different conditions on anterior tibial translation in the anterior cruciate deficient knee**. *Int Orthop*. 2015;39(4):681-687. doi:10.1007/s00264-014-2581-x
75. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD. **The Effect of Medial Versus Lateral Meniscectomy on the Stability of the Anterior Cruciate Ligament-Deficient Knee**. *Am J Sports Med*. 2010;38(8):1591-1597. doi:10.1177/0363546510364402
76. Tang X, Marshall B, Wang JH, et al. **Partial meniscectomy does not affect the biomechanics of anterior cruciate ligament reconstructed knee with a lateral posterior meniscal root tear**. *Knee Surg Sports Traumatology Arthrosc*. 2020;28(11):3481-3487. doi:10.1007/s00167-020-06209-9
77. Frank JM, Moatshe G, Brady AW, et al. **Lateral Meniscus Posterior Root and Meniscofemoral Ligaments as Stabilizing Structures in the ACL-Deficient Knee: A Biomechanical Study**. *Orthop J Sports Medicine*. 2017;5(6):2325967117695756. doi:10.1177/2325967117695756
78. Forkel P, Deimling C von, Lacheta L, et al. **Repair of the lateral posterior meniscal root improves stability in an ACL-deficient knee**. *Knee Surg Sports Traumatology Arthrosc*. 2018;26(8):2302-2309. doi:10.1007/s00167-018-4949-8
79. Shybut TB, Vega CE, Haddad J, et al. **Effect of Lateral Meniscal Root Tear on the Stability of the Anterior Cruciate Ligament–Deficient Knee**. *Am J Sports Medicine*. 2015;43(4):905-911. doi:10.1177/0363546514563910
80. Bonanzinga T, Signorelli C, Lopomo N, et al. **Biomechanical effect of posterolateral corner sectioning after ACL injury and reconstruction**. *Knee Surg, Sports Traumatol, Arthrosc*. 2015;23(10):2918-2924. doi:10.1007/s00167-015-3696-3
81. LaPrade RF, Resig S, Wentorf F, Lewis JL. **The Effects of Grade III Posterolateral Knee Complex Injuries on Anterior Cruciate Ligament Graft Force**. *Am J Sports Med*. 1999;27(4):469- 475. doi:10.1177/03635465990270041101
82. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, Slauterbeck JL. **C ombined knee loading states that generate high anterior cruciate ligament forces**. *J Orthop Res : Off Publ Orthop Res Soc*. 1995;13(6):930-935. doi:10.1002/jor.1100130618
83. Battaglia MJ, Lenhoff MW, Ehteshami JR, et al. **Medial Collateral Ligament Injuries and Subsequent Load on the Anterior Cruciate Ligament**. *Am J Sports Med*. 2009;37(2):305-311. doi:10.1177/0363546508324969
84. Mazzocca AD, Nissen CW, Geary M, Adams DJ. **Valgus medial collateral ligament rupture causes concomitant loading and damage of the anterior cruciate ligament**. *J Knee Surg*. 2003;16(3):148-151.
85. Shapiro MS, Markolf KL, Finerman GA, Mitchell PW. **The effect of section of the medial collateral ligament on force generated in the anterior cruciate ligament**. *J Bone Jt Surg Am Volume*. 1991;73(2):248-256.
86. Kittl C, El-Daou H, Athwal KK, et al. **The Role of the Anterolateral Structures and the ACL in Controlling Laxity of the Intact and ACL-Deficient Knee**. *Am J Sports Med*. 2016;44(2):345- 354. doi:10.1177/0363546515614312

87. Getgood A, Brown C, Lording T, et al. **The anterolateral complex of the knee: results from the International ALC Consensus Group Meeting**. *Knee Surg, Sports Traumatol, Arthrosc*. 2019;27(1):166-176. doi:10.1007/s00167-018-5072-6
88. Thein R, Boorman-Padgett J, Stone K, Wickiewicz TL, Imhauser CW, Pearle AD. **Biomechanical Assessment of the Anterolateral Ligament of the Knee: A Secondary Restraint in Simulated Tests of the Pivot Shift and of Anterior Stability**. *J bone Jt Surg Am Vol*. 2016;98(11):937-943. doi:10.2106/jbjs.15.00344
89. Bernhardson AS, Aman ZS, Dornan GJ, et al. **Tibial Slope and Its Effect on Force in Anterior Cruciate Ligament Grafts: Anterior Cruciate Ligament Force Increases Linearly as Posterior Tibial Slope Increases**. *Am J Sports Med*. 2019;47(2):296-302. doi:10.1177/0363546518820302
90. Imhoff FB, Mehl J, Comer BJ, et al. **Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load**. *Knee Surg, Sports Traumatol, Arthrosc*. 2019;27(10):3381-3389. doi:10.1007/s00167-019-05360-2
91. Imhoff FB, Comer B, Obopilwe E, Beitzel K, Arciero RA, Mehl JT. **Effect of Slope and Varus Correction High Tibial Osteotomy in the ACL-Deficient and ACL-Reconstructed Knee on Kinematics and ACL Graft Force: A Biomechanical Analysis**. *Am J Sports Medicine*. 2020;49(2):410-416. doi:10.1177/0363546520976147
92. Mehl J, Otto A, Kia C, et al. **Osseous valgus alignment and posteromedial ligament complex deficiency lead to increased ACL graft forces**. *Knee Surg, Sports Traumatol, Arthrosc*. 2020;28(4):1119-1129. doi:10.1007/s00167-019-05770-2
93. Pol GJ van de, Arnold MP, Verdonschot N, Kampen A van. **Varus Alignment Leads to Increased Forces in the Anterior Cruciate Ligament**. *Am J Sports Med*. 2009;37(3):481-487. doi:10.1177/0363546508326715
94. Piedade SR, Arruda BPL, Vasconcelos RA de, Parker DA, Maffulli N. **Rehabilitation following surgical reconstruction for anterior cruciate ligament insufficiency: What has changed since the 1960s?—State of the art**. *J ISAKOS*. 2023;8(3):153-162. doi:10.1016/j.jisako.2022.10.001
95. McDermott ID. **Anterior cruciate ligament reconstruction: current concepts and latest thinking**. *Orthop Trauma*. 2023;37(3):195-206. doi:10.1016/j.mporth.2023.03.008
96. Nukuto K, Hoshino Y, Kataoka K, Kuroda R. **Current development in surgical techniques, graft selection and additional procedures for anterior cruciate ligament injury: a path towards anatomic restoration and improved clinical outcomes—a narrative review**. *Ann Jt*. 2023;8(0):39- 39. doi:10.21037/aoj-23-39
97. Na BR, Kwak WK, Seo HY, Seon JK. **Clinical Outcomes of Anterolateral Ligament Reconstruction or Lateral Extra-articular Tenodesis Combined With Primary ACL Reconstruction: A Systematic Review With Meta-analysis**. *Orthop J Sports Med*. 2021;9(9):23259671211023099. doi:10.1177/23259671211023099
98. D'Ambrosi R, Corona K, Cerciello S, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces Graft Reinjury Without Increasing the Rate of Complications: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J Sports Med*. 2024;53(10):2462-2470. doi:10.1177/03635465241285887
99. Brinlee AW, Dickenson SB, Hunter-Giordano A, Snyder-Mackler L. **ACL Reconstruction Rehabilitation: Clinical Data, Biologic Healing, and Criterion-Based Milestones to Inform a Return-to-Sport Guideline**. *Sports Heal: A Multidiscip Approach*. 2022;14(5):770-779. doi:10.1177/19417381211056873
100. Jenkins SM, Guzman A, Gardner BB, et al. **Rehabilitation After Anterior Cruciate Ligament Injury: Review of Current Literature and Recommendations**. *Curr Rev Musculoskelet Med*. 2022;15(3):170-179. doi:10.1007/s12178-022-09752-9

chapter 2

Meniscal Tears, Posterolateral and Posteromedial Corner injuries, Increased Coronal Plane and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament-Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies

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ABSTRACT

Purpose

To obtain a comprehensive list of pathologies that cause increased ACL forces and pathologic knee kinematics to evaluate for in both primary and revision ACL reconstruction to decrease the risk of subsequent graft overload.

Methods

An electronic search was performed in the Embase and MEDLINE databases for the period between January 1, 1990, and December 10, 2020. All articles investigating medial and lateral meniscal injury, (postero)lateral corner injury, (postero)medial corner/medial collateral ligament injury, valgus alignment, varus alignment and tibial slope in relation to ACL (graft) force and knee kinematics were included.

Results

Data of 43 studies were included. The studies reported that high-volume medial and lateral meniscectomies, peripheral meniscus tears, medial meniscus ramp tears, lateral meniscus root tears, posterolateral corner injuries, medial collateral ligament tears, increased tibial slope and valgus and varus alignment were reported to have a significant impact on ACL (graft) force and related knee kinematics.

Conclusion

This systematic review on biomechanical cadaver studies provides a rationale to systematically identify and treat pathologies in ACL-injured knees, because when undiagnosed or left untreated, these specific concomitant pathologies could lead to ACL graft overload in both primary and revision ACL-reconstructed knees.

Clinical Relevance

It is necessary that orthopaedic surgeons who treat ACL-injured knees understand the surgically relevant biomechanical consequences of additional pathologies, and use this knowledge to optimize treatment in ACL-injured patients.

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) is one of the most commonly performed orthopedic surgical procedures. The incidence of anterior cruciate ligament (ACL) injury, and subsequent ACLR, especially among adolescent female athletes is high.[1–3] Although ACLR has proven to be an effective treatment for ACL tears, there is still a significant re-rupture risk, especially in the younger and active population;[4–6] in a recent systematic review it was reported that athletes younger than 25 years who return to sport have a secondary (ipsilateral + contralateral) ACL injury rate of 23%.[6] Risk factors other than age and sex that have been described to influence ACL failure risk are surgical technique/technical errors, unrecognized or untreated concomitant pathology, new trauma, graft selection, greater activity level and physiologic preoperative knee hyperextension.[7–10]

Since revision ACL surgery is associated with significantly worse outcomes in comparison to primary reconstruction, a better understanding of which secondary restraints have an effect on anterior tibial translation and rotational motion and thus may increase the risk of ACL re-rupture is essential.[5] The ACL is the primary restraint to anterior tibial translation (ATT) and contributes to restraint of internal tibial rotation and varus/valgus rotation. An ACL tear is often associated with concomitant intra- and extra-articular injuries.[11] In this regard, the menisci have been recognized as a secondary knee restraint to anteroposterior translation and rotational movement.[12,13] The biomechanical functions of the medial collateral ligament (MCL) and posterolateral corner (PLC) also have been studied to determine their roles in anterior translation and rotational movements, in addition to their role in restraining varus and valgus rotation.[14,15] Furthermore, previous studies have described the influence of valgus alignment[16], varus alignment[17,18], and tibial slope[19–23] on the forces applied to the ACL. Thus, multiple secondary restraints have been identified which can affect the in-situ forces of the native and reconstructed ACL.

Several laboratory studies on cadavers have examined the biomechanical influences of secondary restraint on ACL graft force and pathologic knee kinematics. However, a comprehensive review of these studies is currently lacking. Therefore, this study was conducted to collate the biomechanical cadaveric studies on the causes of increased ACL graft force and pathologic knee kinematics. Our purpose was to obtain a comprehensive list of pathologies that cause increased ACL forces and pathologic knee kinematics to evaluate for in both primary and revision ACL reconstruction to decrease the risk of subsequent ACL graft overload. The hypothesis was that meniscal tears, posterolateral and posteromedial corner injuries, increased coronal plane and increased sagittal plane tibial slope all would increase forces on the native and reconstructed ACL.

METHODS

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta Analyses) guidelines were followed, and a PRISMA flow diagram was used. A systematic review of the current peer reviewed literature was performed using the electronic databases EMBASE and MEDLINE/PubMed (January 1, 1990 – December 10, 2020), with the assistance of an informationist. Search strings were used to screen for biomechanical cadaver studies which measured ACL (graft) force and ACL-related knee kinematics (Appendix).

All resulting titles and abstracts were screened for potential eligibility by two authors (D.T.M., W.A.W.) and confirmed by the senior author (R.F.L.). Thereafter, two authors (D.T.M., W.A.W.) independently retrieved and analyzed the potentially eligible full-text articles. The references of included articles were also screened to identify additional eligible articles.

Inclusion criteria were: 1) peer-reviewed biomechanical studies using human cadaveric knee specimens; 2) analysis of medial meniscal injury, lateral meniscal injury, lateral/posterolateral corner injury, medial/posteromedial corner injury, valgus alignment, varus alignment and tibial slope in relation to ACL (graft) force and knee kinematics; and 3) recording of ACL (graft) force/strain measurements and/or ATT and/or combined valgus and internal rotation force and/or mechanized Lachman and/or mechanized pivot-shift test. If a study was not entirely devoted to the aforementioned inclusion criteria, the pertinent portion of the study was used. Kinematic studies on native ACL, ACL-deficient and ACL-reconstructed knees were included, since we believe these studies are all interrelated in that they can demonstrate, directly or indirectly, the risk of ACL graft overload or failure in the case of untreated or undiagnosed injury or malalignment.

We excluded articles that analyzed the biomechanical influence of anterolateral corner injury on ACL force and knee kinematics because this topic is covered in a separate systematic review. Articles in languages other than English were excluded. Articles were assessed for methodologic quality according to the Quality Appraisal for Cadaveric Studies (QUACS) scale, a validated 13-item checklist that assesses cadaveric studies for inclusion in systematic reviews.[24]

Data collection

Two authors (D.T.M., W.A.W.) independently extracted, summarized and tabulated the following parameters from eligible studies: number of specimens per experiment; knee specimen status and characteristics; kinematic measurements data (the various knee states that measurements were performed upon and the type of kinematic or force measurements performed); and ACLR surgery characteristics or other surgical procedures that were performed.

The results of the included studies are presented in tables per topic. In case only 1 or 2 studies per topic were included, or when only few results could be extracted per topic, the results of these topics were presented descriptively. Results that are presented graphically in the included studies were described as statistically significant or not statistically significant in the tables.

RESULTS

Search results

The initial search yielded 1090 records, of which 309 were duplicates that were removed. The titles and abstracts of the remaining 781 articles were screened, and 739 articles were further excluded. After full-text analysis of the remaining 42 records, 4 articles were excluded. Cross-checking the references of the remaining 38 records added 5 eligible articles, bringing the total of included records to 43 (Figure 1). The data set of these 43 studies represented the mean values of biomechanical data collected from 432 cadaveric specimens, with sample sizes of each experimental group ranging from 4 to 24 specimens. In 23 studies ACL (graft) force or strain was investigated, by the principle of superposition (11 studies); attachment of a load cell to the ACL graft (6 studies); or placement of a transducer in the anteromedial bundle of the ACL (6 studies). In 38 studies ACL-related kinematic measurements were investigated.

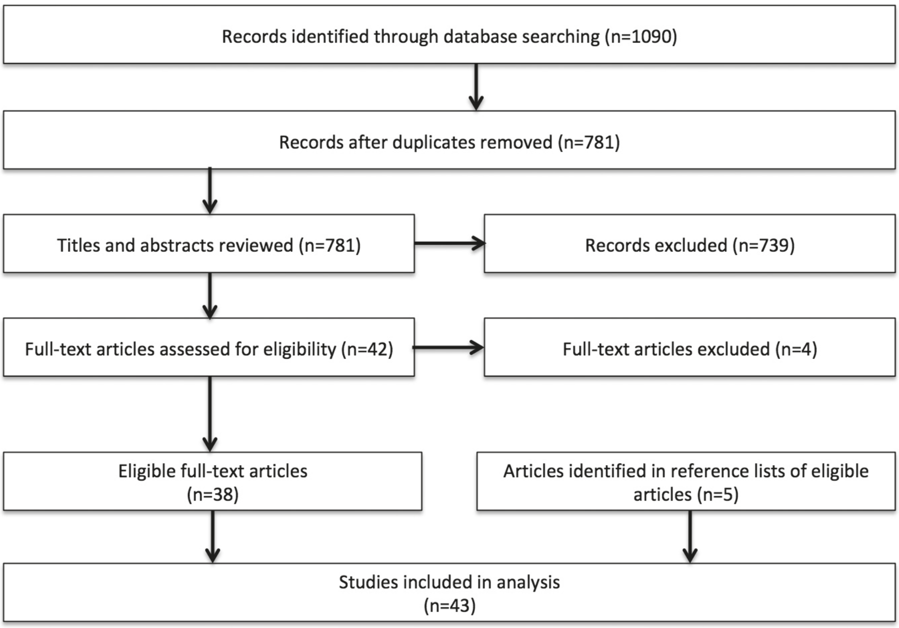

Figure 1. Systematic search flowchart for the systematic review

According to the QUACS scale, eighteen articles received methodologic quality ratings of "excellent" (score >80%), 20 articles were rated as "substantial" (score >60%), and 5 articles were rated as moderate (score >40%). No studies were rated as fair or poor. The QUACS rating degree of agreement between the reviewers (W.A.W. and D.T.M.) was 93.1%.

Medial meniscus
Eleven studies investigated the influence of a meniscectomy or meniscal tear (repair) on ACL force and knee kinematics (Table 1).[25–35] Due to differences in nomenclature between peripheral medial meniscus (MM) and ramp tears, studies specifically mentioning ramp tears were analyzed separately.

In 3 studies ACL strain or force was investigated.[26,28,34] Two studies reported a significant increase of native ACL strain in response to an anterior tibial load after total meniscectomy,[28] or after an untreated longitudinal body tear compared to control ACL and meniscus intact knees.[34] One study reported a significant increase of the in situ forces in an ACL graft in response to a combined anterior and axial tibial load after the removal of the MM, compared to ACL reconstructed knees with an intact MM.[26]

Two studies investigated the influence of medial meniscal injury on the kinematics of ACL intact knees[28,34] and reported a significant increase of ATT after a total meniscectomy[28] or an untreated longitudinal body tear.[34]

Nine studies investigated the influence of medial meniscal injury on the kinematics of ACL-deficient knees. Seven of these 9 studies reported that either 50 or 80% resection of the medial meniscus posterior horn (MMPH),[33,35] subtotal meniscectomy,[27] total meniscectomy,[25,29,30] or MMPH longitudinal tear[30,32,33] in ACL-deficient knees resulted in a significant increase in ATT at most tested flexion angles compared to ACL-deficient knees without a meniscal injury.

Four of these 9 studies investigated the influence of a repair of a longitudinal MMPH[30,32,33] or longitudinal meniscal body tear[34]. Three studies reported that repair of a longitudinal MMPH[30,32,33] tear significantly decreased ATT compared with ACL-deficient knees without repair of the meniscal tear at most flexion angles. In contrast, one study reported no significant differences in ATT when a longitudinal body tear or a medial meniscotibial ligament (MTL) disruption were created or repaired in ACL-deficient knees.[34]

Four studies investigated the influence of meniscal injury on the kinematics of ACLR knees. Two studies reported no significant increase in ATT after partial MMPH resection[31] or total meniscectomy[26] compared to ACLR knees without meniscal injury. One study reported that ACLR in ACL-deficient knees with a MMPH longitudinal tear repair restored ATT to values comparable to intact knees[32], whereas another study reported that ACLR in ACL-deficient knees with a subtotal meniscectomy did not normalize ATT compared with intact knees.[27]

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Allen et al (2000)	10	69	Intact ↓	0°- 15°- 30°- 60°- 90°			134 ANT		
			ACLd ↓	0°- 15°- 30°- 60°- 90°		Si (↑) at all flexion angles			
			ACLd + TM	0°- 15°- 30°- 60°- 90°		Si (↑), Sp (↑) at all flexion angles			
Papageorgiou et al (2001)	10	54	Intact ↓	0°- 30°- 60°- 90°		0°: 4.9 ± 1.1	134 ANT / 200 AX		
						30°: 10.0 ± 6.7			
			ACLd ↓	0°- 30°- 60°- 90°		0°: 10.1 ± 4.7 Si (↑)			
						30°: 21.6 ± 4.6 Si (↑)			
			ACLr ↓	0°- 30°- 60°- 90°		0°: 6.0 ± 2.2 (NSi)			
						30°: 11.0 ± 3.6 (NSi)			
			ACLr + TM	0°- 30°- 60°- 90°		0°: 6.2 ± 2.1 (NSp)			

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
						30°: 11.9 ± 3.9 (NSp)			
			ACLr to ACLr/ TM	30°	116 ± 35 to 155 ± 29 (Nw) (34% ↑)				
				60°	82 ± 29 to 125 ± 32 (Nw) (52% ↑)				
				90°	85 ± 40 to 124 ± 27 (Nw) (46% ↑)				
Seon et al (2009)	8	77	Intact ↓	0°-15°-30°-60°-90°					
			ACLd ↓	0°-15°-30°-60°-90°		Si (↑) at all flexion angles	130 ANT		
			ACLd + ST ↓	0°-15°-30°-60°-90°		Si (↑) at 15°- 30°- 60°- 90°			
			ACLr + ST	0°-15°-30°-60°-90°		Si (↑) at all flexion angles			

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Spang et al (2010)	10	85	Intact ↓	30°		9.6 ± 0.6	150 ANT		
				60°		6.1 ± 0.5			
				90°		4.1 ± 0.4			
			ACLi + TM	30°	NSi (strain)	10.6 ± 0.2 Si (↑)			
				60°	Si (↑) (strain)	7.2 ± 0.2 Si (↑)			
				90°	Si (↑) (strain)	5.1 ± 0.2 Si (↑)			
Musahl et al (2010)	8	85	Intact ↓	iLM 30°		3.1 ± 1.1			
				mPS				2.2 ± 4.6mm	
			ACLd ↓	iLM 30°		5.9 ± 3.1 Si (↑)			
				mPS				10.9 ± 4.0mm Si (↑)	
			ACLd + TM	iLM 30°		11.4 ± 5.2 Si (↑)			
				mPS				13.9 ± 4.3mm (NSp)	
								NSp	

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Ahn et al (2011)	10	77	Intact ↓	0°-15°-30°- 60°-90°		7.1 to 9.0	134 ANT / 200 AX	NS all knee states at 15° and 30°	5IR / 10VALG
			ACLd ↓	0°-15°-30°- 60°-90°		Si (↑) at all flexion angles			
			ACLd + MMPH tear ↓	0°-15°-30°- 60°-90°		Sp (↑) at 0°-15°-30°- 60°			
			ACLd + MMPH tear repair ↓	0°-15°-30°- 60°-90°		Sp (↑) at 0°-15°-30°- 90°			
						NS ACLd knee			
			TM (n=5)	0°-15°-30°- 60°-90°		NS ACLd + MMPH tear			
McCulloch et al (2013)	6	85	Intact ↓	30°		2.6 ± 0.9	134 ANT / combined muscle loads	2.0 ± 0.4 / 9.9 ± 0.7#	
				60°		2.6 ± 0.7		2.1 ± 0.9 / 14.9 ± 1.7#	
			ACLd ↓	30°		9.6 ± 1.4 Si (↑)		6.1 ± 0.6 / 11.2 ± 0.9# Si (↑)	

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
				60°		11.9 ± 0.7 Si (↑)		4.3 ± 1.4 / 15.0 ± 1.6# Si (↑)	
			ACLd + MMPHr 50% ↓			NSp except at root release at 60°		NSp at all flexion angles	
			ACLd + MMPHr 80% ↓						
			ACLd + Root release						
			ACLr / MI ↓	30°		1.4 ± 0.5		2.4 ± 0.7 / 9.0 ± 0.9#	
				60°		5.0 ± 1.0		2.3 ± 1.2 / 14.9 ± 1.6#	
			ACLr + MMPHr 50% ↓			NSp		NSp	
			ACLr + MMPHr 80% ↓						
			ACLr + Root release						

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Lorbach et al (2014)	12	85	Intact ↓	0° - 30° - 90°		30°: 6.6 ± 1.9	134 ANT	0°: 4.8 ± 2.7*	4IR / 10VALG
						90°: 5.7 ± 2.8		30°: 7.0 ± 1.4*	
			ACLd ↓	0° - 30° - 90°		30°: 14.3 ± 4.4 Si (↑)		0°: 6.0 ± 1.5* Si (↑)	
						90°: 11.3 ± 4.7 Si (↑)		30°: 5.9 ± 2.5 (NSi)*	
			ACLd + MMPH tear ↓	0° - 30° - 90°		30°: 20.2 ± 3.5 Si (↑)		0°: 8.8 ± 1.9* Si (↑)	
						90°: 11.4 ± 2.2 Si (↑)		30°: 7.3 ± 2.2 (NSi)*	
			ACLd + MMPH tear repair ↓	0° - 30° - 90°		30°: 13.4 ± 4.4 Si (↑)		0°: 4.8 ± 1.8 (NSi)*	
						90°: 10.1 ± 3.8 Si (↑)		30°: 6.5 ± 1.6 (NSi)*	
			ACLr + MMPH tear repair (n=6)	0° - 30° - 90°		30°: 7.5 ± 1.8 (NSi)		0°: 5.7 ± 3.2 (NSi)*	
						90°: 7.6 ± 2.9 (NSi)		30°: 7.6 ± 1.0 (NSi)*	

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Lorbach et al (2015)	18	77	Intact ↓	0° - 30° - 90°		30°: 7.7 ± 2.5	134 ANT	0°: 3.2 ± 2.3*	4IR / 10VALG
						90°: 5.8 ± 2.3		30°: 5.7 ± 2.8*	
			ACLd ↓	0° - 30° - 90°		30°: 13.6 ± 4.9 Si (↑)		0°: 5.7 ± 3.2 (NSi)*	
						90°: 11.4 ± 4.3 Si (↑)		30°: 7.4 ± 3.3 (NSi)*	
			ACLd + MMPH tear ↓	0° - 30° - 90°		30°: 16.2 ± 5.2 Si (↑)		0°: 6.8 ± 3.1* Si (↑)	
						90°: 12.1 ± 4.5 Si (↑)		30°: 8.1 ± 2.6 (NSi)*	
			ACLd + MMPH tear repair (n=9) ↓	0° - 30° - 90°		30°: 13.4 ± 4.4 Sp (↑)		0°: 4.8 ± 1.8 (NSi)*	
						90°: 10.1 ± 3.8 (NSp)		30°: 6.5 ± 1.6 (NSi)*	
			ACLd + MMPHr 80%	0° - 30° - 90°		30°: 15.4 ± 4.7 Si (↑)		0°: 5.8 ± 2.3 (NSi)*	
						90°: 11.7 ± 5.4 Si (↑)		30°: 8.3 ±4.2 (NSi)*	

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Smith et al (2020)	6	77	Intact (n=3) ↓	0° - 30° - 90°			100 ANT		
			ACLi + MMB tear ↓	0° - 30° - 90°	Si (↑) at all flexion angles (strain)	Si (↑) at all flexion angles			
			ACLi + MMB tear repair	0° - 30° - 60°	NSi at 0° and 30° (strain)	NSi at all flexion angles			
			ACLd (n=3) ↓	0° - 30° - 90°					
			MMB tear ↓	0° - 30° - 90°		Sp (↑) at all flexion angles			
			MMB tear repair	0° - 30° - 90°		Sp (↑) at all flexion angles			

Table 1: Characteristics and outcomes of medial meniscus pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL in situ force (Nw)/ strain (%) in response to ATT	ATT measurements (mean mm ± SD)	Loading conditions (Nw)	Rotational Translation measurements (mean mm/ degrees ± SD)	Rotational loading conditions (Nw)
Ahn et al (2020)	5	85	Intact ↓	0°- 30°- 60°- 90°			40ANT / 20AX / combined muscle loads		
			ACLd ↓	0°- 30°- 60°- 90°		Si (↑) at all flexion angles			
			ACLd + MMPHr 80%	0°- 30°- 60°- 90°		Sp (↑) at 30°- 60°- 90°			

ACL = anterior cruciate ligament; ACLd = ACL-deficient and meniscus intact; ACLi = ACL intact; ACLr = ACL-reconstructed; ANT = anteriorly directed tibial force; ATT = anterior tibial translation; AX = axial directed force; iLM = instrumented lachman; Intact = ACL and meniscus intact; IR = internal tibial rotation directed force; MI = meniscus intact; mm = millimeter;

MMB = medial meniscal body; MMPH = medial meniscus posterior horn; MMPHr = medial meniscus posterior horn resection; mPS = mechanized pivot shift; n = amount of specimens; NS = not statistically significant different compared to; NSi = not statistically significant compared to intact knee state; NSp = not statistically significant compared to previous knee state;

Nw = Newton; SD = standard deviation; Si = statistically significant compared to intact knee state; Sp = statistically significant compared to previous knee state; ST = subtotal meniscectomy; TM = total meniscectomy; VALG = valgus directed force QS = QUACS Score (%) ↑ = increase; ↓ = decrease; ↓= advancement from one to next knee status with a surgical procedure;

*# anterior tibial translation (mm) / internal tibial rotation (degrees); * anterior tibial translation (mm)*

2

MM ramp tear

Four studies specifically investigated the influence of a MM ramp tear on ACL force and knee kinematics (Table 2).[36–39] In all studies a full thickness tear of the meniscocapsular attachment was created, at the meniscocapsular junction of the posterior horn, in the posterior one-third of the meniscus, as described by Bollen et al.[40] In the study of Naendrup et al, the length of the ramp lesion was limited to 25 mm and it was reported that the lesions were not subluxable on extensive probing.[39] Three studies investigated a complete lesion of the posterior horn's MTL.[36,38,39]

Naendrup et al investigated the force on the native ACL under an anterior tibial force and internal and external tibial rotation torques, under axial load, and reported no significant difference between intact knees, knees with combined MM ramp and MTL lesions, and knees with (all-inside) repair of the ramp tear and no repair of the MTL.[39]

Three studies investigated the effect of a MM ramp tear,[37] or the effect of a MM ramp and/or a MTL tear[36,38] on the kinematics of ACL-deficient knees. Two studies reported that ATT and external tibial rotation were significantly increased after creation of a MM ramp[37] and/or a MTL tear[38], whereas another study reported no significant difference in ATT but included only 4 of 10 available knee cadavers for analysis.[36]

One study reported a significant increase in internal and external rotation and pivot-shift after a MM ramp and/or MTL tear in ACLR knees. The pivot shift and tibial rotation at lower flexion angles were restored to normal values only after ACLR in combination with inside-out repair of the MM ramp and MTL lesions and not after ACLR alone.[38] Another study reported a significant increase of ATT and external rotation, but no significant increase of internal rotation after a MM ramp tear in ACLR knees. Anterior tibial translation and external rotation were restored to normal values only after an ACLR combined with a (all-inside) MM ramp tear repair and not after an ACLR without a MM ramp tear repair.[37]

In contrast to the findings of the other 3 studies on the effect of a medial meniscus ramp tear on ACL tear kinematics, Naendrup et al.[39] reported no differences in ATT, internal and external rotation between intact knees, knees with combined MM ramp and MTL lesions, and knees with (all-inside) repair of the MM ramp tear (without repair of the MTL).

Table 2: Characteristics and outcomes of medial meniscus ramp pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ATT measurements (mm)	Loading conditions (Nw)	IR Measurements (degrees)	ER Measurements (degrees)	Rotational IR and ER loading conditions (Nw)	Other measurements
Peltier et al (2015)	4	85	Intact ↓	0° - 30°- 70°- 90°		134 ANT			5 IR and 5 ER	NS all knee states medial laxity at all flexion angles under 10N VALG
			ACLd ↓	0° - 30°- 70°- 90°	Si (↑) at all flexion angles		NSi at all flexion angles			
			ACLd + MMR lesion ↓	0° - 30°- 70°- 90°	NSp at all flexion angles		NSi at all flexion angles			
			ACLd + MMR lesion + MTL lesion	0° - 30°- 70°- 90°	NS ACLd knee at all flexion angles		Si (↑) at 0° and 30°, NSi at 70° and 90°	S ACLd knee (↑) at all flexion angles combined		

2

Table 2: Characteristics and outcomes of medial meniscus ramp pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ATT measurements (mm)	Loading conditions (Nw)	IR Measurements (degrees)	ER Measurements (degrees)	Rotational IR and ER loading conditions (Nw)	Other measurements
Stephen et al (2016)	9	92	Intact ↓	0°-100° at 10° intervals		90 ANT	NS all knee states		5 IR and 5 ER	NS all knee states PTT. NS all knee states ATT after combined ER and ANT loads
			ACLd ↓	0°-100° at 10° intervals	Si (↑) al all flexion angels					
			ACLd + MMR lesion ↓	0°-100° at 10° intervals	Sp (↑) at 0°-60°			Sp (↑) at 0°- 40° and at 70°		
			ACLd + MMR lesion repair ↓	0°-100° at 10° intervals						
			ACLr + MMR lesion repair ↓	0°-100° at 10° intervals	NSi at all flexion angles			NSi at all flexion angles		
			ACLr + MMR lesion ↓	0°-100° at 10° intervals	Sp (↑) at 0°-50°			Sp (↑) at 0°, 20°, 30°, 50°, 60°		
DePhillipo et al (2018)	24	92	Intact ↓	30° and 90°/0-90° (15° increments)		88 ANT			5 IR and 5 ER	
			ACLd ↓	30° and 90°/0°-90° (15° increments)						

Table 2: Characteristics and outcomes of medial meniscus ramp pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ATT measurements (mm)	Loading conditions (Nw)	IR Measurements (degrees)	ER Measurements (degrees)	Rotational IR and ER loading conditions (Nw)	Other measurements
			ACLd + MMR lesion (n=12) *or* MTL lesion (n=12) ↓	30° and 90°/0°-90° (15° increments)	MMR lesion: Sp (↑) at 30° and 90°		MMR lesion: Sp (↑) between 30° and 90°	MMR lesion: Sp (↑) at all flexion angels		MMR lesion: Sp (↑) ATT and IR at mPS test at 15° and 30°
					MTL lesion: Sp (↑) at 30° and 90°		MTL lesion: Sp (↑) at all flexion angles	MTL lesion: Sp (↑) at all flexion angles		MTL lesion: Sp (↑) ATT and IR at mPS test at 15° and 30°
			ACLd + MMR lesion *and* MTL lesion (n=24) ↓	30° and 90°/0°-90° (15° increments)	S (↑) at 30° and 90° ACLd knee		S ACLd knee (↑) at all flexion angles	Si (↑) at all flexion angles		S (↑) ACLd knee ATT and IR at mPS test at 15° and 30°
			ACLr + MMR lesion *and* MTL lesion (n=24) ↓	30° and 90°/0°-90° (15° increments)	NSi at 30° and 90°		Si (↑) at all flexion angles	Si (↑) at all flexion angles		Si (↑) ATT and IR at mPS test at 15° and 30°
			ACLr + MMR lesion repair *and* MTL lesion repair) n=16)	30° and 90°/0°-90° (15° increments)			NSi at 0° and 15°, Si (↑) at 30°-90°	Overconstrained at 0°, NSi at 30°, Si at 30°-90°		NSi ATT and IR at mPS at 15° and 30°

Table 2: Characteristics and outcomes of medial meniscus ramp pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ATT measurements (mm)	Loading conditions (Nw)	IR Measurements (degrees)	ER Measurements (degrees)	Rotational IR and ER loading conditions (Nw)	Other measurements
Naendrup et al (2019)	9	85	Intact ↓	0°- 90° (10° intervals)						
			ACLi + MMR lesion *and* MTL lesion ↓	0°- 90° (10° intervals)	90 ANT: NSi	90 ANT and 134 ANT + 200 AX	NSi	5 ER: NSi	4 IR + 200 AX and 5 ER and 4 ER + 200 AX	S (↓) on in situ ACL forces at higher flexion angles after 4 IR + 200 AX and after 4 ER + 200 AX load
				0°- 90° (10° intervals)	134 ANT + 200 AX: NSi			4 ER + 200 AX: NSi		
			ACLi + MMR lesion repair ↓	0°- 90° (10° intervals)	90 ANT: Si (↑) between 0° and 40°		NSi	5 ER: NSi		
				0°- 90° (10° intervals)	134 ANT + 200 AX: NSi			4 ER + 200 AX: NSi		
			ACLd + MMR lesion repair	0°- 90° (10° intervals)	-		-	-		
					-			-		

ACL = anterior cruciate ligament; ACLd = ACL-deficient and meniscus intact; ACLi = ACL intact; ACLr = ACL reconstruction; ANT = anteriorly directed tibial force;
ATT = anterior tibial translation; AX = axial directed force; ER = external tibial rotation directed force; Intact = ACL and meniscus intact;
IR = internal tibial rotation directed force; mm = millimeter; MMR = medial meniscal ramp; MTL = meniscotibial ligament;
mPS = mechanized pivot shift; n = amount of specimens; NS = not statistically significant different compared to; NSi = not statistically significant compared to intact knee state;
NSp = not statistically significant compared to previous knee state; Nw = Newton; PTT = posterior tibial translation; QS = QUACS Score (%);
S = statistically different compared to; Si = statistically significant compared to intact knee state; Sp = statistically significant compared to previous knee state; VALG = valgus directed force
↓= advancement from one to next knee status with a surgical procedure;
↑ = increase; ↓ = decrease

Medial meniscus posterior root

None of the included studies investigated the influence of a medial meniscus posterior root tear on ACL force and knee kinematics.

Lateral meniscus

Two studies investigated the influence of a total lateral meniscectomy on ACL force and knee kinematics in either ACL-deficient[29,41] or ACLR knees.[41] One study (13 cadaver knees) reported no significant difference in ACL graft force under anterior tibial and simulated pivot-shift loading after total lateral meniscectomy in ACL intact knees compared to meniscus intact and ACL intact knees.[41]

While one study (8 cadaver knees) reported no influence of a total lateral meniscectomy on ATT in ACL-deficient knees[29], the other study reported a significant increase in ATT at low flexion angles in ACLR knees.[41] Both studies reported significantly increased ATT with (simulated) pivot-shift testing for a total lateral meniscectomy in either ACL-deficient[29] or ACLR[41] knees.

Lateral meniscus posterior root

Four studies investigated the influence of a lateral meniscus posterior root (LMPR) tear with or without meniscofemoral ligament(s) (MFL) tear on ACL force and knee kinematics (Table 3).[42–45] In one study tests were performed under an axial load.[45]

One study reported that repair of a LMPR tear significantly increased the ACL graft force under anterior tibial loading compared to ACL-reconstructed knees with a LMPR tear.[44]

Three studies investigated the influence of a LMPR tear[42], a LMPR and MFL tear[43], or a LMPR tear repair[45] on the kinematics of ACL-deficient knees. A significant increase in ATT during the pivot-shift maneuver[42,43] and internal tibial rotation[43,45] was reported after creation of a LMPR tear in ACL-deficient knees compared to ACL-deficient knees with an intact LMPR[42,43]. One study reported that cutting the MFLs in ACL-deficient knees with a LMPR tear further increased tibial internal rotation.[43] Another study investigated the effect of a LMPR tear repair, without repair of the MFLs, and reported a significant decrease in tibial internal rotation compared to ACL, LMPR and MFLs-deficient knees.[45]

One study investigated the effect of a LMPR tear and tear repair on knee kinematics in ACLR knees, and reported a significant increase of ATT, but no significant difference in ATT under simulated pivot-shift loading between the LMPR torn and LMPR tear repaired knees.[44]

Table 3: Characteristics and outcomes of lateral meniscus posterior root pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL graft force	ATT measurements (mm)	Loading conditions (Nw)	IR measurements (degrees)	ATT during PS (mm)	IR during PS (degrees)	Rotational loading conditions (Nw)
Shybut et al (2015)	8	77	Intact ↓	15°- 30° - 45° - 60° - 90°							
				mPS					2.62 ± 0.53		
			ACLd ↓	15°- 30° - 45° - 60° - 90°		Si (↑) at all flexion angles	90 ANT				
				mPS					6.01 ± 0.51 (Si (↑) at all flexion angles)		
			ACLd + LMPR tear	15°- 30° - 45° - 60° - 90°		Si (↑), NSp at all flexion angles					
				mPS					8.13 ± 0.75 (Sp (↑) at all flexion angles)		
Frank et al (2017)	19	85	Intact (n=10) ↓				88 ANT				5 IR / 5IR + 10 VALG
			ACLd (n=10) ↓	0°- 30° - 60° - 90° (ATT)							

Table 3: Characteristics and outcomes of lateral meniscus posterior root pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL graft force	ATT measurements (mm)	Loading conditions (Nw)	IR measurements (degrees)	ATT during PS (mm)	IR during PS (degrees)	Rotational loading conditions (Nw)
			ACLd + LMPR tear (n=19) ↓	0°- 20° - 30° - 60° - 90° (PS)		Sp (↑) at 30°		Sp (↑) at 75° and 90°	Sp (↑) at 0° and 30°	NSp at all flexion angles	
			ACLd + LMPR tear + MFL tear (n=19)	0°- 30° - 60° - 75° - 90° (IR)		S (↑) ACLd knee at 0°		S (↑) ACLd knee at all flexion angels	S (↑) ACLd knee at 20° and 30°	S (↑) ACLd knee at 20° and 60°	
			Intact (n=9) ↓								
			ACLi + LMPR tear (n=9) ↓	0°- 30° - 60° - 90° (ATT)		Si (↑) at 60°		Si (↑) at 30° - 60° - 75° - 90°	Si (↑) at all flexion angles	Si (↑) at 60° and 90°	
			ACLd + LMPR tear (n=19) ↓	0°- 20° - 30° - 60° - 90° (PS)		Si (↑) at 30°		Si (↑) at 75° and 90°			
			ACLd + LMPR tear +MFL tear (n=19)	0°- 30° - 60° - 75° - 90° (IR)				Sp (↑) at 0° - 60° - 75° - 90°			

Table 3: Characteristics and outcomes of lateral meniscus posterior root pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL graft force	ATT measurements (mm)	Loading conditions (Nw)	IR measurements (degrees)	ATT during PS (mm)	IR during PS (degrees)	Rotational loading conditions (Nw)
Forkel et al (2018)	8	85	Intact ↓	20° (ATT), 0°- 30° - 60° - 90° (IR)			50 ANT + 20 AX				5 IR + 20 AX
			ACLd ↓	20° (ATT), 0°- 30° - 60° - 90° (IR)		Si (↑) at all flexion angles					
			ACLd + LMPR tear ↓	20° (ATT), 0°- 30° - 60° - 90° (IR)		NSp at all flexon angles					
			ACLd + LMPR tear + MFL tear ↓	20° (ATT), 0°- 30° - 60° - 90° (IR)		NSp at all flexon angles		S (↑) ACLd knee at all flexion angles			
			ACLd + LMPR tear repair	20° (ATT), 0°- 30° - 60° - 90° (IR)		NS ACLd knee, NS ACLd + LMPR tear knee, NSp at all flexion angles		Sp (↑) at 30° - 60° - 90°			

Table 3: Characteristics and outcomes of lateral meniscus posterior root pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL graft force	ATT measurements (mm)	Loading conditions (Nw)	IR measurements (degrees)	ATT during PS (mm)	IR during PS (degrees)	Rotational loading conditions (Nw)
Tang et al (2019)	13	85	Intact ↓	0°- 15° - 30° - 60° - 90°			89 ANT				5IR + 7 VALG
				mPS 15°and 30°							
			ACLr ↓	0°- 15° - 30° - 60° - 90°	Si (↓) at 30° - 60° - 90° during ANT	Si (↑) at 15° and 60°					
				mPS 15°and 30°	NSi				Si (↑) at 0°		
			ACLr + LMPR tear + MFL tear ↓	0°- 15° - 30° - 60° - 90°		Si (↑) at all flexion angles, Sp (↑) at 15° and 30°					
				mPS 15°and 30°	NSp				Si (↑) at 0°, NSp at all flexion angles		

Table 3: Characteristics and outcomes of lateral meniscus posterior root pathology on ACL force and knee kinematics.

Authors	n	QS	Study protocol	Flexion angle	ACL graft force	ATT measurements (mm)	Loading conditions (Nw)	IR measurements (degrees)	ATT during PS (mm)	IR during PS (degrees)	Rotational loading conditions (Nw)
			ACLr + LMPR tear repair	0°- 15° - 30° - 60° - 90°	S ACLr knee (↑) at 60° - 90°	Si (↑) at 15° and 90°, Sp (↑) at 15° - 30° - 60°					
					Sp (↑) at 60° - 90°	NS ACLr knee at 15° and 30°					
				mPS 15°and 30°	NSp				Sp (↑) at 0°- 15° - 30°, S (↑) ACLr knee at 15° - 30°		
									NSi at all flexion angles		

ACL = anterior cruciate ligament; ACLd = ACL-deficient and meniscus intact; ACLi = ACL intact; ACLr = ACL reconstruction; ANT = anteriorly directed tibial force; ATT = anterior tibial translation; AX = axial directed force; Intact = ACL and meniscus intact; IR = internal tibial rotation directed force;
LMPR = lateral meniscus posterior root; MFL = meniscofemoral ligament(s); mm = millimeter; mPS = mechanized pivot shift; n = amount of specimens; NS = not statistically significant different compared to; NSi = not statistically significant compared to intact knee state; NSp = not statistically significant compared to previous knee state; Nw = Newton;
PS = pivot shift; QS = QUACS score (%); S = statistically different compared to; Si = statistically significant compared to intact knee state; Sp = statistically significant compared to previous knee state; VALG = valgus directed force ; ↓= advancement from one to next knee status with a surgical procedure ↑ = increase; ↓ = decrease

Posterolateral corner

Seven studies investigated the influence of a PLC injury on ACL force and/or knee kinematics (Table 4).[46–52] One study reported a significant increase in tibial external rotation in several flexion angles after isolated sectioning of the popliteus tendon in ACLR knees, resulting in elevated ACL graft forces.[49] In contrast, 2 studies found that the forces in the intact ACL and reconstructed ACL were decreased under tibial external rotation torque when all posterolateral structures were sectioned. Furthermore, cutting of the posterolateral structures significantly increased ACL graft force in ACL intact or ACLR knees, when a varus rotation force, a tibial internal rotation torque, or coupled tibial internal torque and varus rotation force were applied.[46,51] The main structure preventing increased force on the ACL graft appeared to be the FCL.[51]

All studies investigating the effect of cutting the posterolateral corner structures on knee kinematics reported a significant increase in varus [46,47,51,52] and external rotation[46–48,51,52] in ACL intact, ACL-deficient and ACLR knees. No effect on valgus rotation and conflicting effects on tibial internal rotation were reported.[46,47,52] One study reported a significant increase in ATT and tibial internal rotation during a simulated pivot-shift test in ACL-deficient knees with a simulated PLC injury.[50]

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
Markolf et al (1993)	8	62	FCL, AL, PT	Intact ↓	0°- 10° - 20° - 45° - 60° - 80° - 90°							
				FCL, AL, PT deficient	0°- 10° - 20° - 45° - 60° - 80° - 90°	Si (↑) at IR 0°, 10°, 20°			Si (↑) at 60° - 90° (7 Nm)	Si (↑) at all flexion angles (7 Nm)	NSi at all flexion angles (10 Nm)	Si (↑) at all flexion angles (10 Nm)
						Si (↓) at ER 0°, 10°, 20°						
						NSi VALG at all flexion angles						
						Si (↑) VAR at all flexion angles						
Wroble et al (1993)	20/ unclear	46	PT, PLcps	Intact ↓	0°- 15° - 30° - 45° - 60° - 75° - 90°							
				ACLd ↓	0°- 15° - 30° - 45° - 60° - 75° - 90°		Si (↑) at all flexion angles (100)		Si (↑) at 0° and 15° (5 Nm)	NSi at all flexion angles (5 Nm)	NSi at all flexion angles (68 Nw)	NSi at all flexion angles (68 Nw)
				FCL, PT, PLcps	0°- 15° - 30° - 45° - 60° - 75° - 90°		Sp (↑) at 0° (100)		Conflicting results (n=6) (5 Nm)	Si (↑) and Sp (↑) at all flexion angles (5 Nm)	NSp at all flexion angles (68 Nw)	Sp (↑) at all flexion angles (68 Nw)

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
Veltri et all (1995)	5	54	FCL, PFL, PT	Intact ↓	0° - 30° - 45° - 90°							
				FCL, PFL, PT deficient ↓	0° - 30° - 45° - 90°		NSi at all flexion angles (100)	Si (↑) at 0° and 45° (100 Nw)	Si (↑) at 45° and 90° (5 Nm)	Si (↑) at 30°, 45°, 90° (5 Nm)	NSi at all flexion angles (5 Nmw)	NSi at all flexion angles (5 Nm)
									Si (↑) coupled IR to ATT at 45° and 90° (100 Nw)	Si (↑) coupled ER to PTT at all flexion angles (100 Nw)		
				ACLd	0° - 30° - 45° - 90°		Si (↑) and Sp (↑) at all flexion angles (100)	NSp at all flexion angles, Si (↑) at 0°, 30° and 45° (100 Nw)	Si (↑) at all flexion angles, Sp (↑) at 0°, 30°, 90° (5 Nm)	NSi at all flexion angles, Sp (↓) at 0° and 30° (5 Nm)	NSi at all flexion angles (5 Nmw)	NSi at all flexion angles (5 Nm)
									NSi coupled IR to ATT at all flexion angles (100 Nw)	Si (↑) coupled ER to PTT at all flexion angles, Sp (↑) coupled ER to PTT at 30°, 45°, 90° (100 Nw)		

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
LaPrade et al (1999)	8	62	FCL, PFL, PT	ACLr ↓	0° - 30° (- 90°)							
				FCL deficient ↓	0° - 30° (- 90°)	Si (↑) VAR at 0° and 30°	Sr (↑) at 0° (67)			NSr at 0°, NSr at 30°		Sr (↑) at 0° and 30° (12 Nm)
						Si (↑) VAR coupled to IR at 0° and 30°				NSr coupled ER (5 Nm) to PTT (67 Nm) at 30°, Sr (↑) coupled ER (5 Nm) to PTT (67 Nm) at 90°		Sr (↑) at 0° and 30° VAR (12 Nm) coupled to IR (5 Nm)
				PFL deficient ↓	0° - 30° (- 90°)	Si (↑), NSp VAR at 0° and 30°	Sr (↑) at 0° (67)			NSr at 0°, NSr at 30°		Sr (↑) at 0° and 30° (12 Nm)
						Si (↑), NSp VAR coupled to IR at 0° and 30°				NSr coupled ER (5 Nm) to PTT (67 Nm) at 30°, Sr (↑) coupled ER (5 Nm) to PTT (67 Nm) at 90°		Sr (↑) at 0° and 30° VAR (12 Nm) coupled to IR (5 Nm)

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
				PT deficient	0° - 30° (- 90°)	Si (↑), NSp VAR at 0° and 30°	Sr (↑) at 0° (67)			NSr at 0°, Sr (↑) at 30°		Sr (↑) at 0° and 30° (12 Nm)
						Si (↑), NSp VAR coupled to IR at 0° and 30°				Sr (↑) coupled ER (5 Nm) to PTT (67 Nm) at 30°, Sr (↑) coupled ER (5 Nm) to PTT (67 Nm) at 90°		Sr (↑) at 0° and 30° VAR (12 Nm) coupled to IR (5 Nm)
Zantop et al (2006)	10	77	FCL, PFL, PT	Intact ↓	0° - 30° - 60° - 90°							
				ACLd ↓	0° - 30° - 60° - 90°		1: Si (↑) at all flexion angles (134) 2: Si (↑) at 0° and 30° (4 IR + 10 VALG)#					
				FCL deficient ↓	0° - 30° - 60° - 90°		1: Sp (↑) at 0° and 30° (134) 2: Sp (↑) at 0°, 30°, 60° (4 IR + 10 VALG)#					

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
				PFL, PT deficient ↓	0° - 30° - 60° - 90°		1: Sp (↑) at 90° (134) 2: Sp (↑) at all flexion angles (4 IR + 10 VALG)#					
Gadikota et al (2011)	8	69	Unclear; referred to FCL,	ACLr ↓	0° - 30° - 60° - 90°							
			PFL, PT	PT deficient	0° - 30° - 60° - 90°	NSr VAR al all flexion angles	NSr at all flexion angles	NSr at all flexion angles		Sr (↑) at all flexion angles (5 Nm)		NSr at 0° and 30°, Sr at 60° and 90° (10 Nm)
						Sr (↑) ER at all flexion angles		Si (↑) coupled PTT to ER (5 Nm) at 0°, 60°, 90°		Sr (↑) coupled ER (5 Nm) to VAR (10 Nm) at 60° and 90°		Si (↑) coupled VAR to ER (5 Nm) at 0°, 60°, 90°

Table 4: Characteristics and outcomes of posterolateral corner pathology on ACL force and knee kinematics.

Authors	n	QS	Definition PLC	Study protocol	Flexion angle	ACL graft force	(1:) ATT measurements (Nw) (2: ATT and IR during PS (Nm))	PTT measurements	IR measurements	External rotational measurements	Valgus angulation	Varus angulation
Bonanzinga et al (2015)	7	62	FCL, PT and all its	Intact ↓	30° and 90°					**Internal - external rotation range**		
			connections to the fibula,	ACLd ↓	30° and 90°		Si (↑) at 30° and 90° (130)			NSi at 30° and 90° (5 Nm)		
			tibia and meniscus	PFL, PT deficient ↓	30° and 90°		NSp at 30° and 90° (130)			NSp at 30°, Sp at 90° (5 Nm)		
				ACLr ↓	30° and 90°		NSi at 30° and 90° (130)			NSp at 30° and 90° (5 Nm)		
				FCL deficient	30° and 90°		NSp at 30°, Sp (↑) at 90° (130)			Sp (↑) at 30° and 90° (5 Nm)		

ACL = anterior cruciate ligament; ACLd = ACL-deficient and posterolateral corner intact;
ACLr = ACL reconstruction; AL = arcuate ligament; ATT = anterior tibial translation;
ER = external tibial rotation directed force; FCL = femoral collateral ligament;
Intact = ACL and posterolateral corner intact; IR = internal tibial rotation directed force;
n = amount of specimens; Nm = Newtonmeter; NSi = not statistically significant compared to intact knee state; NSp = not statistically significant compared to previous knee state; NSr = not statistically significant compared to ACL-reconstructed knee state;
Nw = Newton; PFL = popliteofibular ligament; PLC = posterolateral corner;
PLcps = posterolateral capsule; PS = pivot shift; PT = popliteus tendon; PTT = posterior tibial translation; QS = QUACS Score (%); Si = statistically significant compared to intact knee state; Sp = statistically significant compared to previous knee state;
Sr = statistically significant compared to ACL-reconstructed knee state; VALG = valgus directed force; VAR = varus directed force;
↓= advancement from one to next knee status with a surgical procedure;
↑ = increase; ↓ = decrease

2

MCL/posteromedial corner

Four studies investigated the influence of medial MCL injury (10 cadaver knees in 3 studies, 12 cadaver knees in 1 study) on ACL force and knee kinematics. In none of the studies an axial compression load was simulated.[53–56] Three studies reported a significant increase of ACL force after partial superficial MCL (sMCL)[56] and complete sMCL sectioning with a deep MCL tear[54–56] under anterior tibial force[56], valgus rotation force[54–56], internal rotation force[56], and external rotation force with and without anterior tibial force.[55]

One study (in 10 knees) reported a significant increase in ATT above 60° of knee flexion after complete transection of the MCL in ACL-deficient knees compared to ACL-deficient and MCL intact knees.[53]

Posterior tibial slope

Ten studies investigated the influence of posterior tibial slope (PTS) on ACL force and knee kinematics (Table 5).[17,57–65]

Four studies reported a significant increase in ACL graft force under axial loading in ACLR knees after PTS increasing osteotomy. In 2 studies, a posterior open-wedge osteotomy was performed; increasing tibial slope led to a linear increase in ACLR graft forces.[63,64] In 2 studies an anterior closing-wedge osteotomy was performed; ACL graft forces were significantly decreased after slope decreasing osteotomy.[17,65]

In contrast to the above described results, 2 studies reported a significant decrease in native ACL strain in response to an increase in PTS after an anterior open wedge osteotomy without axial loading.[57,59] A significant increase in ACL strain in response to an anterior tibial force was observed in 1 of these 2 studies.[59] Vice versa, another study reported a significant decrease in ACL strain in response to an anterior tibial load and/or an axial load after a slope decreasing anterior closing wedge osteotomy.[62]

While one study reported a significant decrease in ATT after increasing PTS with an anterior open wedge osteotomy,[61] 3 studies reported a significant increase in ATT after PTS increasing anterior opening wedge osteotomy in ACL intact knees.[57–59] Likewise, another study reported a significant decrease in ATT after decreasing PTS with an anterior closing wedge osteotomy in ACL intact knees.[62]

One study reported no significant change in ATT during an instrumented Lachman test after an anterior open wedge osteotomy in ACL-deficient knees compared to intact knees; however, a significant increase in ATT was observed during a mechanized pivot-shift test.[60]

Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
Giffin et al (2004)	10	62	Intact ↓	8.8 +/- 1.8°	0°- 30°- 60°- 90°- 120°					
			OT 5mm ↓	AOW 5mm: 13.2 +/- 2.1°	0°- 30°- 60°- 90°- 120°			2.3 +/- 1.9 at 120° to 3.6 +/- 1.4 at 0°	NSi at all flexion angels (134Nw ANT)	
					30°- 90°				Si (↑) at 30° and 90° (200Nw AX)	
			OT + ACLd		30°- 90°				NSi at 30° and 90° (134Nw ANT/200Nw AX)	
					30°- 90°					
Fening et al (2008)	5	62	Intact ↓	12.1 +/- 2.4°	15°	1.88 +/- 1.35% (n=4)	18Nw: -0.10 +/- 1.01	1.44 +/- 0.77		1.00 +/- 2.90 tibial ER
			OT 5mm + intact	AOW 5mm: 15.6 +/- 2.6°	15°	1.06 +/- 1.15%; Si (n=4)	108Nw: 1.14 +/- 1.40	6.15 +/- 4.80 (Si)	NSi (18Nw/108Nw/209Nw)	3.77 +/- 0.04 tibial ER Si (↑)

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Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
			OT 10mm + intact	AOW 10mm: 21.7 +/- 3.0°	15°	minus 0.38 +/- 1.24%: Si (n=4)	209Nw: 1.52 +/- 1.72	9.23 +/- 7.55 (Si, Sp)	NSi (18Nw/108Nw/209Nw)	4.14 +/- 5.71 tibial ER Si (↑)
Martineau et al (2010)	4	54	Intact ↓	8.0 +/- 2.4°	15°	0.84 +/- 1.50%				
			OT 5mm + intact	AOW 5mm: 12.1 +/- 3.1°	15°	-6.28 +/- 5.40%		NSi	Si (↑) (18Nw/108Nw/209Nw)	
			OT 10mm + intact	AOW 10mm: 16.3 +/- 3.2°	15°	-6.77 +/- 4.79		NSi	Si (↑) (18Nw/108Nw/209Nw)	
Voos et al (2012)	11	77	Intact ↓		iLM 30°				4.7 ± 2.4	
					mPS					0.7 ± 1.8 ATT of LT, 4.7 ± 4.1 of MT during PS
			ACLd ↓		iLM 30°				8.4 ± 1.9	
					mPS					7.5 ± 4.0 Si (↑) ATT of LT, 8.2 ± 4.4 Si (↑) of MT during PS
			OT + ACLd	AOW + 5° and -5°	iLM 30°				5° ↑: 8.1 ± 3.0 (NSp); 5°↓: 7.2 ± 3.3 (NSp)	

Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
					mPS					5° ↑: 9.7 ± 5.9 (NSp); 5°↓: 3 ± 6.7 (NSp) ATT of LT during PS
										5° ↑: 10.6 ± 7.4 Sp (↑); 5°↓: 3.9 ± 6.9 (NSp) ATT of MT during PS
Netlitz et al (2013)	9	77	Intact ↓		0°- 30°- 90°					
			OT 5°- 10°- 15°	AOW 0°- 5°- 10°- 15°	0°- 30°- 90°	S (↓) 0° to 5° (200 AX), NS all other measurements (strain)			Si (↓) with ↑ PTS	Si (↓) of tibial rotation with slope ↑ to 15° for many of the load cases tested
Yamaguchi et al (2017)	11	77	Intact ↓	minus 8.0° (medial)/- 6.6° (lateral)	0°- 10°- 20°- 30°- 40°-50°					
			OT 10° ↓	AOW 10°; 2.1 (medial)/+3.2 (lateral)		S (↓) > 5° of knee flexion (200 AX) (force)	S (↓) > 5° of knee flexion (45 ANT/200N AX) (force)	Si (↓) at all flexion angles	Si (↓) between 5° and 45° (45Nw ANT /200Nw AX)	

Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
						S (↓) > 5° of knee flexion (20o AX / 5Nm VALG) (force)				
						NSi > 5° of knee flexion (200 AX / 2Nm IR) and (200 AX / 45 ANT / 5Nm VALG / 2Nm IR) (force)				
Bernhard-son et al (2019)	10	85	Intact ↓		0°- 15°- 30°- 45°- 60°					
			OT + ACLr	PW -2° to 20° (2° increments)		Si (linear ↓) with ↑ slope at all flexion angles for unloaded testing (force)				

Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
						Si (linear ↑) with ↑ slope at all flexion angles for loaded testing (200N AX) (force)				
Samuelson et al (2019)	10	85	Intact ↓		0°- 30°					
			OT + ACLr	POW 0° to 15° (3° increments)		Si (linear ↑) with ↑ slope at both flexion angles for loaded testing (1000 AX) (force)				
Imhoff et al (2019)	10	85	Intact ↓		30°					
			ACLd ↓		30°					
			OT + ACLd	ACW 10°	30°			Sp (↓) (200 AX); Sp (↓) (400 AX)	Sp (↑) (134Nw ANT); Sp (↑) (134Nw ANT / 200Nw AX)	Sp (↑) of IR (200 AX); Sp (↑) of IR (400 AX)
			ACLr ↓		30°					

Table 5: Characteristics and outcomes of posterior tibial slope on ACL force and knee kinematics.

Authors	n	QS	Study protocol	OT	Flexion angle	ACL strain (%) / in situ force (Nw) in response to slope change	ACL strain (%) in response to ATT	Anterior tibial shift in resting position compared to intact knee (mm)	ATT measurements (mean mm ± SD)	Rotational Translation measurements (mean mm/ degrees ± SD)
			OT + ACLr	ACW 10°	30°	Sp (↓) (200 AX); Sp (↓) (400 AX) (force)	Sp (↑) (134 ANT) / NSp (134 ANT/200 AX) (force)	NSp (220 AX); NSp (400 AX)	NSp (134Nw ANT); NSp (134Nw ANT / 200Nw AX)	NSp of IR (200 AX); NSp of IR (400 AX)
Imhoff et al (2020)	10	77	Intact		30°					
			ACLd							
			OT + ACLd	ACW 10°				Si (↓) (400 AX)		Si of IR (400 AX)
			OT + ACLr	ACW 10°		Si (↓) (200 AX); Si (↓) (400 AX) (force)		NSi (400 AX)		NSi of IR (400 AX)

ACL = anterior cruciate ligament; ACLd = ACL-deficient knee state; ACLr = ACL-reconstructed knee state; ACW = anterior closed wedge osteotomy; ANT = anteriorly directed tibial force; AOW = anterior open wedge osteotomy; AX = axial directed force;
ER = external tibial rotation directed force; iLM = instrumented Lachman; Intact = intact knee state; IR = internal tibial rotation directed force; LT = lateral compartment; mm = millimeter; mPS = mechanized pivot shift MT = medial compartment; n = amount of specimens; Nm = Newtonmeter; NS = not statistically significant different compared to; NSi = not statistically significant compared to intact knee; NSp = not statistically significant compared to previous knee state; Nw = Newton; OT = Osteotomy; POW = posterior open wedge osteotomy; PS= Pivot shift; PTS = posterior tibial slope; PW = posterior wedge osteotomy; QS = QUACS Score (%); S = statistically significant; SD = standard deviation; Si = statistically significant compared to intact knee; Sp = statistically significant compared to previous knee state; VALG = valgus directed force; ↓= advancement from one to next knee status with a surgical procedure; ↑ = increase; ↓ = decrease

Varus alignment

Two studies investigated the influence of varus knee malalignment on ACL (graft) force and knee kinematics.[17,18] One study (10 cadaver knees) reported a significant decrease in ACL graft force, under axial loading, after correction to neutral alignment as compared with slight varus alignment (mean medial proximal tibial angle 86.5° ± 2.1°).[17]

Another study (6 cadaver knees) reported a significant increase in native ACL force in axially loaded varus malaligned knees with the weight-bearing line medial to the medial tibial plateau (“advanced varus alignment”) compared to neutral aligned knees. In ACL-deficient knees, there was a significant increase in lateral joint line opening in knees with advanced varus malalignment compared to the neutral aligned knees, and a simulated varus thrust could sometimes be observed.[18]

Valgus alignment

One study (10 cadaver knees) investigated the influence of valgus malalignment on ACL graft force. A lateral distal femur osteotomy was done to adjust for 3 different alignment conditions according to the position, where the axial weight-bearing line dissected the tibial plateau (% from medial to lateral); 50%, 85% and 115%. A significant increase of force on ACL grafts under axial joint compression was reported for the 85% and 115% weight-bearing line state. Furthermore, it was reported that ACL graft force further increased when the posteromedial ligament complex (PMC; sMCL and posterior oblique ligament) was deficient, and that, in valgus malaligned and PMC-deficient knees, correction to neutral knee alignment was significantly more effective in decreasing ACL graft force compared to reconstruction of the PMC structures.[16]

Figure 2 summarizes and illustrates the pathologies (not including the anterolateral complex) influencing ACL graft force.

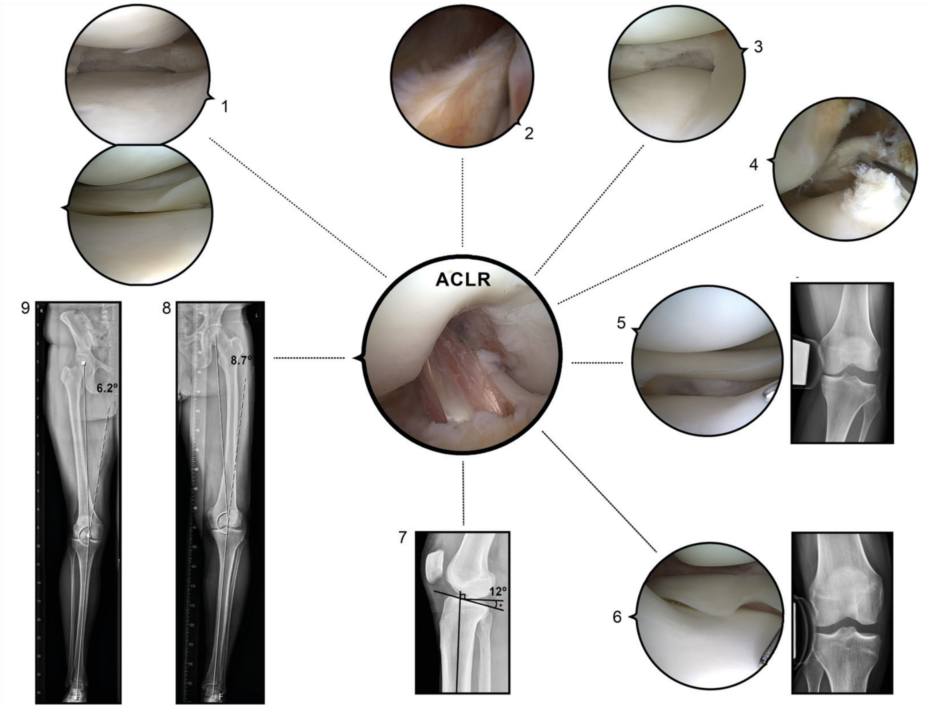

Figure 2. Summary of pathologies influencing ACL graft force (not including the anterolateral complex): 1. Arthroscopic image of partial medial meniscectomy and MMPH tear; 2. Arthroscopic image (posteromedial view) of MM ramp tear; 3. Arthroscopic image of partial lateral meniscectomy; 4. Arthroscopic image of LMPR tear; 5. Arthroscopic image of lateral drive through sign / varus stress radiograph with increased lateral compartment opening in PLC injured knee; 6. Arthroscopic image of medial drive thru sign / valgus stress radiograph with increased medial compartment opening in MCL injured knee; 7. Radiograph of increased PTS; 8. Weight-bearing full leg radiograph with varus alignment; 9. Weight-bearing full leg radiograph with valgus alignment.

DISCUSSION

The most important finding of this systematic review was that the majority of studies demonstrated that high-volume medial and lateral meniscectomies, peripheral meniscus tears, MM ramp tears, lateral meniscus root tears, PLC injuries, MCL tears, increased tibial slope and valgus and varus alignment were reported to have a significant impact on ACL (graft) force and ACL-related knee kinematics. The majority of studies found that MM (ramp) injury and increasing PTS cause a significant increase in ATT, whereas a MM ramp injury and PLC injury cause a significant increase in tibial external rotation; lateral meniscal injuries cause a significant increase in ATT with simulated pivot-shift testing, whereas a LM root injury causes a significant increase in tibial internal rotation. MCL injury significantly increases valgus rotation, whereas PLC injury significantly increases varus rotation. These findings imply that when these pathologies are undiagnosed or left untreated in case of injury, they could lead to ACLR graft overload and failure. In our opinion, it is necessary that clinicians who treat ACL-injured knees understand the biomechanical consequences of additional pathologies, and use this knowledge to perform the best possible treatment in ACL-injured patients.

The small sample sizes and the large variations in specimen characteristics, surgical procedures performed, kinematic testing systems, and testing protocols among the studies made it not possible to perform a meta-analysis. In addition, due to the extent of studies investigating the influence of anterolateral corner injury on ACL (graft) force and ACL-related knee kinematics this subject is systematically reviewed in a separate review.

The MM was found to be an important secondary restraint to ATT, especially in ACL-deficient knees,[25,27,29,30,32,33,35] in which the MMPH acts as a “bumper” to ATT and is therefore prone to injury due to recurrent trauma in ACL-injured knees.[25,30,33,35] The significant increase in strain or in situ force on the native ACL with anterior tibial loading after a total meniscectomy[26,28] or longitudinal body tear[34] further stresses the importance of preserving the MM when it is torn. A repair of a MMPH tear contributed to the restoration of knee kinematics[30,32,33], implying that it functionally protects the native or reconstructed ACL, and thus possibly reducing the incidence of ACL graft failures. The studies investigating the influence of meniscal injury on the kinematics of ACLR knees reported conflicting results, however.[26,27,31,32] Although one study reported that total meniscectomy did not have any significant effect on ATT in ACLR knees[26], another study reported that ACL reconstruction in ACL-deficient and subtotal meniscectomy knees significantly reduced ATT, although ATT was not restored to the intact level.[27] A possible explanation for the different findings is the differences in experimental protocol, mainly the different loading conditions (axial compressive load[26] versus no axial compressive load[27]). Two other studies also reported differences in their findings. While one study reported no differences in ATT and simulated pivot shift between intact knees and ACLR with meniscal repaired knees[32], another study reported that ACL reconstruction was capable of restoring knee stability regardless of the degree of MMPH resection.[31] Different loading conditions (combination of quadriceps and hamstring external load forces with anterior tibial loading compared to anterior tibial loading only) and the usage of different grafts and reconstruction techniques (bone-patellar-tendon-bone autograft with medial portal drilling and metal interference screw[31] vs porcine flexor digitorum allograft with medial parapatellar drilling and flip button/bio-interference screw fixation) can possibly explain the different findings. [32]

The studies on MM ramp tears reported conflicting results. Possible reasons for this are the small sample size in one study (n=4),[36] the smaller MM ramp tear that was created in one study[39] in comparison with larger tears in the other 3 studies,[36–38] and the difference in the MM ramp repair technique that was used; inside-out repair with fixation in 90 degrees of knee flexion, with the capsule slack,[38] versus all-inside repair at near knee extension, with the capsule taut.[37] There is still controversy about the definition of a MM ramp tear; whether the MTL is involved and whether MM ramp tears are complete or partial tears of the peripheral posterior horn. It is also possible that MM ramp tears are not all the same. The findings of a recent descriptive laboratory study can be used to provide the anatomic foundation for an improved understanding of the meniscocapsular and meniscotibial attachments of the MMPH, which may help provide a more precise definition of a meniscal ramp lesion.[66] Furthermore, different repair techniques should be compared.

The lateral meniscus was found to be a secondary stabilizer under pivot-shift loading in ACL-deficient[29,41] and ACLR knees[41]. While one study (8 cadaver knees) reported no influence of a total lateral meniscectomy on ATT in ACL-deficient knees[29], another study reported a significant increase in ATT at low flexion angles in ACLR knees.[41]

The LMPR was found to be a secondary stabilizer under pivot-shift loading[42,43] and internal tibial rotation in ACL-deficient knees.[43,45] These findings, and the findings of the lateral meniscus studies, imply that injury to the lateral meniscus may result in a higher-grade pivot-shift in ACL-injured knees and should be carefully evaluated and surgically repaired in the presence of ACL tears. The cause of the finding in one study that repair of a LMPR tear significantly increased the ACL graft force under anterior tibial loading compared with ACL-reconstructed knees with a LMPR tear was theorized that the lateral meniscus root repair was positioned such that further load was placed on the ACL graft, while we postulate that may have been due to a nonanatomic root repair for this to occur.[44] The clinical relevance of injury to the MFLs remains unclear; both studies investigating injury to the MFLs reported a significant increase in tibial internal rotation after sequential cutting of the LMPR and MFLs in ACL-deficient knees.[43,45] However, a LMPR tear repair without repair of the MFLs in ACL-deficient knees was sufficient to obtain a significant decrease in tibial internal rotation compared to ACL, LMPR and MFLs-deficient knees.[45]

The studies evaluating the influence of PLC injury suggested it is important to diagnose and treat PLC injuries in the presence of ACL tears to avoid elevated levels of force, especially due to increased lateral compartment gapping, which can lead to ACL graft failure.[46,49,51] While one study reported elevated ACL graft forces after a significant increase in tibial external rotation after isolated sectioning of the popliteus tendon,[49] 2 studies found that the forces in the intact ACL and reconstructed ACL were decreased under tibial external rotation torque when all posterolateral structures were sectioned.[46,51] Differences in loading conditions, sequence of sectioning of the posterolateral structures and coupled motions under external tibial torque may have contributed to these contrasting findings. Complete lesions of the sMCL and deep MCL were found to significantly increase ACL force under valgus loading[54–56], as was partial injury of the sMCL in combination with rotational loads[56], implying the need to treat MCL injuries in the setting of ACL injury and to protect the ACL graft from valgus and rotatory stress during postoperative rehabilitation.[56]

In terms of bony morphology issues, 4 studies reported a significant increase in ACL graft force under axial loading in ACLR knees after PTS increasing osteotomy.[17,63–65] It was suggested that at slopes >12°, a slope changing osteotomy could be considered in the setting of a revision ACLR with a concomitant medial meniscus tear.[64] The goal of a slope-decreasing osteotomy was suggested to decrease the tibial slope to <6°.[17,63–65] In contrast to their hypotheses, 2 studies reported a significant decrease in native ACL strain in response to an increase in PTS after an anterior open wedge osteotomy without axial loading.[57,59] It was hypothesized that a possible reason could be the observed anterior shift of the tibia after increasing PTS, possibly bringing the attachment sites of the ACL closer to each other, effectively increasing ligament laxity while maintaining the same relative joint position. Furthermore, a change in external rotation potentiating a reduction in ACL strain and altered joint anatomy were suggested as possible reasons.[59] It must be noticed however, that only 4 and 5 cadaver knees were tested in these studies.

Two studies found a direct relationship between varus alignment and increased ACL force.[17,18] It was reported that with increasing lateral joint opening, a thrust could sometimes experimentally be observed suggesting that in unstable ACL-deficient knees with a varus thrust, it might be safer to perform a high valgus tibial osteotomy to minimize the risk of ACLR failure.[18]

Finally, one study reported that correction of a valgus aligned and PMC-deficient knee to a neutral aligned knee was significantly more efficient in decreasing ACL force than ACLR and PMC reconstruction alone.[16]

Limitations

A systematic review on biomechanical cadaver studies has inevitable limitations, many of which are inherent to in vitro testing. In general, the mean specimen age was older than the typical age for patients sustaining ACL injury. In many studies, muscle loads were not applied, making it harder to extrapolate the results to physiologic conditions. Furthermore, all reported biomechanical findings are only valid at time zero because the biological effects of tissue healing could not be accounted for in these studies. Most included studies investigated the effect of one certain injury or condition on ACL (graft) force and knee kinematics. In reality, however, a combination of injuries in a certain knee status is present, making it difficult to extrapolate potentially concomitant pathologies to a real-life ACL knee injury situation. Furthermore, it is possible that relevant articles were not identified through the literature search and that studies published after the performed search were not included.

CONCLUSION

This systematic review on biomechanical cadaver studies provides a rationale to systematically identify and treat pathologies in ACL-injured knees, because when undiagnosed or left untreated, these specific concomitant pathologies could lead to ACL graft overload in both primary and revision ACL-reconstructed knees.

APPENDIX

Pubmed search

Filters: January 1, 1990 – December 10, 2020; English; human

(“Biomechanical Phenomena”[MeSH Terms] OR “biomechanical phenomena*”[Title/Abstract] OR “biomechanics”[Title/Abstract] OR “kinematic*”[Title/Abstract] OR “biomechanic phenomena*”[Title/Abstract] OR “biomechanical”[Title/Abstract] OR “biomechanically”[Title/Abstract] OR “laboratory study”[Title/Abstract]) AND (“Knee”[MeSH Terms] OR “Knee”[Title/Abstract]) AND (“Anterior Cruciate Ligament Injuries”[MeSH Terms] OR “acl injuries”[Title/Abstract] OR “acl injury”[Title/Abstract] OR “acl tear*”[Title/Abstract] OR “anterior cruciate ligament injury”[Title/Abstract] OR “anterior cruciate ligament tear”[Title/Abstract] OR “Anterior Cruciate Ligament”[MeSH Terms] OR “ACL”[Title/Abstract] OR “anterior cruciate ligament*”[Title/Abstract]) AND (“Cadaver”[MeSH Terms] OR “Cadaver”[Title/Abstract] OR “cadaveric”[Title/Abstract] OR “cadavera”[Title/Abstract])

Embase search

#2 AND #4 AND #7 AND [humans]/lim AND [english]/lim
346
Edit
Email alert
RSS feed
#8
#2 AND #4 AND #7
365
#7
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54,438
#6
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#3
'anterior cruciate ligament'
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#2
'knee'/exp OR knee.ti,ab,kw
71,082
#1
'knee'/exp OR 'knee'

REFERENCES

1. Bram JT, Magee LC, Mehta NN, Patel NM, Ganley TJ. **Anterior Cruciate Ligament Injury Incidence in Adolescent Athletes: A Systematic Review and Meta-analysis**. *Am J Sports Medicine*. Published online 2020:036354652095961. doi:10.1177/0363546520959619
2. Gornitzky AL, Lott A, Yellin JL, Fabricant PD, Lawrence JT, Ganley TJ. **Sport-Specific Yearly Risk and Incidence of Anterior Cruciate Ligament Tears in High School Athletes**. *Am J Sports Medicine*. 2016;44(10):2716-2723. doi:10.1177/0363546515617742
3. Sanders TL, Kremers HM, Bryan AJ, et al. **Incidence of Anterior Cruciate Ligament Tears and Reconstruction**. *Am J Sports Medicine*. 2016;44(6):1502-1507. doi:10.1177/0363546516629944
4. Magnussen RA, Meschbach NT, Kaeding CC, Wright RW, Spindler KP. **ACL Graft and Contralateral ACL Tear Risk within Ten Years Following Reconstruction**. *Jbjs Rev*. 2015;3(1):NA; doi:10.2106/jbjs.rvw.n.00052
5. Grassi A, Kim C, Muccioli GMM, Zaffagnini S, Amendola A. **What Is the Mid-term Failure Rate of Revision ACL Reconstruction? A Systematic Review**. *Clin Orthop Relat R*. 2017;475(10):2484-2499. doi:10.1007/s11999-017-5379-5
6. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Medicine*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
7. Group TM, Cooper DE, Dunn WR, et al. **Physiologic Preoperative Knee Hyperextension Is a Predictor of Failure in an Anterior Cruciate Ligament Revision Cohort: A Report From the MARS Group**. *Am J Sports Medicine*. 2018;46(12):2836-2841. doi:10.1177/0363546518777732
8. Group MK, Spindler KP, Huston LJ, et al. **Anterior Cruciate Ligament Reconstruction in High School and College-Aged Athletes: Does Autograft Choice Influence Anterior Cruciate Ligament Revision Rates**? *Am J Sports Medicine*. 2019;48(2):298-309. doi:10.1177/0363546519892991
9. Kaeding CC, Pedroza AD, Reinke EK, et al. **Risk Factors and Predictors of Subsequent ACL Injury in Either Knee After ACL Reconstruction**. *Am J Sports Medicine*. 2015;43(7):1583-1590. doi:10.1177/0363546515578836
10. Vermeijden HD, Yang XA, List JP van der, DiFelice GS, Rademakers MV, Kerkhoffs GMMJ. **Trauma and femoral tunnel position are the most common failure modes of anterior cruciate ligament reconstruction: a systematic review**. *Knee Surg Sports Traumatology Arthrosc*. 2020;28(11):3666-3675. doi:10.1007/s00167-020-06160-9
11. Bates NA, McPherson AL, Rao MB, Myer GD, Hewett TE. **Characteristics of inpatient anterior cruciate ligament reconstructions and concomitant injuries**. *Knee Surg Sports Traumatology Arthrosc*. 2016;24(9):2778-2786. doi:10.1007/s00167-014-3478-3
12. Levy IM, Torzilli PA, Gould JD, Warren RF. **The effect of lateral meniscectomy on motion of the knee**. *J Bone Jt Surg*. 1989;71(3):401-406. doi:10.2106/00004623-198971030-00014
13. Levy IM, Torzilli PA, Warren RF. **The effect of medial meniscectomy on anterior-posterior motion of the knee**. *J Bone Jt Surg*. 1982;64(6):883-888. doi:10.2106/00004623-198264060-00011
14. Shoemaker SC, Markolf KL. **Effects of joint load on the stiffness and laxity of ligament-deficient knees. An in vitro study of the anterior cruciate and medial collateral ligaments**. *J Bone Jt Surg*. 1985;67(1):136-146. doi:10.2106/00004623-198567010-00017
15. Gollehon DL, Torzilli PA, Warren RF. **The role of the posterolateral and cruciate ligaments in the stability of the human knee. A biomechanical study**. *J Bone Jt Surg*. 1987;69(2):233-242. doi:10.2106/00004623-198769020-00010

16. Mehl J, Otto A, Kia C, et al. **Osseous valgus alignment and posteromedial ligament complex deficiency lead to increased ACL graft forces**. *Knee Surg Sports Traumatology Arthrosc*. 2020;28(4):1119-1129. doi:10.1007/s00167-019-05770-2
17. Imhoff FB, Comer B, Obopilwe E, Beitzel K, Arciero RA, Mehl JT. **Effect of Slope and Varus Correction High Tibial Osteotomy in the ACL-Deficient and ACL-Reconstructed Knee on Kinematics and ACL Graft Force: A Biomechanical Analysis**. *Am J Sports Medicine*. 2020;49(2):410-416. doi:10.1177/0363546520976147
18. Pol GJ van de, Arnold MP, Verdonschot N, Kampen A van. **Varus Alignment Leads to Increased Forces in the Anterior Cruciate Ligament**. *Am J Sports Medicine*. 2009;37(3):481-487. doi:10.1177/0363546508326715
19. Simon RA, Everhart JS, Nagaraja HN, Chaudhari AM. **A case-control study of anterior cruciate ligament volume, tibial plateau slopes and intercondylar notch dimensions in ACL-injured knees**. *J Biomech*. 2010;43(9):1702-1707. doi:10.1016/j.jbiomech.2010.02.033
20. Zeng C, Yang T, Wu S, et al. **Is posterior tibial slope associated with noncontact anterior cruciate ligament injury**? *Knee Surg Sports Traumatology Arthrosc*. 2016;24(3):830-837. doi:10.1007/s00167-014-3382-x
21. Dean RS, Larson CM, Waterman BR. **Posterior Tibial Slope: Understand Bony Morphology to Protect Knee Cruciate Ligament Grafts**. *Arthrosc J Arthrosc Relat Surg*. 2021;37(7):2029-2030. doi:10.1016/j.arthro.2021.05.006
22. Terauchi M, Hatayama K, Yanagisawa S, Saito K, Takagishi K. **Sagittal Alignment of the Knee and Its Relationship to Noncontact Anterior Cruciate Ligament Injuries**. *Am J Sports Medicine*. 2011;39(5):1090-1094. doi:10.1177/0363546510393305
23. Ziegler CG, DePhillipo NN, Kennedy MI, Dekker TJ, Dornan GJ, LaPrade RF. **Beighton Score, Tibial Slope, Tibial Subluxation, Quadriceps Circumference Difference, and Family History Are Risk Factors for Anterior Cruciate Ligament Graft Failure: A Retrospective Comparison of Primary and Revision Anterior Cruciate Ligament Reconstructions**. *Arthrosc J Arthrosc Relat Surg*. 2021;37(1):195-205. doi:10.1016/j.arthro.2020.08.031
24. Wilke J, Krause F, Niederer D, et al. **Appraising the methodological quality of cadaveric studies: validation of the QUACS scale**. *J Anat*. 2015;226(5):440-446. doi:10.1111/joa.12292
25. Allen CR, Wong EK, Livesay GA, Sakane M, Fu FH, Woo SL. **Importance of the medial meniscus in the anterior cruciate ligament-deficient knee**. *J Orthopaed Res*. 2000;18(1):109-115. doi:10.1002/jor.1100180116
26. Papageorgiou CD, Gil JE, Kanamori A, Fenwick JA, Woo SLY, Fu FH. **The Biomechanical Interdependence between the Anterior Cruciate Ligament Replacement Graft and the Medial Meniscus***. *Am J Sports Medicine*. 2001;29(2):226-231. doi:10.1177/03635465010290021801
27. Seon JK, Gadikota HR, Kozanek M, Oh LS, Gill TJ, Li G. **The Effect of Anterior Cruciate Ligament Reconstruction on Kinematics of the Knee With Combined Anterior Cruciate Ligament Injury and Subtotal Medial Meniscectomy: An In Vitro Robotic Investigation**. *Arthrosc J Arthrosc Relat Surg*. 2009;25(2):123-130. doi:10.1016/j.arthro.2008.09.020
28. Spang JT, Dang ABC, Mazzocca A, et al. **The Effect of Medial Meniscectomy and Meniscal Allograft Transplantation on Knee and Anterior Cruciate Ligament Biomechanics**. *Arthrosc J Arthrosc Relat Surg*. 2010;26(2):192-201. doi:10.1016/j.arthro.2009.11.008
29. Musahl V, Citak M, O'Loughlin PF, Choi D, Bedi A, Pearle AD. **The Effect of Medial Versus Lateral Meniscectomy on the Stability of the Anterior Cruciate Ligament-Deficient Knee**. *Am J Sports Medicine*. 2010;38(8):1591-1597. doi:10.1177/0363546510364402
30. Ahn JH, Bae TS, Kang KS, Kang SY, Lee SH. **Longitudinal Tear of the Medial Meniscus Posterior Horn in the Anterior Cruciate Ligament–Deficient Knee Significantly Influences Anterior Stability**. *Am J Sports Medicine*. 2011;39(10):2187-2193. doi:10.1177/0363546511416597

31. McCulloch P, Shybut T, Isamaily S, et al. **The Effect of Progressive Degrees of Medial Meniscal Loss on Stability after Anterior Cruciate Ligament Reconstruction**. *J Knee Surg*. 2013;26(05):363-370. doi:10.1055/s-0033-1341578
32. Lorbach O, Kieb M, Domnick C, et al. **Biomechanical evaluation of knee kinematics after anatomic single- and anatomic double-bundle ACL reconstructions with medial meniscal repair**. *Knee Surg Sports Traumatology Arthrosc*. 2015;23(9):2734-2741. doi:10.1007/s00167-014-3071-9
33. Lorbach O, Kieb M, Herbort M, Weyers I, Raschke M, Engelhardt M. **The influence of the medial meniscus in different conditions on anterior tibial translation in the anterior cruciate deficient knee**. *Int Orthop*. 2015;39(4):681-687. doi:10.1007/s00264-014-2581-x
34. Smith P, Humpherys J, Stannard J, Cook J. **Impact of Medial Meniscotibial Ligament Disruption Compared to Peripheral Medial Meniscal Tear on Knee Biomechanics**. *J Knee Surg*. Published online 2020. doi:10.1055/s-0039-3402483
35. Ahn JH, Koh IJ, McGarry MH, et al. **Knee laxity in anterolateral complex injuries versus medial meniscus posterior horn injuries in anterior cruciate ligament injured knees: A cadaveric study**. *Orthop Traumatology Surg Res*. 2020;106(5):945-955. doi:10.1016/j.otsr.2020.03.025
36. Peltier A, Lording T, Maubisson L, Ballis R, Neyret P, Lustig S. **The role of the meniscotibial ligament in posteromedial rotational knee stability**. *Knee Surg Sports Traumatology Arthrosc*. 2015;23(10):2967-2973. doi:10.1007/s00167-015-3751-0
37. Stephen JM, Halewood C, Kittl C, Bollen SR, Williams A, Amis AA. **Posteromedial Meniscocapsular Lesions Increase Tibiofemoral Joint Laxity With Anterior Cruciate Ligament Deficiency, and Their Repair Reduces Laxity**. *Am J Sports Medicine*. 2016;44(2):400-408. doi:10.1177/0363546515617454
38. DePhillipo NN, Moatshe G, Brady A, et al. **Effect of Meniscocapsular and Meniscotibial Lesions in ACL-Deficient and ACL-Reconstructed Knees: A Biomechanical Study**. *Am J Sports Medicine*. 2018;46(10):2422-2431. doi:10.1177/0363546518774315
39. Naendrup JH, Pfeiffer TR, Chan C, et al. **Effect of Meniscal Ramp Lesion Repair on Knee Kinematics, Bony Contact Forces, and In Situ Forces in the Anterior Cruciate Ligament**. *Am J Sports Medicine*. 2019;47(13):3195-3202. doi:10.1177/0363546519872964
40. Bollen SR. **Posteromedial meniscocapsular injury associated with rupture of the anterior cruciate ligament**. *Bone Joint J*. 2010;92-B(2):222-223. doi:10.1302/0301-620x.92b2.22974
41. Tang X, Marshall B, Wang JH, et al. **Partial meniscectomy does not affect the biomechanics of anterior cruciate ligament reconstructed knee with a lateral posterior meniscal root tear**. *Knee Surg Sports Traumatology Arthrosc*. 2020;28(11):3481-3487. doi:10.1007/s00167-020-06209-9
42. Shybut TB, Vega CE, Haddad J, et al. **Effect of Lateral Meniscal Root Tear on the Stability of the Anterior Cruciate Ligament–Deficient Knee**. *Am J Sports Medicine*. 2015;43(4):905-911. doi:10.1177/0363546514563910
43. Frank JM, Moatshe G, Brady AW, et al. **Lateral Meniscus Posterior Root and Meniscofemoral Ligaments as Stabilizing Structures in the ACL-Deficient Knee: A Biomechanical Study**. *Orthop J Sports Medicine*. 2017;5(6):2325967117695756. doi:10.1177/2325967117695756
44. Tang X, Marshall B, Wang JH, et al. **Lateral Meniscal Posterior Root Repair With Anterior Cruciate Ligament Reconstruction Better Restores Knee Stability**. *Am J Sports Medicine*. 2019;47(1):59-65. doi:10.1177/0363546518808004
45. Forkel P, Deimling C von, Lacheta L, et al. **Repair of the lateral posterior meniscal root improves stability in an ACL-deficient knee**. *Knee Surg Sports Traumatology Arthrosc*. 2018;26(8):2302-2309. doi:10.1007/s00167-018-4949-8

46. Markolf KL, Wascher DC, Finerman GA. **Direct in vitro measurement of forces in the cruciate ligaments. Part II: The effect of section of the posterolateral structures**. *J Bone Jt Surg*. 1993;75(3):387-394. doi:10.2106/00004623-199303000-00010
47. Wroble RR, Grood ES, Cummings JS, Henderson JM, Noyes FR. **The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee**. *Am J Sports Medicine*. 1993;21(2):257-263. doi:10.1177/036354659302100216
48. Bonanzinga T, Signorelli C, Lopomo N, et al. **Biomechanical effect of posterolateral corner sectioning after ACL injury and reconstruction**. *Knee Surg Sports Traumatology Arthrosc*. 2015;23(10):2918-2924. doi:10.1007/s00167-015-3696-3
49. Gadikota HR, Seon JK, Wu JL, Gill TJ, Li G. **The effect of isolated popliteus tendon complex injury on graft force in anterior cruciate ligament reconstructed knees**. *Int Orthop*. 2011;35(9):1403-1408. doi:10.1007/s00264-010-1118-1
50. Zantop T, Schumacher T, Diermann N, Schanz S, Raschke MJ, Petersen W. **Anterolateral rotational knee instability: role of posterolateral structures**. *Arch Orthop Traum Su*. 2007;127(9):743-752. doi:10.1007/s00402-006-0241-3
51. LaPrade RF, Resig S, Wentorf F, Lewis JL. **The Effects of Grade III Posterolateral Knee Complex Injuries on Anterior Cruciate Ligament Graft Force**. *Am J Sports Medicine*. 1999;27(4):469-475. doi:10.1177/03635465990270041101
52. Veltri DM, Deng XH, Torzilli PA, Warren RF, Maynard MJ. **The Role of the Cruciate and Posterolateral Ligaments in Stability of the Knee**. *Am J Sports Medicine*. 1995;23(4):436-443. doi:10.1177/036354659502300411
53. Sakane M, Livesay GA, Fox RJ, Rudy TW, Runco TJ, Woo SLY. **Relative contribution of the ACL, MCL, and bony contact to the anterior stability of the knee**. *Knee Surg Sports Traumatology Arthrosc*. 1999;7(2):93-97. doi:10.1007/s001670050128
54. Mazzocca AD, Nissen CW, Geary M, Adams DJ. **Valgus medial collateral ligament rupture causes concomitant loading and damage of the anterior cruciate ligament**. *J Knee Surg*. 2003;16(3):148-151.
55. Shapiro MS, Markolf KL, Finerman GA, Mitchell PW. **The effect of section of the medial collateral ligament on force generated in the anterior cruciate ligament**. *J Bone Jt Surg Am Volume*. 1991;73(2):248-256.
56. Battaglia MJ, Lenhoff MW, Ehteshami JR, et al. **Medial Collateral Ligament Injuries and Subsequent Load on the Anterior Cruciate Ligament**. *Am J Sports Medicine*. 2009;37(2):305-311. doi:10.1177/0363546508324969
57. Martineau PA, Fening SD, Miniaci A. **Anterior opening wedge high tibial osteotomy: the effect of increasing posterior tibial slope on ligament strain**. *Can J Surg J Can De Chir*. 2010;53(4):261-267.
58. Giffin JR, Vogrin TM, Zantop T, Woo SLY, Harner CD. **Effects of Increasing Tibial Slope on the Biomechanics of the Knee**. *Am J Sports Medicine*. 2004;32(2):376-382. doi:10.1177/0363546503258880
59. Fening S, Kovacic J, Kambic H, McLean S, Scott J, Miniaci A. **The Effects of Modified Posterior Tibial Slope on Anterior Cruciate Ligament Strain and Knee Kinematics - A Human Cadaveric Study**. *J Knee Surg*. 2008;21(03):205-211. doi:10.1055/s-0030-1247820
60. Voos JE, Suero EM, Citak M, et al. **Effect of tibial slope on the stability of the anterior cruciate ligament–deficient knee**. *Knee Surg Sports Traumatology Arthrosc*. 2012;20(8):1626-1631. doi:10.1007/s00167-011-1823-3
61. Nelitz M, Seitz AM, Bauer J, Reichel H, Ignatius A, Dürselen L. **Increasing posterior tibial slope does not raise anterior cruciate ligament strain but decreases tibial rotation ability**. *Clin Biomech*. 2013;28(3):285-290. doi:10.1016/j.clinbiomech.2013.01.011

62. Yamaguchi KT, Cheung EC, Markolf KL, et al. **Effects of Anterior Closing Wedge Tibial Osteotomy on Anterior Cruciate Ligament Force and Knee Kinematics**. *Am J Sports Medicine*. 2018;46(2):370-377. doi:10.1177/0363546517736767
63. Bernhardson AS, Aman ZS, Dornan GJ, et al. **Tibial Slope and Its Effect on Force in Anterior Cruciate Ligament Grafts: Anterior Cruciate Ligament Force Increases Linearly as Posterior Tibial Slope Increases**. *Am J Sports Medicine*. 2019;47(2):296-302. doi:10.1177/0363546518820302
64. Samuelsen BT, Aman ZS, Kennedy MI, et al. **Posterior Medial Meniscus Root Tears Potentiate the Effect of Increased Tibial Slope on Anterior Cruciate Ligament Graft Forces**. *Am J Sports Medicine*. 2019;48(2):334-340. doi:10.1177/0363546519889628
65. Imhoff FB, Mehl J, Comer BJ, et al. **Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load**. *Knee Surg Sports Traumatology Arthrosc*. 2019;27(10):3381-3389. doi:10.1007/s00167-019-05360-2
66. DePhillipo NN, Moatshe G, Chahla J, et al. **Quantitative and Qualitative Assessment of the Posterior Medial Meniscus Anatomy: Defining Meniscal Ramp Lesions**. *Am J Sports Medicine*. 2019;47(2):372-378. doi:10.1177/0363546518814258

chapter 3

The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction can Restore Native Knee Kinematics in the Anterior Cruciate Ligament Reconstructed Knee. A Systematic Review of Biomechanical Cadaveric Studies.

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ABSTRACT

Purpose

Our purpose was to obtain a comprehensive overview of comparative biomechanical cadaveric studies investigating the effect of both the iliotibial band (ITB) and anterolateral ligament (ALL) on anterolateral rotatory instability (ALRI) in anterior cruciate ligament (ACL) injured knees, and the effect of lateral extra-articular tenodesis (LET) versus ALL reconstruction (ALLR) in ACL-reconstructed knees.

Methods

An electronic search was performed in the Embase and MEDLINE databases for the period between January 1, 2010, and October 1, 2022. All sectioning studies comparing the role of both the ITB and ALL on ALRI, and all studies comparing the effect of both LET and ALLR were included. Articles were assessed for methodologic quality according to the Quality Appraisal for Cadaveric Studies scale.

Results

Data of 15 studies were included, representing the mean values of biomechanical data collected from 203 cadaveric specimens, with sample sizes ranging from 10 to 20 specimens. All 6 sectioning studies reported that the ITB acts as a secondary stabilizer to the ACL and helps resist internal knee rotation, whereas in only 2 of 6 sectioning studies the ALL contributed significantly to tibial internal rotation (IR). Most reconstruction studies reported that both a modified Lemaire tenodesis and an ALLR could significantly reduce the residual ALRI in isolated ACL-reconstructed knees and were able to restore IR stability/ IR stability during the pivot shift.

Conclusion

The ITB acts as the main secondary stabilizer to the ACL in resisting IR/IR during pivot shift, and an anterolateral corner (ALC) reconstruction with either a modified Lemaire tenodesis or ALLR can improve residual knee rotatory laxity in ACL-reconstructed knees.

Clinical Relevance

This systematic review provides insight in the biomechanical function of the ITB and ALL and emphasizes the importance of adding an ALC reconstruction to ACL reconstruction.

INTRODUCTION

Anterior cruciate ligament reconstruction (ACLR) has proven to be an effective treatment for anterior cruciate ligament (ACL) tears. However, the risk of re-rupture is significant, especially in the younger and active population.[1,2] Other known risk factors than age that have been described to influence ACL failure risk are female sex, surgical technique/technical errors, new trauma, use of allograft, greater activity level and physiological preoperative knee hyperextension.[3–6] Furthermore, concomitant pathology could lead to ACL graft overload in both primary and revision ACL-reconstructed knees. In a recent systematic review of van der Wal et al.[7] of biomechanical cadaver studies it was reported that high-volume medial and lateral meniscectomies, peripheral meniscus tears, medial meniscal (MM) ramp tears, lateral meniscus root tears, posterolateral injuries, MCL tears, increased tibial slope, and valgus and varus alignment had a significant impact on ACL (graft) force and ACL-related knee kinematics. It was argued that it is necessary to understand the surgically relevant biomechanical consequences of these additional pathologies and use this knowledge to optimize treatment in ACL-injured patients.[7]

Pathology to the anterolateral corner (ALC) structures of the knee has regained attention in the past decade because of the recharacterization of anterolateral knee anatomy[8] although historical publications already referred to this region of the knee.[9,10] Injuries to ALC structures of the knee in combination with an ACL tear have been suggested to cause anterolateral rotatory instability (ALRI).[10–12] It has been reported in biomechanical cadaver and clinical studies that isolated ACLR without surgical treatment of the injured ALC structures may result in residual rotatory instabilities.[13–16] The biomechanical explanation behind ALRI is based on the fact that the rotational axis of the tibia shifts medially from the center of the tibial plateau after an ACL rupture.[17,18] As a result, the lateral tibial plateau tends to subluxate anteriorly, especially in the presence of injury to the ALC structures,[10,12,19] clinically detectable as the pivot-shift phenomenon.[20]

The primary stabilizing structures of the ALC include the iliotibial band (ITB) deep (Kaplan) fibers and capsulo-osseous layer, and the anterolateral ligament (ALL), although there remains disagreement on the precise anatomic locations and biomechanical relevance of these structures.[21] Several techniques have been proposed to address ALRI in ACLR surgery and these can be divided into lateral extra-articular tenodesis (LET) techniques of the ITB and ALL reconstruction techniques with a free tendon graft.

Several biomechanical laboratory cadaver studies have investigated the effect of the ALL or the ITB, and the effect of LET or ALLR procedures on knee rotatory stability in the setting of both the ACL-injured and reconstructed knee. However, a comprehensive review of cadaveric studies that compare sectioning of the ITB to ALL, and studies that compare LET to ALLR is currently lacking. Therefore, this study was conducted. Our purpose was to obtain a comprehensive overview of comparative biomechanical cadaveric studies investigating the effect of both the ITB and ALL on ALRI in ACL-injured knees, and the effect of LET versus ALLR in ACL-reconstructed knees.

The hypothesis was that both the ITB and ALL act as secondary stabilizers to the ACL and help resist internal tibial rotation (IR) / IR during the pivot shift. The second hypothesis was that both LET and ALLR effectively minimize ALRI.

METHODS

The Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) guidelines were followed, and a PRISMA flow diagram was used (Figure 1). A systematic review of the current peer reviewed literature was performed using the electronic databases EMBASE and MEDLINE/PubMed (January 1, 2010 – October 1, 2022), with the assistance of an informationist. We focused on the recently published studies that appeared since the renewed interest in the anterolateral corner since Steven Claes' publication on the ALL[8], to include all studies that have been published in the current era of ACL + ALC reconstruction.

Search strings were used to screen for biomechanical cadaver studies which measured ACL (graft) force and ACL-related knee kinematics (Appendix). All resulting titles and abstracts were screened for potential eligibility by 2 authors (D.T.M., W.A.W.) and confirmed by the senior author (R.F.L.). Thereafter, 2 authors (D.T.M., W.A.W.) independently retrieved and analyzed the potentially eligible full-text articles. The references of included articles were also screened to identify additional eligible articles.

Inclusion criteria were: 1) peer-reviewed biomechanical studies using human cadaveric knee specimens; 2) analysis of comparative ALC (ITB and ALL) sectioning studies or comparative (LET and ALLR) ALC reconstruction studies. Biomechanical studies on native ACL, ACL-deficient and ACL-reconstructed knees were included, because these studies are all interrelated in that they can demonstrate, directly or indirectly, the influence on ACL-related knee kinematics.

Studies solely investigating the ITB or ALL, or solely investigating a LET or ALLR (i.e., without direct comparison) were excluded. Articles in languages other than English were excluded. Articles were assessed for methodologic quality according to the Quality Appraisal for Cadaveric Studies (QUACS) scale, a validated 13-item checklist that assesses cadaveric studies for inclusion in systematic reviews.[22]

Data collection

Two authors (D.T.M., W.A.W.) independently extracted, summarized and tabulated the following parameters from eligible studies: number of specimens per experiment; knee specimen status and characteristics; sequential sectioning protocol; kinematic measurements data (the various knee states that measurements were performed upon and the type of kinematic or force measurements performed); ACLR, LET and ALLR surgery characteristics (Tables 1 and 2).

RESULTS

Search results

The initial search yielded 851 records, of which 177 were duplicates that were removed. The titles and abstracts of the remaining 674 articles were screened, and 657 articles were further excluded. After full-text analysis of the remaining 17 records, 2 more articles were excluded. After cross-checking the references of the remaining 15 records, no more records were added, retaining the total of included records to 15 (Figure 1). The data set of these 15 studies represented the mean values of biomechanical data collected from 203 cadaveric specimens, with sample sizes of each experimental group ranging from 10 to 20 specimens.

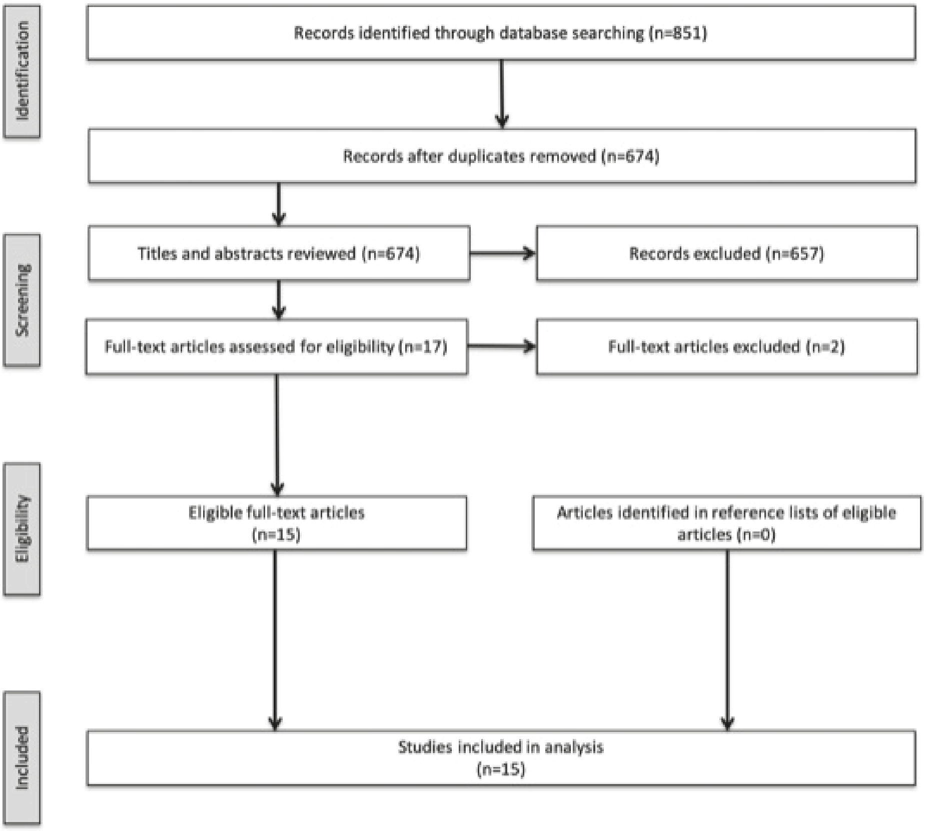

Figure 1. Systematic search flowchart for the systematic review

According to the QUACS scale, 11 articles received methodologic quality ratings of "excellent" (score >80%, mean score 11.4, SD 0.5), and 4 articles scored 77% and were rated as "substantial" (score >60%, mean score 10, SD 0). The QUACS rating degree of agreement between the reviewers (D.T.M., W.A.W.) was 93.3%.

SEQUENTIAL SECTIONING STUDIES

Six studies investigated the influence of sectioning the ITB and ALL on ACL knee kinematics.[23–28] The sectioning protocols, tests performed, and conclusions are reported in Table 1.

ACL-deficient knees

Two studies investigated the influence of sectioning the ITB and ALL on the kinematics of ACL-deficient knees[25,29] and in 2 studies this was investigated in ACL-deficient as well as in ACL intact knees.[23,24]

Two studies compared the effect of IR torque or simulated pivot shift; Noyes et al[25] reported a significant increase in tibial IR, IR during the pivot shift and lateral compartment translation during the pivot shift after section of the ITB at Gerdy's tubercle and no significant differences after section of the ALL; Geeslin et al[29] reported significant increases of IR and of ATT/IR during the pivot shift after sectioning of the Kaplan fibers as well as after sectioning of the ALL.

Sonnery-Cottet et al.[24] reported a significant increase of IR and of ATT/IR during the pivot shift after sectioning of the ALL and after additional ITB sectioning (performed after a longitudinal split of the ITB).

Two studies compared the effect of anterior tibial load; Noyes et al.[25] reported a significant increase in ATT after section of the ITB at Gerdy's tubercle and no significant difference after sectioning of the ALL; Geeslin et al.[29] reported a significant increase in ATT after sectioning of both the proximal and distal Kaplan fibers and a significant increase in ATT after sectioning of the ALL at 30° and 90°. Additional ALL sectioning in the study of Geeslin et al.[29] in ACL-deficient and Kaplan fiber–sectioned states did not significantly increase ATT. However, additional Kaplan fiber sectioning in ACL-deficient and ALL-sectioned state resulted in significantly increased ATT at 90° but not at 30°.[30] Kittl et al.[23] reported a significant increase in ATT after sectioning of sITB at 60° and 90° and after sectioning of dITB at 0°, 30°, 60° and 90°.

ACL intact knees

Two studies investigated the influence of sectioning the ITB and ALL on the kinematics of ACL intact knees[26,27] and in 2 studies this was investigated in ACL intact as well as in ACL-deficient knees.[23,24]

All 3 studies comparing the effect of tibial IR torque reported a significant increase in tibial IR after sectioning the ITB, no significant difference after sectioning the ALL, and no significant additional effect after ALL sectioning concomitant to ITB sectioning in ACL intact knees.[23,26,27] Kittl et al.[23] reported that the superficial ITB (sITB) had a greater effect on IR at high flexion angles, and the deep ITB (dITB) had a greater effect at low flexion angles.

Sonnery-Cottet et al.[24] reported a significant increase in tibial IR after sectioning of the ITB and a significant increase in IR after an additional ALL section (performed after a longitudinal split of the ITB) after transection of the ITB.

With regard to a simulated pivot shift, 2 of the 3 studies reported a significant increase in IR after transection of the sITB[24] or sectioning the sITB or the deep ITB with a significant role of the sITB only at 45° and the dITB at 15°, 30° and 45°,[23] and no significant differences after sectioning the ALL,[23,24] whereas 1 study reported no significant difference after transection of the ITB or after sectioning the ALL.[26] In 2 studies there was no significant additional effect after ALL sectioning concomitant to sectioning the sITB or the deep ITB[23] or transection of the ITB from its attachment site at Gerdy's tubercle,[26] whereas 1 study did report a significant increase after an additional ALL section (performed after a longitudinal split of the ITB) after transection of the ITB.[24]

With regard to ATT, 2 of the 3 studies comparing the effect of anterior tibial load reported no significant difference after transection of the ITB[26] or sectioning the sITB or the deep ITB[23] and no significant difference after sectioning the ALL[23,26], whereas 1 study reported a significant increase in ATT and IR after release of the ITB at Gerdy's tubercle and the distal tibia and no significant difference after sectioning the ALL in ACL intact knees.[27]

Table 1: Characteristics and results of ALC sequential sectioning studies

Authors	n	QS	Dissection protocol	Tests performed	ATT measurements	IR measurements	PS measurements	Conclusion
Kittl et al (2016)	16	85	n = 8: Intact-->sITB*-->dcITB#-->ALL-->Cap	AP (90N) at 0º, 30º, 60º, 90º	NS restraint of all structures except ACL ACL intact group)	sITB restraint at 90º: 56% ± 20% (ACL intact group) / 56% ± 16% (ACLd group)	ITB 72% ± 14% PS restraint (ACLd)	The ALL and anterolateral capsule had a minor role in restraining IR; the ITB was the primary restraint at 30° to 90° and at 30º to 45º in a simulated PS
			n = 8: Intact-->ACL-->sITB-->dcITB-->ALL-->Cap	IR and ER (5nM) at 0º, 30º, 60º, 90º	sITB S restraint at 60º and 90º,dcITB S restraint at 0º and 90º	dcITB restraint at 30º: 26% ± 9% (ACL intact group) / 33% ± 12% (ACLd group)	ALL no significant PS restraint	
				simulated PS (4nM IR, 8nM VALG) at 15º, 30º, 45º		ALL no significant IR restraint		
Sonnery-Cottet et al (2016)	12	92	n=6: Intact-->ACL-->ALL transection after ITB longitudinal split-->ITB (midporting transection)	IR (2nM) at 20º, 90º		*compared to ACL intact knee:*	*compared to ACL intact knee:*	the ACL, ITB, and ALL play a role in rotational control of the knee. The ALL is involved in rotational control of the knee at varying degrees of knee flexion and during a simulated PS. Concomitant to an ACL or ITB transection, sectioning the ALL further increased rotational laxity
				simulated PS at 30º		ALL S↑ IR 19% (20º) / 22% (90º), additional ITB S↑ 42% (20º) / 38% (90º)	ALL S↑ 43%, additional ITB S↑ 94%	
						compared to ACLd knee:	*compared to ACLd knee:*	
						ALL S↑ IR 13% (90º), additional ITB S↑ 30% (20º) / 28% (90º)	ALL S↑ 43%, additional ITB S↑ 78%	

Table 1: Characteristics and results of ALC sequential sectioning studies

Authors	n	QS	Dissection protocol	Tests performed	ATT measurements	IR measurements	PS measurements	Conclusion
			n=6: Intact-->ITB (midportion transection)-->ALL transection after ITB longitudinal split-->ACL			*compared to ITB intact knee:*	*compared to ITB intact knee:*	
						ALL S↑ IR 39% (20º) / 63% (90º), additional ACL S↑ 54% (20º) / 75% (90º)	ALL S↑ 60%, additional ACL S↑ 147%	
						compared to ITB deficient knee:	*compared to ITB deficient knee:*	
						ALL S↑ IR 15% (90º), additional ITB S↑ 23% (90º)	additional ITB S↑ 76%	
Noyes et al (2017)	14	85	n=7: Intact-->ACL-->ALL (limited incision)-->ITB (at Gerdy)	ANT (100N) at 25º, 60º, 90º	ALL after ACL: NS at all flexion angles	ALL after ACL: NS at all flexion angles	ALL after ACL: NS at all flexion angles	The ALL and ITB are not primary restraints to PS anterior subluxation but function together as anterolateral secondary restraints. Concurrent dissection of ALL and ITB in the ACLd knee resulted in a grade 3 PS subluxation and major increase in IR in a majority of knees

Table 1: Characteristics and results of ALC sequential sectioning studies

Authors	n	QS	Dissection protocol	Tests performed	ATT measurements	IR measurements	PS measurements	Conclusion
			n=7: Intact-->ACL-->ITB (at Gerdy)-->ALL (limited incision)	IR (5nM) at 25°, 60°, 90°	ITB after ACL: S↑ at 25° and 60° (highest 2.0mm at 60°)	ITB after ACL: S↑ at all flexion angles (highest 2.5° at 60°)	ITB after ACL: S↑ (1.8mm / 2.0°)	
				simulated PS (1nm IR, 7nM VALG, 100N ANT) at 25°	Both ALL and ITB after ACL: S↑ at all flexion angles	Both ALL and ITB after ACL: S↑ at all flexion angles (highest 5.6° at 60°)	Both ALL and ITB after ACL: S↑ (4.4mm / 5.2°)	
				simulated PS (5nm IR, 7nM VALG, 100N ANT) at 25°	(highest 5.4mm medial and 2.0mm lateral at 60°)			
Huser et al (2017)	19	77	n=10: Intact-->ALL (limited incision)-->ITB lateral tibial tubercle transection	ANT (100N) at 25°, 60°, 90°	ALL after intact: NS at all flexion angles	ALL after intact: NS at all flexion angles	ALL after intact: NS	Sectioning the ALL does not lead to an increase in tibiofemoral compartment subluxations in the PS test with an intact ACL. ALL sectioning alone does not lead to an increase in IR motion limits, however sectioning both the ALL and ITB did produce small increases in rotation limits at higher flexion angles which would likely not be clinically detactable.
			n=9: Intact-->ITB lateral tibial tubercle transection-->ALL (limited incision)	IR (5nM) at 25°, 60°, 90°	ITB after intact: NS at all flexion angles	ITB after intact: S↑ 3.0° (60°) / 2.2° (90°)	ITB after intact: NS	
				simulated PS (1nm IR, 7nM VALG, 100N ANT) at 25°	Both ALL and ITB after intact: NS at all flexion angles	Both ALL and ITB after intact: S↑ 1.7° (25°) / 4.5° (60°) / 3.9° (90°)	Bot ALL and ITB after intact: S↑ IR 2.0°	
				simulated PS (5nm IR, 7nM VALG, 100N ANT) at 25°				

Table 1: Characteristics and results of ALC sequential sectioning studies

Authors	n	QS	Dissection protocol	Tests performed	ATT measurements	IR measurements	PS measurements	Conclusion
Lording et al (2017)	12	77	n=12: Intact-->sITB (release at Gerdy)-->dcITB (at tibia distally)--> n=6: ALL	ANT (200N) at 30°	sITB S↑ 0.7mm, dcITB additional S↑ 0.3mm, ALL additional S↑ 0.2mm	sITB S↑ 2.6°, dcITB additional S↑ 0.8°, ALL additional S↑ 0.6°		While the sequential release of the sITB, dcITB, and ALL caused similar pattern changes in the three investigated tests, the extent of change due to release of the ALL was markedly less than after release of the dcITB which was markedly less than after release of the sITB
				IR and ER (5nM) at 30°				
				VAR and VALG (14nM) at 30°				
Geeslin et al (2018)	18	92	n=9: Intact-->ACL-->ALL (limited incision)-->dcITB^	ANT (88N, 10N AX)) at 30°, 90°	ALL after ACL: S↑ (0.3mm at 30° and 90°)	ALL after ACL: S↑ (15°-90°) (highest 0.5° at 90°)	ALL after ACL: S↑ ATT and IR at 15° (0.4°/0.4mm) and 30° (0.4°/0.5mm)	The ALL and Kaplan fibers restrain IR in the ACLd knee. Sectioning the Kaplan fibers led to greater tibial IR at higher flexion angles (60°-90°) as compared with ALL sectioning.
			n=9: Intact-->ACL-->dcITB^-->ALL (limited incision)	IR (5nM, 10N AX) 0° to 90° at 15° increments	dcITB after ACL: S↑ (0.2mm at 30°, 0.9mm at 90°)	dcITB after ACL: S↑ (15°, 60-90°) (highest 2.2° at 90°)	dcITB after ACL: S↑ ATT at 15°, S↑ IR at 15° (0.4°/0.3mm) and 30° (0.5°/0.6mm)	Additionally, the ALL and Kaplan fibers contribute to restraint of the PS and ATT in the ACLd knee.
				simulated PS (5nM IR, 10nM VALG, 10N AX) at 15°, 30°				

n = amount of specimens;

QS - QUACS scale; IR = internal rotation (directed force); ER = external rotation (directed force); N = Newton; nM = Newton Meter; VALG= valgus directed force; VAR = varus directed force; ITB = Iliotibial Tract; sITB = superficial ITB; dcITB = deep and capsulo-osseous layer of the ITB;

ALL - anterolateral ligament; Cap = whole anterolateral capsule; ACL = anterior cruciate ligament; ACLd = ACL-deficient; ANT = anterior translation; ATT = anterior tibial translation; AX = axial compression force: PS = pivot shift; S = statistically significant; S↑ = significant increase; NS = non-significant

** longitudinal cut sITB, resection biceps femoris complex, resection from sITB off dcITB; # including Kaplan fibers and distal tibial attachment; ^proximal and distal Kaplan fibers*

ITB (at Gerdy): transection of all ITB fibers that insert onto Gerdy tubercle

3

ALC RECONSTRUCTION STUDIES

Nine reconstruction studies compared the influence of LET and ALLR on ACL knee kinematics.[28,30–37] The study protocols, surgical techniques, and tests performed are reported in Table 2. In none of the studies were ACL (graft) force or strain investigated.

ACL-deficient knees

One study compared the effect of LET and ALLR on ACL knee kinematics in ACL-deficient knees.[30] It was reported that after sectioning of the ACL and ALL, ALLR did not significantly reduce internal rotation or anterior translation during a simulated early-phase pivot shift test. After LET, a significant decrease in anterior translation, but not for internal rotation, was found. There was no evidence of overconstraint of the knee with either ALLR or LET.

ACL-reconstructed knees

Eight studies compared the effect of LET and ALLR on ACL knee kinematics in ACL-reconstructed knees.[29,31–37] All 8 studies reported significant residual laxity in ATT[34], tibial IR[29,33], or both ATT and tibial IR[31,32,35-37] after cutting of the anterolateral structures followed by ACLR, compared to the intact knee states.

In 7 studies, a modified Lemaire LET technique was compared to ALLR with well-defined femoral and tibial attachment points. The femoral attachment points were in close range to one another.[29,31-36] In 1 study, a modified Lemaire LET technique was compared to an ALLR with a graft that was continuous with a double strand ACL graft with the tibial attachment point located medial to Gerdy's tubercle.[37] Six studies compared the modified Lemaire LET to an ALLR and reported that both the LET and ALLR techniques significantly reduced the residual internal rotation laxity in ACL-reconstructed knees.[29,33–37] Inderhaug et al.[32] reported that the modified Lemaire LET was able to restore native knee stability and ALLR did not. In another study by Inderhaug et al.[31] ALL restored native knee stability only when tensioned at 0° of flexion, whereas a residual internal rotation laxity persisted when the ALL procedure was tensioned at greater angles of knee flexion.

Smith et al.[34] reported that an ALLR restored native knee stability, whereas the modified Lemaire LET showed a significant increase in ATT compared to the native state. In the study of Neri et al.,[36] both the ALLR and modified Lemaire LET demonstrated a significant increase in ATT compared to the native state, whereas tibial IR was restored to the native state.

Two studies investigated other LET techniques than the modified Lemaire.[32,36] Inderhaug et al.[32] reported that both a modified superficial Lemaire LET technique and a modified Macintosh LET technique were able to restore native knee kinematics. Neri et al.[36] reported that the modified Lemaire, modified superficial Lemaire, modified Ellison, and modified MacIntosh LET techniques restored internal rotation stability, but not anterior tibial translation stability. In their study, overconstraint of IR torque was found after the modified Lemaire, superficial Lemaire and modified MacIntosh tenodesis in the ACL-reconstructed knee, whereas ALLR and the modified Ellison procedure did restore native knee kinematics. [38]

In 3 studies, overconstraint of IR torque[33], IR during pivot shift,[29,37] or ATT during pivot shift[29] was found for both an ALLR and modified Lemaire tenodesis.

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
Spencer et al (2015)	12	85	Intact↓	Fibertape Swivelock anchors (70º)	Modified Lemaire, staple (70º)		ATT: 90				
			ACL AMd↓	F: lateral epicondyle			Pivot shift: 5IR / 10VALG				
			ACLd↓	T: halfway Gerdy - fibular head				Anterior drawer: Si (↑), Sp (↑), Lachman: Si (↑), NSp	Si (↑) (IR)		
			ALL(tibial)-d↓ *-retract ITB anteriorly-*					Anterior drawer: NSp, Lachman: Si (↑), NSp, S ACL AMd (↑)	Sp, ACL AMd (↑) (IR)		
			ALLR↓					Lachman: Si (↑)	NSi, ACL AMd, ACLd, ALLd (IR and ATT)		
			LET					Anterior drawer: Si, ACLd, ALLd, ALLR (↓), Lachman: Si (↑), NSp	S ALLd (↓) (ATT)		
Geeslin et al (2017)	20	92	Intact↓	Semitendinosis (30º or 70º)	Modified Lemaire (30º or 70º) Custom fixation clamp	ATT: 30º and 90º	ATT: 88				

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			ACLd, ALL(tibial)-d, Kaplan(prox+dist)-d ↓ *-posterior ITB incision-*	F: prox and post to FCL (custom fixation clamp)		PS: 15° and 30°	PS: 5IR / 10 VALG		IR during PS - ATT during PS		
			ACLR ↓	T: halfway Gerdy - fibular head (interference screw)		IR: 15° increments 0-90°	IR: 5	NSi in most testing states	Si (↑) in most cases	NSi 15°, 30° / Si (↑) 45°, 60°, 75°, 90°	
			Randomize 30° 70° graft fixation angle								
			ALLR 20N ↓ LET 20N ↓					ALLR: NSi except at 30° with 30° fixation angle	ALLR: Sp (↓), NSi at 15°, Si (↓) at 30° (both flexion angles)	Si, Sp (↓) at nearly all flexion angles	
			remove ALL graft remove LET graft								
			LET 20N ↓ ALL 20N ↓					LET: NSi except at 30° with 30° fixation angle	LET: Si (↓), Sp (↓) at 15° and 30° (both fixation angles)	Si, Sp (↓) at nearly all flexion angles	
									S (↓) for LET at 30° fixation compared to ALLR, NS IR at 70° fixation	S (↓) for LET at 30° fixation compared to ALLR except at 30° flexion angle	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			Remove LET graft remove ALL graft						ATT during PS		
			ALLR 40N					NSi except at 30° with 30° fixation angle	Sp (↓), NSi at 15°, Si (↓) at 30° (both flexion angles)		
Inderhaug et al (2017)	12	85	Intact↓	Gracilis autograft	Modified MacIntosh: 15x150 ITB strip deep to LCL	0° to 90°	ATT: 90				
			ACLd ↓	F: prox and slightly post to lateral epicondyle, interference screw	F: 70mm prox to epicondyle at intramuscular septum (interference screw)		IR: 5	Si (↑)		Si (↑)	Si (↑)
			ALL (femoral to tibial)-d, capsule (femoral to tibial)-d, Kaplan (prox + dist)-d ↓ *-ITB split-*	T: halfway Gerdy - fibular head (suture anchor)				Si (↑)		Si (↑)	Si (↑)
			ACLR ↓		Modified Lemaire			Si (↑) 0° to 60°		Si (↑) 0° to 40° and 70° to 90°	Si (↑) 0° to 70°

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			ALLR ↓ (ranodomized) 20N and 40N)		F: prox and slightly post to lateral epicondyle (interference screw)			20N: Si (↑) 0° to 70°		20N: Si (↑) at all flexion angles | 40N: Si (↑) at 0° and 30°	
			Modified MacIntosh ↓ (randomized) 20N and 40N					40N: overconstraint at 80°		20N: NSi at all flexion angles | 40N: NSi at all flexion angles	
			Modified Lemaire ↓ (randomized) 20N and 40N		Modified superficial Lemaire (as deep Lemaire with graft over the FCL)			20N: Si (↑) at 0° and 70°, NSi at any other angle		20N: NSi at all flexion angles | 40N: NSi at all flexion angles	
			Modified superficial Lemaire (randomized) 20N and 40N					20N: Si (↑) at 0° and 70°, NSi at any other angle | 40N: overconstraint 70° to 90°		20N: overconstraint at 10°, 40° and 50° | 40N: overconstraint at 10°, 40° and 50°	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
Inderhaug et al (2017)	12	85	Intact↓	2-strand gracilis autograft inverted V (0° or 30° or 60º)	Modified Lemaire (0° or 30° or 60º)	0° to 90°	ATT: 90				
			ACLd ↓	F: 8mm prox and 5mm post to lateral epicondyle (interference screw)	F: 8mm prox and 5mm post to lateral epicondyle		IR: 5	Si (↑)		Si (↑)	Si (↑)
			ALL (femoral to tibial)-d, capsule (femoral to tibial)-d, Kaplan (prox + dist)-d ↓ *-ITB split-*	T: 2 tibial tunnels between Gerdy and fibular head (interference screw)	interference screw		ATT: 90 + IR 5	Si (↑)		Si (↑)	Si (↑)
			ACLR ↓					Si (↑)		Si (↑)	Si (↑)
			ALLR (randomized)					NSi at all fixation angles		NSp, NSi with 0º fixation angle, Si (↑) at 20º and 50º-70º with 30º fixation angle, at 60º-90º with 60º fixation angle	NSi at al fixation angles

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			LET (randomized)					NSi at all fixation angles		Sp (↓), NSi with al fixation angles	NSi at al fixation angles
Jette et al (2019)	12	85	Intact↓	Gracilis autograft folded in 2 (0°)	Modified Lemaire (0°)	0°, 30°, 60°, 90°	ATT: 90				
			ACLd↓	F: prox and post to lateral epicondyle and FCL (interference screw)	F: prox and post to lateral epicondyle and FCL (interference screw)		IR: 7	Si (↑) at all flexion angles		NSi, except at 30°	
			ALL (tibial)-d, Kaplan (prox+dist)-d ↓ *-posterior ITB incision-*	T: halfway Gerdy - fibular head (interference screw)				Si (↑) at all flexion angles		Si (↑), Sp (↑)	
			ACLR ↓					Nsi at all flexion angles		Si (↑)	
			ALLR ↓ LET ↓					ALLR: NSi, NSp at all flexion angles LET: NSi, NSp at all flexion angles		ALLR AND LET: NSi at 0° and 30°, Si (↓) at 60° and 90° (overconstraint)	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			remove ALL remove LET								
			LET ALL					ALLR: NSi, NSp at all flexion angles LET: NSi, NSp at all flexion angles		ALLR AND LET: NSi at 0° and 30°, Si (↓) at 60° and 90° (overconstraint)	
Smith et al (2019)	12	85	Intact↓	Allograft Biocomposite Swivelocks (0°)	Modified Lemaire 70, staple, looped back underneath FCL and sutured back to itself	0°, 30°, 90°	PS: 100 ANT / 5IR / 10 VALG				
			ACLd↓	F: lateral gastrocnemius tubercle dist to the lateral intermuscular septum					ATT during PS		
			Kaplan (prox+dist)-d ↓ ALL (tibial)-d, capsule (femoral)-d ↓ -*ITB split-*	T: halfway Gerdy - fibular head					ITBd: Si (↑), ALLd: Si (↑), ITBd S compared to ALLd (↑)	ITBd: Si (↑) at 0° and 90°, ALLd: Si (↑) at 0°, ITBd S (↑) compared to ALLd at 0°	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			ALL (tibial)-d, capsule (femoral)-d ↓ Kaplan (prox+dist)-d ↓ *-ITB split-*								
			ACLR ↓						Si (↑) at 0° and 30°	NSi	
			ALR LET						ALR: NSi, LET: Si (↑) at 30° and 90°, NS ALLR compared to LET	ALR: NSi, LET: NSi, NS ALLR compared to LET	
Delaloye (2020)	12	92	Intact↓	2-strand gracilis autograft inverted V (0°)	Modified Lemaire (70°)	15° increments 0° - 90°	ATT: 134				
			ACLd↓	F: slightly prox and post to lateral epicondyle (interference screw)	F: slightly prox and post to lateral epicondyle		IR: 5	Si (↑) (whole range of motion comparison)		Si (↑) (whole range of motion comparison)	
			ALL (femoral)-d, Kaplan-d ↓ *-ITB split-*	T: tibial tunnels between Gerdy and fibular head 1cm below joint line	interference screw			Sp (↑), Si (↑) (whole range of motion comparison)		Sp (↑), Si (↑) (whole range of motion comparison)	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			ACLR ↓					Si (↑) (whole range of motion comparison)		Si (↑) (whole range of motion comparison)	
			ALL LET					ALLR: NSi (whole range of motion comparison) LET: NSi (whole range of motion comparison)		ALLR: NSi (whole range of motion comparison) LET: NSi (whole range of motion comparison)	
Neri (2020)	10 77		Intact↓	Free gracilis graft (30º)	All reconstructions (30º)	ATT: 30° and 90°	ATT: 90				
			ACLd↓	F: 5mm prox and 5mm post to lateral epicondyle (interference screw)	Modified Ellison modified by Devitt et al	IR: 0° to 90°	IR: 5	Si (↑)		Si (↑)	
			ALL (femoral)-d, capsule (femoral)-d, Kaplan (prox+dist)-d ↓ *-retract ITB anteriorly-*	T: halfway Gerdy - fibular head 1cm below joint line (interference screw)	Modified Lemaire 5mm prox and 5mm post to lateral epicondyle (interference screw)			Sp (↑), Si (↑)		Sp (↑), Si (↑)	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
			ACLR ↓		Modified superficial Lemaire (as deep Lemaire with graft over the FCL			Si (↑) at 30°, NSi at 90°		Si (↑)	
			ALLR 20N ↓		Modified MacIntosh			Si (↑) at 30° and 90°, NSp at 30° and 90°		NSi at 0° - 90°	
			Modified Ellison 20N ↓					Si (↑) at 30° and 90°, NSp at 30° and 90°		NSi at 0° - 45°, Si (↑) > 45°	
			Modified Lemaire 20N ↓ (randomized)					Si (↑) at 30° and 90°, NSp at 30° and 90°		overconstraint	
			Modified superficial Lemaire 20N ↓ (randomized)					Si (↑) at 30° and 90°, NSp at 30°, Sp (↓) at 90°		overconstraint	
			Modified MacIntosh 20N (randomized)					Si (↑) at 30° and 90°, NSp at 30° and 90°		overconstraint	

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
Xu (2021)	10	77	Intact↓	single strand graft continuous with double strand ACL graft (0°)	Modified Lemaire (70°), interference screw	ATT: 0°, 30°, 60°, 90°	ATT: 90		IR during PS - ATT during PS		
			ACLd, ALL (femoral)-d, capsule (femoral)-d, Kaplan (dist)-d ↓	F: 5mm post to lateral epicondyle	F: 5mm post to lateral epicondyle	IR: 0°, 30°, 60°, 90°	IR: 5	Si (↑) at all flexion angles	Si (↑) at 0°, 15°, 30° and 45°	Si (↑) at 30°, 60° and 90°	
			ACLR ↓	T: just medial to Gerdy (tied over button)		PS: 0°, 15°, 30°, 45°	PS: 100 ANT / 5IR / 10 VALG	Si (↑) at 30°, 60° and 90°	Si (↑) at 0°, 15°, 30° and 45°	Si (↑) at 30°, 60° and 90°	
			ALLR 20N LET 20N					ALLR: Sp (↓) at 60°, NSi at all flexion angles	ALLR: Sp (↓) at 0°, 15°, 30° and 45°, NSi at 0°, 15° and 30° for IR and 45° ATT	ALLR: Sp (↓) at 0°, 30°, 60° and 90°, overconstraint compared to intact knee at 60° and 90°	

3

Table 2: Characteristics and outcomes of ALC reconstruction studies

Authors	n	QS	Study protocol	ALLR technique (fixation angle)	LET technique (fixation angle)	Flexion angle	Loading conditions (N / Nm)	ATT	PS	IR measurements (degrees)	ATT and IR
								LET: Sp (↓) at 30° and 60°	LET: Sp (↓) at 15°, 30° and 45°, overconstraint compared to intact knee at 30° and 45°	LET: Sp (↓) at 0°, 30°, 60° and 90°, overconstraint compared to intact knee at 30°, 60° and 90°	

ACL = anterior cruciate ligament; ACL AMd = ACL anteromedial bundle deficient; ACLd = ACL-deficient; ACLR = ACL reconstruction; ALL = anterolateral ligament; ALLd = ALL deficient; ALLR = ALL reconstruction; ANT = anterior translation; ATT = anterior tibial translation;
d = deficient; dist = distal; FCL = fibular collateral ligament; F = femoral; IR = internal rotation (directed force); ITB = Iliotibial Tract; LET = lateral extra-articular tenodesis;
n = amount of specimens; N = Newton; nM = Newton Meter; PS = pivot shift; prox = proximal; post = posterior; QS = QUACS scale;
S = statistically significant compared to; Si = statistically significant compared to intact knee state; Sp = statistically significant compared to previous knee state; T = tibial; VALG= valgus directed force

DISCUSSION

The most important finding of this systematic review was that the majority of sectioning studies found that the ITB acts as a secondary stabilizer to the ACL and helps to resist both IR and IR during the pivot shift. Most sectioning studies reported no secondary stabilizing effect of the ALL in resisting IR and IR during the pivot shift. This is in contrary to our first hypothesis that both the ITB and ALL act as a secondary stabilizer to the ACL. The second most important finding was that, in agreement with our second hypothesis, in the majority of studies a modified Lemaire LET and an ALLR could significantly reduce the residual ALRI in isolated ACL-reconstructed knees and were able to improve IR laxity[29,33–37]/IR laxity during the pivot shift.[29,37]

In the sectioning studies of Huser et al.[26] they found no effect on the pivot shift after individual sectioning of the ITB in ACL intact knees, in contrast to Kittl et al.[23] and Sonnery-Cottet et al.[24] A possible explanation is that in the study of Huser et al[27] an anterior load was added during pivot shift loading, minimizing the function of the ACL, as compared to no anterior loading in the study of Kittl et al.[23] and to a manual performed pivot shift in the study of Sonnery-Cottet et al.[24] Furthermore, Sonnery-Cottet et al.[24] reported a significant increase in tibial IR and of ATT/IR during the pivot shift in ACL intact knees after additional ALL sectioning concomitant to ITB sectioning, whereas Kittl et al.[23] and Huser et al.[26] found no significant additional effects. A possible explanation is that in the study of Sonnery-Cottet et al.[24] the pivot shift loadings were performed manually, while in the study of Kittl et al.[23] and in the study of Huser et al.[26] a 6 degrees of freedom robotic system was used.

Geeslin et al.[29] found a significant contribution of both the ITB and the ALL on ATT, IR and ATT/IR during pivot shift in ACL-deficient knees, whereas Noyes et al.[25] found a significant increase in ATT, tibial IR, IR during pivot shift and lateral compartment translation during pivot after section of the ITB and no significant differences after section of the ALL. A possible explanation for this difference is that in the study of Noyes et al.,[25] the ITB was completely released off Gerdy's tubercle, potentially limiting the clinical relevance of this scenario, as compared to sectioning of the proximal and distal Kaplan fibers in the study of Geeslin et al.[29]

There were conflicting results of the effect of anterior tibial load after ITB sectioning in ACL intact knees; although Kittl et al.[23] and Huser et al.[26] found no effect, Lording et al.[27] did find a significant increase in ATT. A possible explanation is that in the study of Lording et al.[27] a load of 200 Newtons was applied compared to a load of 100 Newtons in the other 2 studies.[23,26]

Most sectioning studies in this systematic review found no secondary stabilizing effect of the ALL, in contrast to our first hypothesis. In another recently published systematic review on the biomechanical function of the ALL in which 12 biomechanical studies were included, 5 studies reported a minor increase or no significant increase in anterior tibial translation and internal tibial rotation with further sectioning of the ALL in ACL-deficient knees; 5 studies

reported a significant increase in knee laxity in tibial internal rotation or pivot shift with addition of sectioning the ALL in ACL-deficient knees; and 2 studies reported a significant increase in both anterior tibial translation and internal tibial rotation during application of the anterior-drawer and pivot-shift tests after ALL sectioning. The main reason for the inconsistencies in the biomechanical characteristics of the ALL, the differences in magnitude of torque applied, and the position of the knees for simulating Lachman and pivot shift tests were mentioned,[38] as is the case in the current review. However, because universal protocols to simulate the pivot shift and anterior drawer tests of the knee are lacking, such inconsistencies may be inevitable.

In the 6 studies comparing the effect of a modified Lemaire tenodesis to an ALLR in ACL-reconstructed knees, the residual IR laxity during pivot shift could be restored with both procedures. A possible explanation for these similar results is that the same or almost same femoral attachment points were used in both techniques.[29,33–37] Furthermore, in the studies mentioning the tension that was used during fixation of the graft, this was the same for both techniques.[29,35-37] In the studies of Inderhaug et al.[31,32] the modified Lemaire procedure was able to restore native knee laxity, whereas an ALLR was not when tensioned at an angle of fixation of 30°[32] or was only when tensioned at 0° of flexion.[31] The differences in angle of fixation possibly explain the differences in outcome.

Spencer et al.[30] compared the effect of a modified Lemaire tenodesis and ALLR on ACL knee kinematics in ACL-deficient knees and reported that ALLR did not improve ALRI. However, studying the effect of ALLR without subsequent ACLR makes this difficult to interpret.

In 3 studies overconstraint of IR torque[33], IR during pivot shift,[29,37] or ATT during pivot shift[29] was found for both ALLR and modified Lemaire tenodesis, and in one overconstraint of IR torque was found for modified Lemaire, superficial Lemaire and modified MacIntosh tenodesis.[36] Clinical studies with long-term follow-up are needed to determine whether overconstraint causes the ALC reconstruction grafts to elongate or if overconstraint may contribute to the development of early osteoarthritis, although a recent systematic review revealed no clinical evidence to support this.[39]

In this systematic review on comparative biomechanical studies, we found that the ITB acts as a secondary stabilizer to the ACL whereas the ALL seems to contribute to a lesser extent. A possible explanation for this finding is that the ALL acts synergistic to the ITB in resisting tibial internal rotation. Furthermore, we found that a reconstruction with either a graft fixated both at the femur and tibia, or with an ITB strip fixed at the femur, both resulted in significantly reduced residual ALRI in isolated ACL-reconstructed knees. We therefore suggest to refer to both these reconstructions as anterolateral corner reconstructions instead of denominating them separately, as they both have the same biomechanical effect.

Limitations

The low sample sizes and the large variations in specimen characteristics, sectioning protocols, kinematic testing systems, and surgical procedures performed among the studies made it not possible to perform a meta-analysis. Furthermore, a systematic review on biomechanical cadaver studies has inevitable limitations, many of which are inherent to in vitro testing. In general, the number of specimens tested was small and the mean specimen age was above the typical age for patients sustaining ACL and ALC injury. In many studies, muscle loads and axial compression were not applied, making it harder to extrapolate the results to physiologic conditions. Furthermore, all reported biomechanical findings are only valid at time zero because the biological effects of tissue healing could not be accounted for in these studies. The injury locations in a clinical setting might be different from the sectioning locations and in some studies a worst-case scenario was presented because all ALC structures were cut which is not comparable to a clinical injury. Multiple biomechanical testing methods were used ranging from clinical pivot shift testing, custom made knee testing systems, biaxial materials testing machines providing 3 degrees of freedom, and robotic arms providing 6 degrees of freedom, potentially influencing the differences between study results. It is possible that relevant articles were not identified through the literature search and that studies published after the performed search were not included.

CONCLUSION

The ITB acts as the main secondary stabilizer to the ACL in resisting IR/IR during pivot shift, and an anterolateral corner reconstruction with either a modified Lemaire tenodesis or ALLR can improve residual knee rotatory laxity in ACL-reconstructed knees.

REFERENCES

1. Barber-Westin S, Noyes FR. **One in 5 Athletes Sustain Reinjury Upon Return to High-Risk Sports After ACL Reconstruction: A Systematic Review in 1239 Athletes Younger Than 20 Years**. *Sports Health Multidiscip Approach*. 2020;12(6):587-597. doi:10.1177/1941738120912846
2. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
3. Group MK, Spindler KP, Huston LJ, et al. **Anterior Cruciate Ligament Reconstruction in High School and College-Aged Athletes: Does Autograft Choice Influence Anterior Cruciate Ligament Revision Rates**? *Am J Sports Med*. 2019;48(2):298-309. doi:10.1177/0363546519892991
4. Group TM, Cooper DE, Dunn WR, et al. **Physiologic Preoperative Knee Hyperextension Is a Predictor of Failure in an Anterior Cruciate Ligament Revision Cohort: A Report From the MARS Group**. *Am J Sports Med*. 2018;46(12):2836-2841. doi:10.1177/0363546518777732
5. Kaeding CC, Pedroza AD, Reinke EK, et al. **Risk Factors and Predictors of Subsequent ACL Injury in Either Knee After ACL Reconstruction**. *Am J Sports Med*. 2015;43(7):1583-1590. doi:10.1177/0363546515578836
6. Vermeijden HD, Yang XA, van der List JP, DiFelice GS, Rademakers MV, Kerkhoffs GMMJ. **Trauma and femoral tunnel position are the most common failure modes of anterior cruciate ligament reconstruction: a systematic review**. *Knee Surg Sports Traumatol Arthrosc*. 2020;28(11):3666-3675. doi:10.1007/s00167-020-06160-9
7. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **Meniscal Tears, Posterolateral and Posteromedial Corner injuries, Increased Coronal Plane and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament-Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**. *Arthroscopy*. 2021;38(5):1664-1688.e1. doi:10.1016/j.arthro.2021.11.044
8. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J. **Anatomy of the anterolateral ligament of the knee**. *J Anat*. 2013;223(4):321-328. doi:10.1111/joa.12087
9. P. S. **Recherches Cliniques et Experimentales Sur Les Epanchements Sanguins Du Genou Par Entorse**. . ; 1879.
10. Terry GC, Norwood LA, Hughston JC, Caldwell KM. **How iliotibial tract injuries of the knee combine with acute anterior cruciate ligament tears to influence abnormal anterior tibial displacement**. *Am J Sports Med*. 1993;21(1):55-60. doi:10.1177/036354659302100110
11. Monaco E, Ferretti A, Labianca L, et al. **Navigated knee kinematics after cutting of the ACL and its secondary restraint**. *Knee Surg Sports Traumatology Arthrosc*. 2012;20(5):870-877. doi:10.1007/s00167-011-1640-8
12. Wroble RR, Grood ES, Cummings JS, Henderson JM, Noyes FR. **The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee**. *Am J Sports Med*. 1993;21(2):257-263. doi:10.1177/036354659302100216
13. Ristanis S, Stergiou N, Patras K, Tsepis E, Moraiti C, Georgoulis AD. **Follow-up Evaluation 2 Years After ACL Reconstruction With Bone–Patellar Tendon–Bone Graft Shows That Excessive Tibial Rotation Persists**. *Clin J Sport Med*. 2006;16(2):111. doi:10.1097/00042752-200603000-00005
14. Lie DTT, Bull AMJ, Amis AA. **Persistence of the Mini Pivot Shift after Anatomically Placed Anterior Cruciate Ligament Reconstruction**. *Clin Orthop Relat R*. 2007;457(NA;):203-209. doi:10.1097/blo.0b013e3180314b01

15. Georgoulis AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N. **Tibial Rotation is Not Restored after ACL Reconstruction with a Hamstring Graft**. *Clin Orthop Relat Res*. 2007;454(NA;):89-94. doi:10.1097/blo.0b013e31802b4a0a
16. Logan MC, Williams A, Lavelle J, Gedroyc W, Freeman M. **Tibiofemoral Kinematics following Successful Anterior Cruciate Ligament Reconstruction Using Dynamic Multiple Resonance Imaging**. *Am J Sports Med*. 2004;32(4):984-992. doi:10.1177/0363546503261702
17. Mannel H, Marin F, Claes L, Dürselen L. **Anterior cruciate ligament rupture translates the axes of motion within the knee**. *Clin Biomech*. 2004;19(2):130-135. doi:10.1016/j.clinbiomech.2003.11.007
18. Lipke JM, Janecki CJ, Nelson CL, et al. **The role of incompetence of the anterior cruciate and lateral ligaments in anterolateral and anteromedial instability. A biomechanical study of cadaver knees**. *J Bone Joint Surg*. 1981;63(6):954-960. doi:10.2106/00004623-198163060-00013
19. Hughston JC, Andrews JR, Cross MJ, Moschi A. **Classification of knee ligament instabilities. Part II. The lateral compartment**. *J Bone Joint Surg Am*. 1976;58(2):173-179.
20. Yamamoto Y, Hsu W, Fisk JA, Scyoc AHV, Miura K, Woo SL. **Effect of the iliotibial band on knee biomechanics during a simulated pivot shift test**. *J Orthopaed Res*. 2006;24(5):967-973. doi:10.1002/jor.20122
21. Geeslin AG, Chahla J, LaPrade RF. **Combined Anterior Cruciate Ligament and Lateral Extra-Articular Reconstruction**. *Arthroscopy*. 2022;38(9):2600-2601. doi:10.1016/j.arthro.2022.07.001
22. Wilke J, Krause F, Niederer D, et al. **Appraising the methodological quality of cadaveric studies: validation of the QUACS scale**. *J Anat*. 2015;226(5):440-446. doi:10.1111/joa.12292
23. Kittl C, El-Daou H, Athwal KK, et al. **The Role of the Anterolateral Structures and the ACL in Controlling Laxity of the Intact and ACL-Deficient Knee**. *Am J Sports Med*. 2016;44(2):345-354. doi:10.1177/0363546515614312
24. Sonnery-Cottet B, Lutz C, Daggett M, et al. **The Involvement of the Anterolateral Ligament in Rotational Control of the Knee**. *Am J Sports Med*. 2016;44(5):1209-1214. doi:10.1177/0363546515625282
25. Noyes FR, Huser LE, Levy MS. **Rotational Knee Instability in ACL-Deficient Knees**. *J Bone Joint Surg*. 2017;99(4):305-314. doi:10.2106/jbjs.16.00199
26. Huser LE, Noyes FR, Jurgensmeier D, Levy MS. **Anterolateral Ligament and Iliotibial Band Control of Rotational Stability in the Anterior Cruciate Ligament–Intact Knee: Defined by Tibiofemoral Compartment Translations and Rotations**. *Arthroscopy*. 2017;33(3):595-604. doi:10.1016/j.arthro.2016.08.034
27. Lording T, Stinton SK, Neyret P, Branch TP. **Diagnostic findings caused by cutting of the iliotibial tract and anterolateral ligament in an ACL intact knee using a standardized and automated clinical knee examination**. *Knee Surg Sports Traumatology Arthrosc*. 2017;25(4):1161-1169. doi:10.1007/s00167-017-4499-5
28. Geeslin AG, Chahla J, Moatshe G, et al. **Anterolateral Knee Extra-articular Stabilizers: A Robotic Sectioning Study of the Anterolateral Ligament and Distal Iliotibial Band Kaplan Fibers**. *Am J Sports Med*. 2018;46(6):1352-1361. doi:10.1177/0363546518759053
29. Geeslin AG, Moatshe G, Chahla J, et al. **Anterolateral Knee Extra-articular Stabilizers: A Robotic Study Comparing Anterolateral Ligament Reconstruction and Modified Lemaire Lateral Extra-articular Tenodesis**. *Am J Sports Med*. 2018;46(3):607-616. doi:10.1177/0363546517745268
30. Spencer L, Burkhart TA, Tran MN, et al. **Biomechanical Analysis of Simulated Clinical Testing and Reconstruction of the Anterolateral Ligament of the Knee**. *Orthop J Sports Med*. 2016;4(2_suppl):2325967116S00027. doi:10.1177/2325967116s00027

31. Inderhaug E, Stephen JM, Williams A, Amis AA. **Anterolateral Tenodesis or Anterolateral Ligament Complex Reconstruction: Effect of Flexion Angle at Graft Fixation When Combined With ACL Reconstruction**. *Am J Sports Med*. 2017;45(13):3089-3097. doi:10.1177/0363546517724422
32. Inderhaug E, Stephen JM, Williams A, Amis AA. **Biomechanical Comparison of Anterolateral Procedures Combined With Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2017;45(2):347-354. doi:10.1177/0363546516681555
33. Jette C, Gutierrez D, Sastre S, Llusa M, Combalia A. **Biomechanical comparison of anterolateral ligament anatomical reconstruction with a semi-anatomical lateral extra-articular tenodesis. A cadaveric study**. *Knee*. 2019;26(5):1003-1009. doi:10.1016/j.knee.2019.07.005
34. Smith PA, Thomas DM, Pomajzl RJ, Bley JA, Pfeiffer FM, Cook JL. **A Biomechanical Study of the Role of the Anterolateral Ligament and the Deep Iliotibial Band for Control of a Simulated Pivot Shift With Comparison of Minimally Invasive Extra-articular Anterolateral Tendon Graft Reconstruction Versus Modified Lemaire Reconstruction After Anterior Cruciate Ligament Reconstruction**. *Arthroscopy*. 2019;35(5):1473-1483. doi:10.1016/j.arthro.2018.11.011
35. Delaloye JR, Hartog C, Blatter S, et al. **Anterolateral Ligament Reconstruction and Modified Lemaire Lateral Extra-Articular Tenodesis Similarly Improve Knee Stability After Anterior Cruciate Ligament Reconstruction: A Biomechanical Study**. *Arthroscopy*. 2020;36(7):1942-1950. doi:10.1016/j.arthro.2020.03.027
36. Neri T, Dabirrahmani D, Beach A, et al. **Different anterolateral procedures have variable impact on knee kinematics and stability when performed in combination with anterior cruciate ligament reconstruction**. *J Isakos Joint Disord Orthop Sports Med*. 2021;6(2):74-81. doi:10.1136/jisakos-2019-000360
37. Xu J, Han K, Lee TQ, et al. **Anterolateral Structure Reconstruction Similarly Improves the Stability and Causes Less Overconstraint in Anterior Cruciate Ligament-Reconstructed Knees Compared With Modified Lemaire Lateral Extra-articular Tenodesis: A Biomechanical Study**. *Arthroscopy*. 2022;38(3):911-924. doi:10.1016/j.arthro.2021.06.023
38. Lee JK, Seo YJ, Jeong SY, Yang JH. **Biomechanical function of the anterolateral ligament of the knee: a systematic review**. *Knee Surg Relat Res*. 2020;32(1):6. doi:10.1186/s43019-019-0021-3
39. Devitt BM, Bouguennec N, Barfod KW, Porter T, Webster KE, Feller JA. **Combined anterior cruciate ligament reconstruction and lateral extra-articular tenodesis does not result in an increased rate of osteoarthritis: a systematic review and best evidence synthesis**. *Knee Surg Sports Traumatology Arthrosc*. 2017;25(4):1149-1160. doi:10.1007/s00167-017-4510-1

APPENDIX

Pubmed search

Filters: January 1, 2010 – October 1, 2022; English; human

(“Biomechanical Phenomena”[MeSH Terms] OR “biomechanical phenomena*”[Title/Abstract] OR “biomechanics”[Title/Abstract] OR “kinematic*”[Title/Abstract] OR “biomechanic phenomena*”[Title/Abstract] OR “biomechanical”[Title/Abstract] OR “biomechanically”[Title/Abstract] OR “laboratory study”[Title/Abstract]) AND (“Knee”[MeSH Terms] OR “Knee”[Title/Abstract]) AND (“Anterior Cruciate Ligament Injuries”[MeSH Terms] OR “acl injuries”[Title/Abstract] OR “acl injury”[Title/Abstract] OR “acl tear*”[Title/Abstract] OR “anterior cruciate ligament injury”[Title/Abstract] OR “anterior cruciate ligament tear”[Title/Abstract] OR “Anterior Cruciate Ligament”[MeSH Terms] OR “ACL”[Title/Abstract] OR “anterior cruciate ligament*”[Title/Abstract]) AND (“Cadaver”[MeSH Terms] OR “Cadaver”[Title/Abstract] OR “cadaveric”[Title/Abstract] OR “cadavera”[Title/Abstract])

Embase search

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chapter 4

Lateral Meniscus Posterior Root Repair with Lateral Extra-articular Tenodesis Significantly Decreased Internal Rotation and Pivot Shift Loading in a Cadaveric Study of Anterior Cruciate Ligament Reconstructed Knees.

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ABSTRACT

Purpose

To determine the biomechanical effects of lateral meniscus posterior root (LMPR) and Kaplan fiber tears in anterior cruciate ligament (ACL)-deficient knees and assess the impact of LMPR repair, modified Lemaire lateral extra-articular tenodesis (LET), or both, after ACL reconstruction (ACLR).

Methods

Ten paired cadaveric knees were randomized into four groups and mounted in a six degrees of freedom robotic system. The ACL, LMPR, and Kaplan fibers were sequentially sectioned in random order. After ACLR, LMPR repair and Lemaire were performed in random order. Tibial displacements and rotations were measured under internal rotation (IR) torque and a simulated pivot shift at 0°–90° knee flexion.

Results

ACLR alone did not fully restore stability, with significant residual increases in isolated IR between 15 and 90° (all $p<0.001$), coupled IR at all flexion angles (all $p<0.01$), coupled anterior tibial translation (ATT) between 0 and 45°, (all $p<0.05$), and coupled valgus rotation between 15 and 90° (all $p<0.003$) during pivot shift. Adding Lemaire to ACLR, without or with LMPR repair, restored stability comparable to the intact knee for isolated IR (without, all $p>0.086$, with, all $p>0.132$), coupled IR (without, all $p>0.102$, with, all $p>0.172$, and coupled ATT (without, all $p>0.537$, with, $p>0.872$) during pivot shift. LMPR repair in ACLR with Kaplan fiber injury restored valgus rotation stability at most flexion angles (all $p>0.053$).

Conclusion

Both the LMPR and Kaplan fibers act as secondary stabilizers to IR and pivot shift loading in the ACL-deficient knee, with an additive biomechanical effect of the Kaplan fibers to the ACL with LMPR deficient knee for isolated IR and for coupled IR and ATT during pivot shift. Furthermore, the most important reconstruction state which best restored stability comparable to the ACL intact state was the addition of lateral extra-articular tenodesis to either the ACLR alone or ACLR with LMPR repair state, except for valgus rotation during pivot shift, where LMPR repair contributes most.

Clinical Relevance

Both LMPR repair and anterolateral corner reconstruction are necessary to restore stability in knees with ACL, Kaplan fiber, and LMPR injuries.

INTRODUCTION

Knee anterolateral rotatory instability (ALRI) may persist after isolated anterior cruciate ligament (ACL) reconstruction (ACLR).[1] Identifying and treating concomitant pathologies contributing to residual ALRI is essential to restore knee kinematics and prevent ACLR graft overload or failure.[2]

Lateral meniscus posterior root (LMPR) tears occur in 6.6–16% of patients with ACL injuries.[3–7] Biomechanical studies have shown increased anterior tibial translation (ATT) during pivot shift maneuvers[8,9] and isolated internal rotation (IR)[9,10] after LMPR tears in ACL-deficient knees compared to knees with intact LMPR.[8,9] One study found reduced IR after LMPR repair in ACL-deficient knees compared to unaddressed LMPR tears.[10] Another study reported increased ATT—but no difference in coupled ATT during pivot shift—between LMPR tear and LMPR repair states in ACL-reconstructed knees.[11]

Anterolateral corner injuries frequently accompany ACL tears. There is conflicting evidence on the incidence of associated injury to the anterolateral ligament (ALL) and Kaplan fibers. While some magnetic resonance imaging studies reported a higher incidence of (partial) Kaplan fiber injury,[12,13] other magnetic resonance imaging studies reported a higher incidence of (partial) ALL injury.[14–17] Reported incidence of injury were 21% to 60% for Kaplan fibers and 21 to 71% for ALL.[12–17] In a systematic review investigating the incidence of ALL injury accompanying ACL injury in magnetic resonance imaging and ultrasound studies, the reported incidence ranged from 10.8 to 62.5%.[18] An open exploration study reported 93% incidence of Kaplan fiber injury during ACLR.[19] Biomechanical data show increased IR and coupled ATT and IR during pivot shift testing after Kaplan fiber sectioning in ACL-deficient knees.[20] Kaplan fibers were identified as the primary IR restraint at >30° knee flexion.[21] A systematic review reported that modified Lemaire lateral extra-articular tenodesis (LET) significantly reduces residual ALRI and improves IR laxity and pivot shift kinematics in most biomechanical studies.[22]

Although the contributions of the ACL, anterolateral structures, LMPR[23], and Kaplan fibers[21] to knee stability have been examined, limited data exist on the biomechanical effects of LMPR repair and/or LET in ACLR knees with LMPR or Kaplan fiber injury. The purpose of this study was to determine the biomechanical effects of LMPR and Kaplan fiber tears in ACL-deficient knees and to assess the impact of LMPR repair, modified Lemaire LET, or both, after ACLR.

We hypothesized that both LMPR and Kaplan fibers serve as secondary stabilizers to IR and pivot shift in ACL-deficient knees and that their combined injury has additive biomechanical effects. We further hypothesized that both LMPR repair and modified Lemaire LET are necessary to restore knee kinematics comparable to the intact state.

METHODS

No institutional review board approval was required for this laboratory investigation, as de-identified cadaveric knee specimens were used. The specimens were obtained from a tissue bank (University of Minnesota) and donated for medical research. Ten paired (n=20; 7 male/3 female pairs) cadaveric knees were used (mean age 69.9 years, range 58–82 years).

Specimen Preparation

Knees with prior injury, surgery, gross anatomic abnormality, or degeneration were excluded. Specimens were stored at –20°C and thawed for 24 hours at room temperature. The femoral and tibial diaphyses were cut 20 cm from the joint line. The skin was removed, soft tissues within 10 cm of the joint line were preserved, and the rest was removed to allow potting in polymethyl methacrylate.

Robotic Testing

Specimens were mounted to a 6 degrees-of-freedom robotic arm (KUKA KR300, KUKA Robotics), fitted with a universal force-torque sensor (Delta F/T, ATI Industrial Automation; measurement error, 0.25 N and 0.05 Nm), one attached to the end effector of a 6 degrees of freedom robotic arm (Kuka KR-300 Ultra 2500; Kuka Robotics) and the other attached to a stationary base (Figure 1). A 5 Nm internal rotation (IR) torque was applied at 15° increments from 0° to 90° flexion. A simulated pivot shift was performed by applying combined 5 Nm IR torque, 5 Nm valgus torque, and 90 N of ATT, also at 15° increments.[24] During all tests, a 50 N compressive load was applied to the tibia to maintain tibiofemoral contact. Flexion angle was fixed, while the other five degrees of freedom (rotation and translation) moved freely in response to the applied loads. Loads were maintained for at least 30 seconds per test.

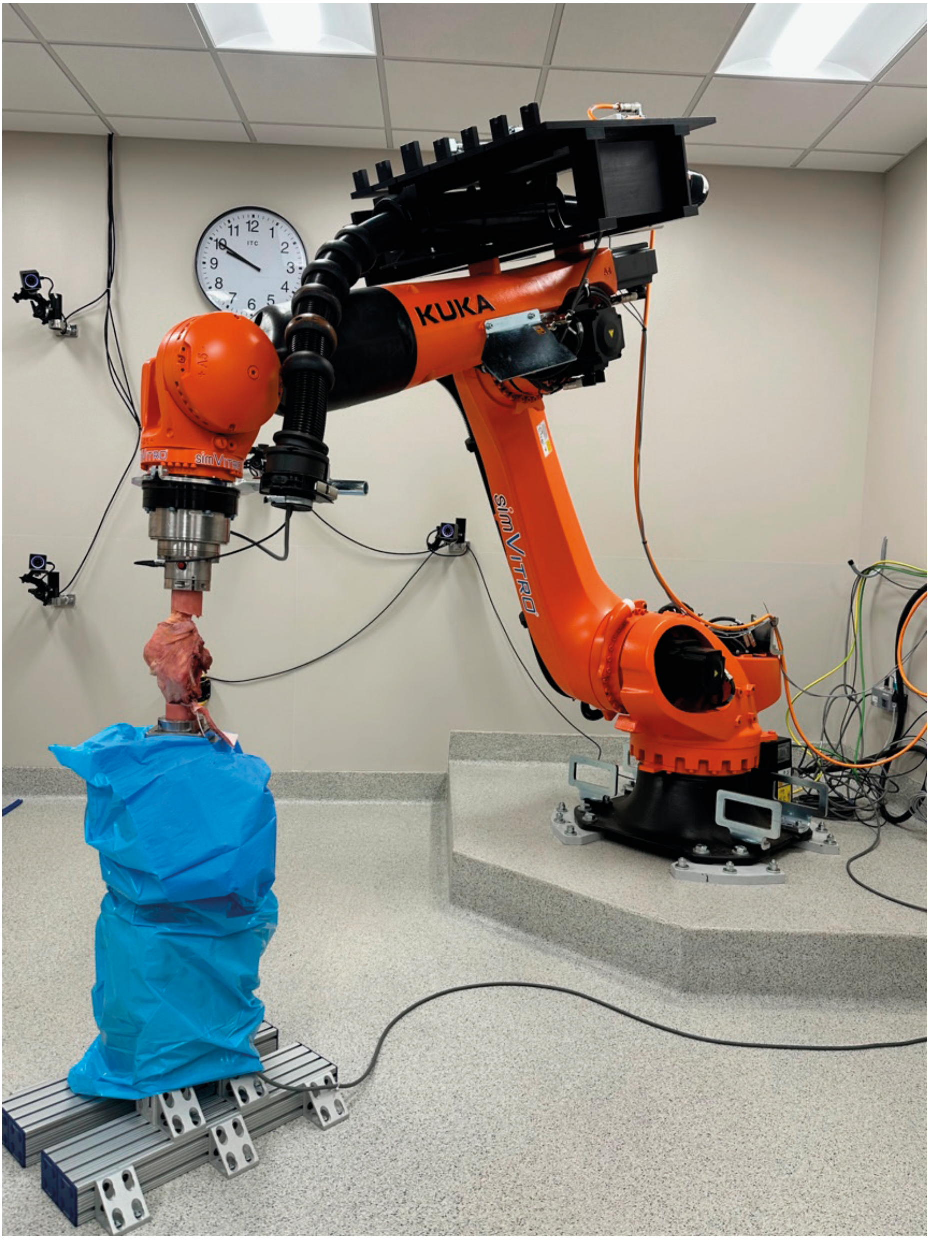

Figure 1. Robotic testing set-up with a 6 degrees-of-freedom robotic arm (KUKA KR300, KUKA Robotics), fitted with a universal force-torque sensor (Delta F/T, ATI Industrial Automation).

Sectioning Protocol Before surgical testing, knees were randomized into groups 1 or 2 for sectioning order, and into groups 3 or 4 for reconstruction order using a random number generator. The right knee of each pair was randomly assigned, and the left assigned to the remaining group.

- Group 1: ACL → LMPR → Kaplan fibers
- Group 2: ACL → Kaplan fibers → LMPR
- Group 3: ACLR → LMPR repair → LET
- Group 4: ACLR → LET → LMPR repair

Potential hysteresis of the specimens was addressed by randomizing the order of cutting the structures. The ACL was transected with a motorized shaver. An LMPR tear was created arthroscopically using a surgical beaver knife to create a footprint tear while preserving the meniscofemoral ligaments. A probe verified mobility of the posterior lateral meniscus to confirm full detachment. Kaplan fibers were accessed by creating a window between the posterior border of the iliotibial band and the biceps femoris tendon, at the level of the diaphyseal-metaphyseal junction. As previously described, proximal fibers were sectioned ~7 cm above the joint line, and distal fibers ~5 cm above the joint line at the supracondylar flare (Figure 2).[25,26]

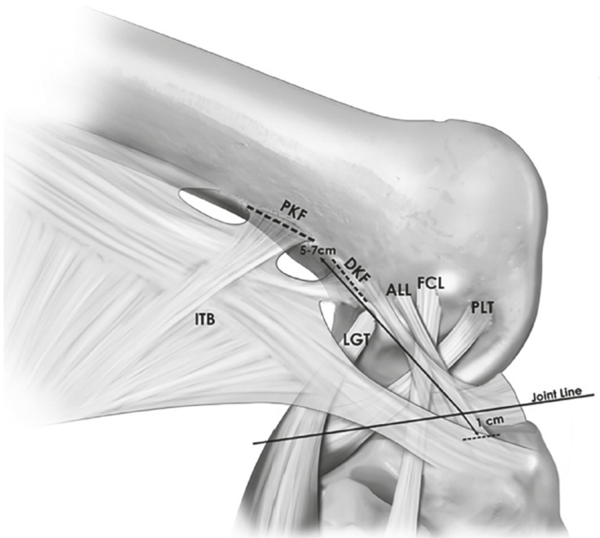

Figure 2. Right knee lateral structures depicting sectioning of the Kaplan fibers off the femur (dashed lines). ALL, anterolateral ligament; DKF, distal Kaplan fibers; FCL, fibular collateral ligament; ITB, iliotibial band; LGT, lateral gastrocnemius tendon; PKF, proximal Kaplan fibers; PLT, popliteus tendon. Adapted with permission from Geeslin et al.[24]

Surgical Technique

Procedures were performed by two fellowship-trained sports medicine orthopedic surgeons (W.A.W., E.L.S.).

Graft preparation

Semitendinosus tendons were harvested and grafts were prepared before potting the knees. Each graft was looped around an adjustable cortical suspensory fixation device (TightRope II RT, Arthrex, Naples, FL, USA), and then quadrupled. Free ends were whip-stitched and sutured using a buried-knot technique (two stitches on one side, one on the opposite).[27]

ACLR

Anatomic single-bundle all-inside ACL reconstruction was performed using retrograde drills (third generation FlipCutter, Arthrex).[28] The femoral aimer was placed at the center of the anteromedial femoral ACL footprint, and the tibial aimer at the center of the tibial footprint with a 55° angle. The graft was passed first into the femoral socket, then the tibial socket, and tensioned manually with cortical suspension button fixation in full extension by alternating traction on the shortening strands. Tension was verified with a probe.

LET

LET was performed using the modified Lemaire technique as described by Williams et al.[29] A 1 cm × 10 cm iliotibial band strip was harvested while preserving its attachment to Gerdy's tubercle. The proximal end was whip-stitched with a Vicryl suture and passed deep to the fibular collateral ligament. It was fixed to the lateral femur at 30° of flexion and neutral rotation using a knotless anchor (FiberTak, Arthrex) (Figure 3) with 20 N tension applied via a tensiometer. The femoral attachment point was just posterior and proximal to the lateral epicondyle. The graft was doubled back and sutured to itself, and the donor site was closed with Vicryl.

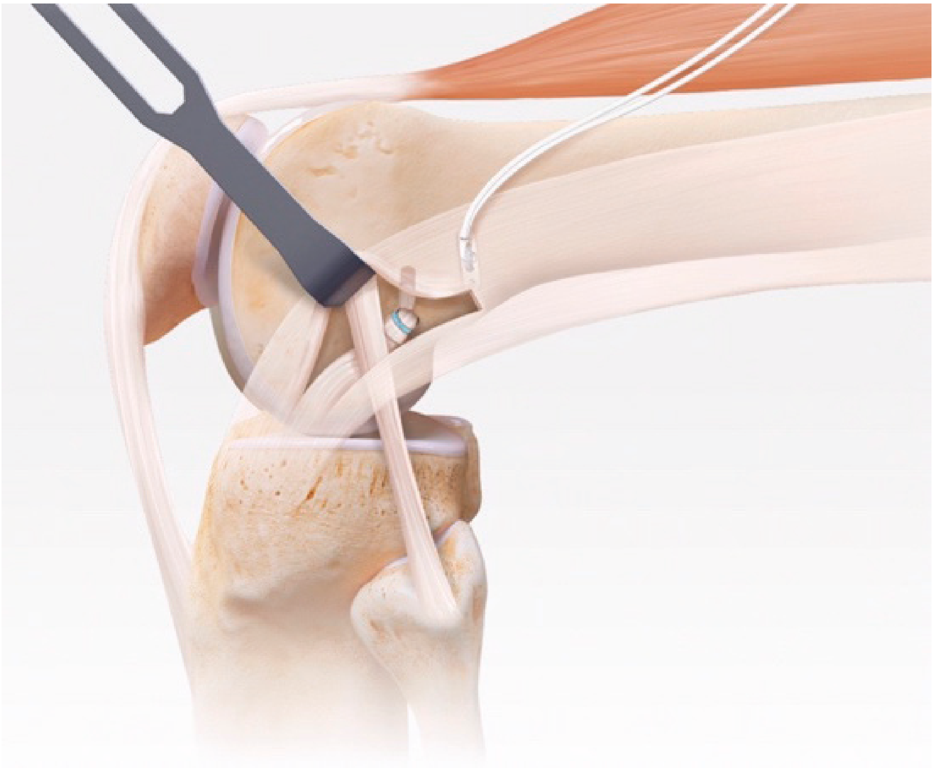

Figure 3. Left knee lateral side depicting modified Lemaire lateral extra-articular tenodesis (LET). The proximal end of a 1 cm × 10 cm harvested iliotibial band strip is whip-stitched and passed deep to the fibular collateral ligament, and fixed to the lateral femur using a knotless anchor (FiberTak, Arthrex) with the femoral attachment point just posterior and proximal to the lateral epicondyle. The graft is doubled back and sutured to itself. A cortical suspensory device of the all-inside anterior cruciate ligament (ACL) reconstruction is located proximal to the anchor fixation.

LMPR Repair

The LMPR was repaired using a transtibial tunnel and knotless anchor technique (SutureLoc, Arthrex) (Figure 4). A guide was placed at the LMPR footprint with a 70° angle to avoid convergence with the ACL tibial tunnel. A tibial tunnel was drilled and a passing wire was used. Repair sutures were passed through the LMPR in a suture bridge configuration and tensioned under direct visualization. Final tension was confirmed with a probe to ensure firm contact between the root and its footprint.

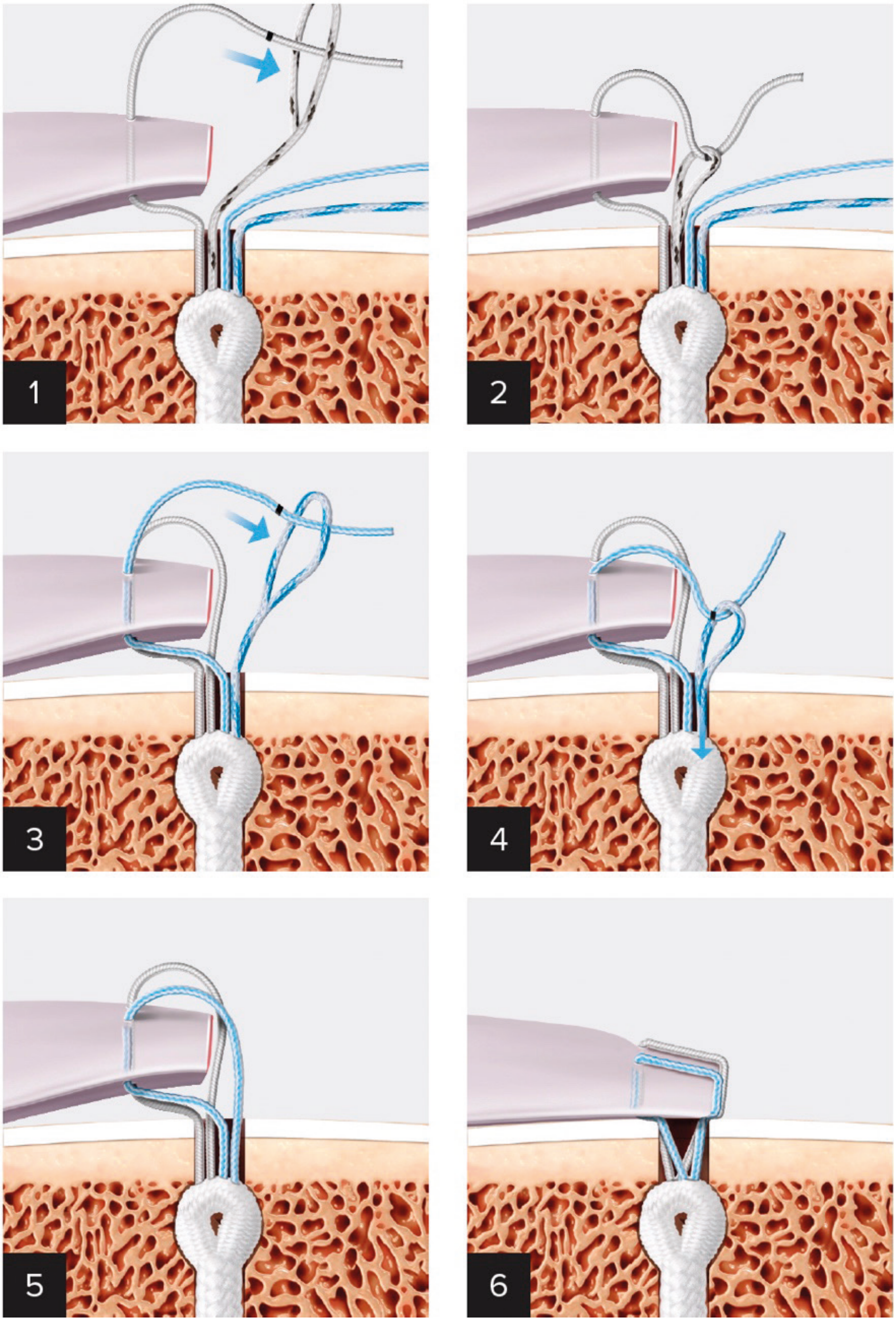

Figure 4. Meniscal root repair technique using an all-suture, knotless anchor (SutureLoc, Arthrex) technique. Once the anchor is passed just below the tibial plateau at the footprint of the lateral meniscus posterior root (LMPR), the 2 repair sutures can be passed through the tissue, tensioned, and retensioned when needed.

Data Analysis
Kinematic data were collected at 300 Hz. Final IR angle, valgus angle, and ATT were recorded when applied loads were held stable within 1 N and 0.1 Nm for at least 3 seconds. Data processing was performed using custom RStudio scripts (Posit PBC, Boston, MA).

Statistical Analysis
All specimens for the reconstruction analysis that had failures were excluded.

Means and standard deviations of IR, valgus, and ATT were calculated per condition, including across all surgical states and within each group. For overall comparisons, two-sample t-tests and one-factor linear mixed-effects models were used to account for randomization and maximize statistical power. Within-group comparisons were analyzed using repeated-measures ANOVA with Tukey HSD correction. Matched comparisons between groups 1 and 2 or 3 and 4 used paired two-sample t-tests. Values are presented as mean ± standard deviation.

RESULTS

Three specimen pairs were excluded and replaced: 2 due to undiagnosed meniscal root tears and 1 due to an ACL tear. Key clinically relevant results are summarized below; full data are in tables and figures.

SECTIONING KNEE STATES

Isolated IR
IR increased significantly after cutting the ACL at 0° (P = .035) and 15° (P = .049), and after cutting the ACL and LMPR at 0° (P < .001) and 15° (P = .039), compared to the intact knee state (Table 1). Cutting the Kaplan fibers along with the ACL caused significant IR increases at all flexion angles (all $P \leq .001$) (Table 1, Figure 5).

Table 1. Internal rotation measured with sectioning of the anterior cruciate ligament (ACL), lateral meniscus posterior root (LMPR), and Kaplan fibers.

Flexion Angle	Internal Rotation				
	Rotation at Intact State, deg (n=20)	Difference from Intact, deg			
		ACL Cut (n=20)	ACL Tear + LMPR Tear (n=10)	ACL Tear + Kaplan Injury (n=10)	Fully Injured (n=20)
0°	13.8 ± 3.6	1.9 ± 1.4[a]	2.5 ± 1.4[a]	1.9 ± 1.5[a]	3.0 ± 1.6[a,b]
15°	12.3 ± 2.3	1.6 ± 1.1[a]	2.0 ± 1.0[a]	2.1 ± 1.5[a]	3.5 ± 2.2[a,b,c]
30°	12.6 ± 2.3	1.3 ± 1.1	1.6 ± 1.3	2.8 ± 1.8[a,b]	4.3 ± 2.7[a,b,c]
45°	12.5 ± 2.5	1.2 ± 1.3	1.5 ± 1.9	3.6 ± 2.6[a,b]	5.0 ± 3.3[a,b,c]
60°	11.7 ± 2.4	1.5 ± 2.0	1.7 ± 2.4	4.0 ± 3.0[a,b]	5.3 ± 3.3[a,b,c]
75°	11.1 ± 2.5	1.6 ± 2.5	1.7 ± 2.4	3.6 ± 3.2[a,b]	4.7 ± 3.1[a,b,c]
90°	10.4 ± 2.4	1.5 ± 2.5	1.5 ± 2.4	2.8 ± 2.8[a]	3.7 ± 2.9[a,b]

Deg = degrees, a = significantly different from intact state, b = significantly different from ACL cut state, c = significantly different from ACL cut with LMPR tear first.

Cutting both ACL and LMPR produced no additional IR increase at any flexion angle compared to ACL-only sectioning (all P > .980). However, cutting both Kaplan fibers and ACL led to further IR increases at 30° (P = .007), 45° (P = .005), 60° (P = .006), and 75° (P = .022).

In knees where Kaplan fibers were cut last (ACL and LMPR already cut), IR further increased at 15° to 75° (P = .020) (Table 1, Figure 5).

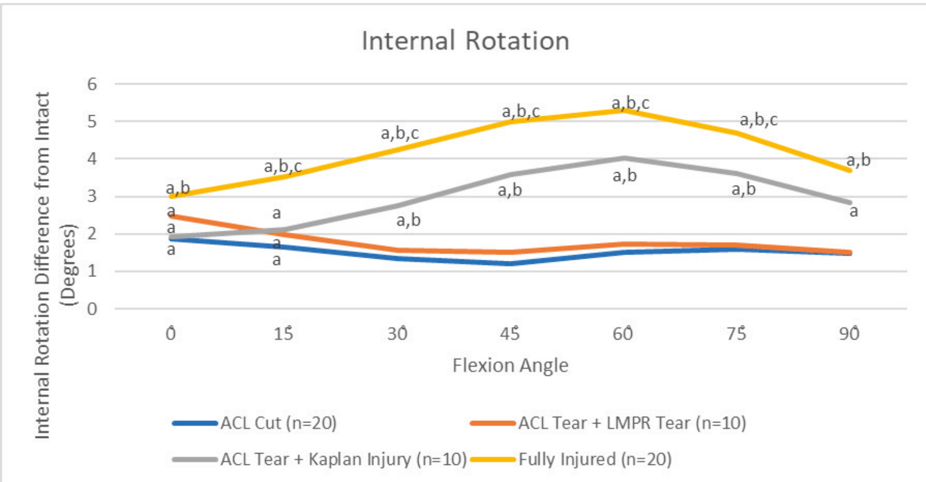

Figure 5. Flexion arc graph of isolated internal rotation difference compared to the intact knee state for the different knee sectioning states. a = significantly different from intact state, b = statistically different from anterior cruciate ligament (ACL) cut state, c = statistically different from ACL cut with lateral meniscus posterior root (LMPR) tear first.

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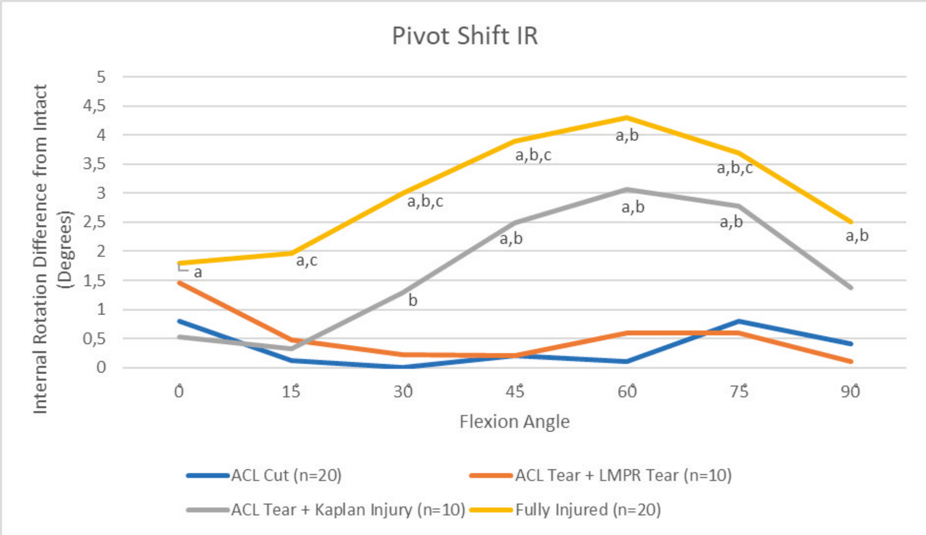

Figure 6. Flexion arc graph of coupled internal rotation during a pivot shift difference from intact knee state for the different knee sectioning states. a = significantly different from intact state, b = significantly different from anterior cruciate ligament (ACL) cut state, c = significantly different from ACL cut with lateral meniscus posterior root (LMPR) tear first.

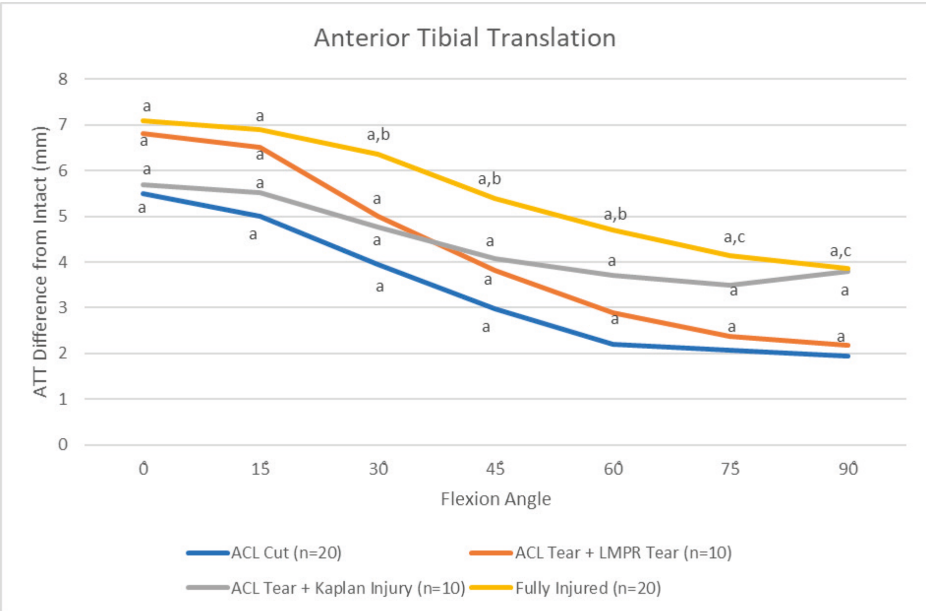

Figure 7. Flexion arc graph of coupled anterior tibial translation (ATT) during a pivot shift difference from intact knee state for the different knee sectioning states. a = significantly different from intact state, b = significantly different from anterior cruciate ligament (ACL) cut state, c = significantly different from ACL cut with lateral meniscus posterior root (LMPR) tear first.

Coupled IR During a Pivot Shift

Kaplan fiber and ACL cutting led to increased IR during pivot shift at 45° to 75° (all *P* < .005) versus intact (Table 2, Figure 6). Kaplan fiber cutting in ACL-deficient knees also caused significant IR during pivot shift increases at 30° to 75° (all *P* < .008) compared to ACL-deficient knees with intact Kaplan fibers. In fully injured knees with Kaplan fibers cut last, IR during pivot shift increased significantly compared to the ACL-deficient and LMPR cut knee state at 15° to 75° (all *P* < .038 (Table 2, Figure 6).

Table 2. Coupled internal rotation during a pivot shift measured with sectioning of the anterior cruciate ligament (ACL), lateral meniscus posterior root (LMPR), and Kaplan fibers.

Flexion Angle	Coupled Internal Rotation during a Pivot Shift				
	Rotation at Intact State, deg (n=20)	Difference from Intact, deg			
		ACL Cut (n=20)	ACL Tear + LMPR Tear (n=10)	ACL Tear + Kaplan Injury (n=10)	Fully Injured (n=20)
0°	14.1 ± 3.2	0.8 ± 2.3	1.5 ± 2.0	0.5 ± 2.6	1.8 ± 2.4[a]
15°	12.4 ± 1.7	0.1 ± 1.8	0.5 ± 1.4	0.3 ± 2.0	2.0 ± 2.9[a,c]
30°	12.4 ± 1.8	0.0 ± 1.7	0.2 ± 1.7	1.3 ± 1.7[b]	3.0 ± 3.4[a,b,c]
45°	11.9 ± 2.6	0.2 ± 2.1	0.2 ± 2.4	2.5 ± 2.6[a,b]	3.9 ± 3.8[a,b,c]
60°	10.6 ± 2.2	0.1 ± 3.2	0.6 ± 2.9	3.1 ± 2.8[a,b]	4.3 ± 3.8[a,b]
75°	9.6 ± 2.2	0.8 ± 2.8	0.6 ± 2.5	2.8 ± 2.8[a,b]	3.7 ± 3.5[a,b,c]
90°	8.7 ± 2.0	0.4 ± 2.8	0.1 ± 2.3	1.4 ± 2.5	2.5 ± 3.1[a,b]

Deg = degrees, a = significantly different from intact state, b = significantly different from ACL cut state, c = significantly different from ACL cut with LMPR tear first.

Coupled ATT During a Pivot Shift

ACL sectioning increased ATT during pivot shift at 0°to 45° versus intact (*P* < .001–.008). Adding LMPR or Kaplan fiber sectioning in ACL-deficient knees further increased ATT during pivot shift at all angles compared to the intact knee state (all *P* ≤ .006) (Table 3, Figure 7).

When Kaplan fibers were cut last, additional ATT during pivot shift increase occurred at 75° (*P* = .024) and 90° (*P* = .013) versus the ACL+LMPR-deficient state (Table 3, Figure 7).

Table 3. Coupled anterior tibial translation (in mm) during a pivot shift measured with sectioning of the anterior cruciate ligament (ACL), lateral meniscus posterior root (LMPR), and Kaplan fibers.

Flexion Angle	Coupled Anterior Tibial Translation during a Pivot Shift				
	Translation at Intact State, mm (n=20)	Difference from Intact, mm			
		ACL Cut (n=20)	ACL Tear + LMPR Tear (n=10)	ACL Tear + Kaplan Injury (n=10)	Fully Injured (n=20)
0°	3.8 ± 2.3	5.5 ± 2.8[a]	6.8 ± 4.4[a]	5.7 ± 1.9[a]	7.1 ± 4.1[a]
15°	3.3 ± 1.4	5.0 ± 2.5[a]	6.5 ± 4.1[a]	5.5 ± 1.7[a]	6.9 ± 3.5[a]
30°	3.0 ± 1.6	4.0 ± 2.3[a]	5.0 ± 3.9[a]	4.8 ± 2.0[a]	6.4 ± 3.1[a,b]
45°	2.7 ± 1.4	3.0 ± 2.2[a]	3.8 ± 3.4[a]	4.1 ± 2.8[a]	5.4 ± 3.1[a,b]
60°	2.3 ± 1.4	2.2 ± 2.1	2.9 ± 2.8[a]	3.7 ± 3.0[a]	4.7 ± 2.8[a,b]
75°	2.0 ± 1.3	2.1 ± 2.0	2.4 ± 2.2[a]	3.5 ± 3.0[a]	4.2 ± 2.6[a,c]
90°	2.0 ± 1.02	1.9 ± 1.9	2.2 ± 1.9[a]	3.8 ± 2.8[a]	3.9 ± 2.5[a,c]

Deg = degrees, a = significantly different from intact state, b = significantly different from ACL cut state, c = significantly different from ACL cut with LMPR tear first.

Coupled Valgus Rotation During a Pivot Shift:

Valgus rotation during pivot shift increased after ACL cutting at 0° to 45° (all $P \leq .034$). Additional LMPR sectioning in ACL-deficient knees increased valgus during pivot shift at 0°, 15°, 30°, 45°, and 90° (all $P \leq .044$). Kaplan fiber sectioning in ACL-deficient knees increased valgus during pivot shift at all flexion angles (all $P < .002$). In fully injured knees where LMPR was cut last, valgus during pivot shift was significantly higher at 30° ($P = .026$) compared to the ACL + Kaplan-deficient state (Table 4, Figure 8).

Table 4. Coupled valgus rotation during a pivot shift measured with sectioning of the anterior cruciate ligament (ACL), lateral meniscus posterior root (LMPR), and Kaplan fibers.

Flexion Angle	Coupled Valgus Rotation during a Pivot Shift				
	Rotation at Intact State, deg (n=20)	Difference from Intact, deg			
		ACL Cut (n=20)	ACL Tear + LMPR Tear (n=10)	ACL Tear + Kaplan Injury (n=10)	Fully Injured (n=20)
0°	1.6 ± 1.7	1.8 ± 1.1[a]	1.7 ± 1.3[a]	2.2 ± 1.2[a]	2.3 ± 1.5[a]
15°	2.1 ± 1.7	2.0 ± 1.5[a]	2.3 ± 2.0[a]	2.7 ± 1.5[a]	3.2 ± 1.9[a,b]
30°	2.5 ± 1.7	1.6 ± 1.5[a]	2.1 ± 2.5[a]	2.5 ± 1.8[a]	3.5 ± 2.5[a,b,d]
45°	2.9 ± 1.8	1.2 ± 1.2[a]	1.9 ± 2.7[a]	2.2 ± 2.0[a]	3.3 ± 2.5[a,b]
60°	3.2 ± 1.8	0.7 ± 1.2	1.5 ± 2.4	2.2 ± 2.1[a]	3.2 ± 2.5[a,b]
75°	3.4 ± 1.8	0.9 ± 1.2	1.5 ± 2.3	2.3 ± 2.1[a]	3.3 ± 2.6[a,b]
90°	3.8± 1.9	1.0 ± 1.2	1.7 ± 2.4[a]	2.3 ± 2.0[a]	3.3 ± 2.6[a,b]

Deg = degrees, a = significantly different from intact state, b = significantly different from ACL cut state, c = significantly different from ACL cut with LMPR tear first, d = significantly different from ACL cut with Kaplan injury first.

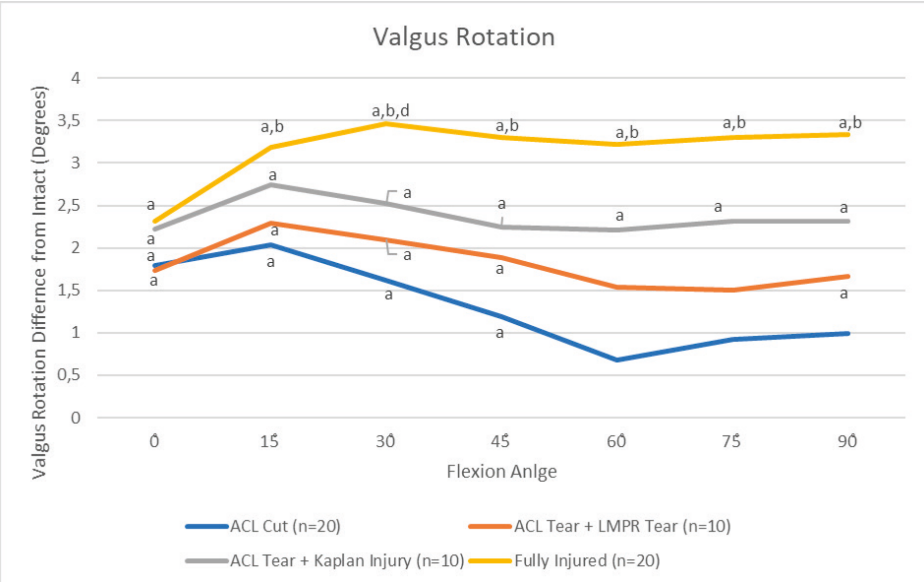

Figure 8. Flexion arc graph of coupled valgus rotation during a pivot shift difference from intact knee state for the different knee sectioning states. a = significantly different from intact state, b = significantly different from anterior cruciate ligament (ACL) cut state, d = significantly different from ACL cut with Kaplan injury first, LMPR = lateral meniscus posterior root.

RECONSTRUCTION/REPAIR KNEE STATES

Post-test inspection showed LMPR repair failure in 5 knees (group 3) and 3 knees (group 4). These were excluded from final analysis, leaving 5 repaired knees in group 3 and 7 in group 4.

Isolated IR

After ACLR in fully injured knees, IR remained significantly increased at all flexion angles (all $P < .001$) except at 0° ($P = .641$) compared to the intact knee state (n=20). Adding LMPR repair first (to the ACL-reconstructed and Kaplan fiber injured knee) (n=5) resulted in IR comparable to the intact knee at 60° ($P = .064$), 75°, ($P = .087$), and 90° ($P = .093$). Subsequent LET resulted in IR comparable to the intact knee at all flexion angles (all $P >.05$) except at 75° ($P = .043$) (Table 5).

Adding LET first (to the ACL-reconstructed and LMPR injured knee) (n=10) resulted in IR comparable to the intact knee state at all flexion angles (all $P > .086$). Subsequent LMPR repair (n=7) resulted in a further significant decrease in IR compared to the ACL-reconstructed with LET knee at all flexion angles (all $P > .153$) (Table 5), and to IR comparable to the intact knee at all flexion angles (all $P > .132$).

Table 5. Internal rotation after anterior cruciate ligament reconstruction (ACLR), lateral meniscus posterior root (LMPR), and lateral extra-articular tenodesis (LET).

Internal Rotation							
Flexion Angle	Rotation at Intact State (n=20)	Difference from Intact, deg					
		Fully Cut (n=20)	ACLR (n=20)	ACLR + LMPR repair (n=5)	Fully Repaired LMPR→LET (n=5)	ACLR + LET (n=10)	Fully Repaired LET→LMPR (n=7)
0°	13.8 ± 3.6	3.0 ± 1.6[a]	0.9 ± 3.8[b]	2.4 ± 1.9[a]	0.9 ± 1.9	-2.2± 3.6[b]	0.6 ± 3.5[e]
15°	12.3 ± 2.3	3.5 ± 2.2[a]	2.8 ± 2.9[a]	2.3 ± 1.0[a]	-0.2 ± 2.0[b]	-1.6 ± 3.8[b,c]	1.0 ± 3.9[e]
30°	12.6 ± 2.3	4.3 ± 2.7[a]	3.9 ± 3.1[a]	2.3 ± 1.3[a]	-0.4 ± 3.0	-0.6 ± 3.9[b,c]	2.0 ± 4.4[e]
45°	12.5 ± 2.5	5.0 ± 3.3[a]	5.0 ± 3.3[a]	2.4 ± 1.6[a]	-0.1 ± 4.0	1.0 ± 4.6[b,c]	3.0 ± 5.0[e]
60°	11.7 ± 2.4	5.3 ± 3.3[a]	5.3 ± 3.3[a]	3.4 ± 3.0	0.0 ± 4.0	1.2 ± 5.1[b,c]	3.4 ± 5.4[e]
75°	11.1 ± 2.5	4.7 ± 3.1[a]	4.7 ± 3.2[a]	3.0 ± 3.0	-0.4 ± 3.1[a,d]	0.8 ± 5.1[b,c]	2.8 ± 5.8[e]
90°	10.4 ± 2.4	3.7 ± 2.9[a]	3.7 ± 2.9[a]	2.4 ± 2.5	-0.6 ± 2.2[c]	0.2 ± 4.8[b,c]	1.8 ± 5.5[e]

Deg = degrees, a = significantly different from intact state, b = significantly different from fully cut state, c = significantly different from ACLR, d = significantly different from ACLR with LMPR first, e = significantly different from ACLR with LET first.

Coupled IR During a Pivot shift

After ACLR, IR during pivot shift remained significantly increased at all flexion angles compared to the intact knee state (n=20) (all $P < .010$). Adding LMPR repair first (to the ACL-reconstructed and Kaplan fiber injured knee) (n=5) resulted in IR during pivot shift comparable to the intact knee at 30°- 90° (all $P > .106$). Subsequent LET resulted in IR during pivot shift comparable to the intact knee at all flexion angles (all $P > .05$) (Table 6).

Adding LET first (to the ACL-reconstructed and LMPR injured knee) (n=10) resulted in IR during pivot shift comparable to the intact knee at all flexion angles (all $P > .102$). Subsequent LMPR repair (n=7) resulted in a further significant decrease in IR during pivot shift compared to the ACL-reconstructed and LET knee at all flexion angles (all $P > .172$) (Table 6), and to IR during pivot shift comparable to the intact knee at all flexion angles (all $P > .359$).

Table 6. Coupled internal rotation during a pivot shift seen after anterior cruciate ligament reconstruction (ACLR), lateral meniscus posterior root (LMPR), and lateral extra-articular tenodesis (LET).

Coupled Internal Rotation during a Pivot Shift							
Flexion Angle	Rotation at Intact State (n=20)	Difference from Intact, deg					
		Fully Cut (n=20)	ACLR (n=20)	ACLR + LMPR repair (n=5)	Fully Repaired LMPR→LET (n=5)	ACLR + LET (n=10)	Fully Repaired LET→LMPR (n=7)
0°	14.1 ± 3.2	1.8 ± 2.4[a]	2.0 ± 2.8[a]	2.8 ± 1.5[a]	1.1 ± 1.8	-2.1 ± 3.7[b,c]	0.9 ± 3.7[e]
15°	12.4 ± 1.7	2.0 ± 2.9[a]	2.9 ± 3.3[a]	1.9 ± 1.2[a]	-1.2 ± 2.6	-1.9 ± 4.0[b,c]	0.8 ± 4.1[e]
30°	12.4 ± 1.8	3.0 ± 3.4[a]	3.9 ± 3.6[a]	1.7 ± 1.8	-1.7 ± 3.9	-0.3 ± 4.1[b,c]	1.6 ± 4.4[e]
45°	11.9 ± 2.6	3.9 ± 3.8[a]	4.9 ± 3.8[a]	1.3 ± 1.8	-1.5 ± 4.8	0.6 ± 4.80[b,c]	2.5 ± 4.9[e]
60°	10.6 ± 2.2	4.3 ± 3.8[a]	5.3 ± 3.7[a]	2.7 ± 3.6	-1.1 ± 4.3	1.2 ± 5.0[b,c]	3.2 ± 5.4[e]
75°	9.6 ± 2.2	3.7 ± 3.5[a]	4.7 ± 3.4[a]	2.6 ± 3.2	-1.1 ± 3.2[c]	0.7 ± 5.2[b,c]	2.6 ± 5.8[e]
90°	8.7 ± 2.0	2.5 ± 3.1[a]	3.5 ± 3.2[a]	2.0 ± 2.6	-1.6 ± 2.2[c]	0.0 ± 4.8[b,c]	1.3 ± 5.4[e]

Deg = degrees, a = significantly different from intact state, b = significantly different from fully cut state, c = significantly different from ACLR, e = significantly different from ACLR with LET first.

Coupled ATT During a Pivot Shift

After ACLR, ATT during pivot shift remained significantly increased at 0° to 45° compared to the intact knee state (all $P < .05$) (n=20). Adding LMPR repair first (to the ACL-reconstructed and Kaplan fiber injured knee) (n=5) resulted in ATT during pivot shift comparable to the intact knee at 75° ($P = .065$) and 90° ($P = .115$). Subsequent LET resulted in ATT during pivot shift comparable to the intact knee at 0°, 15°, 30° 75°, and 90° (all $P > .086$) (Table 7).

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Adding LET first (to the ACL-reconstructed and LMPR injured knee) (n=10), resulted in ATT during pivot shift comparable to the intact knee at all flexion angles (all *P* > .537). Subsequent LMPR repair (n=7) resulted in a further significant decrease in ATT during pivot shift compared to the ACL-reconstructed and LET knee at 30° (*P* = .029) and 75° (*P* = .033). (Table 7), and to ATT during pivot shift comparable to the intact knee at all flexion angles (all *P* > .872)

Table 7. Coupled anterior tibial translation (mm) during a pivot shift seen after anterior cruciate ligament reconstruction (ACLR), lateral meniscus posterior root (LMPR), and lateral extra-articular tenodesis (LET).

Coupled Anterior Tibial Translation during a Pivot Shift							
Flexion Angle	Translation at Intact State (n=20)	Difference from Intact, mm					
		Fully Cut (n=20)	ACLR (n=20)	ACLR + LMPR repair (n=5)	Fully Repaired LMPR→LET (n=5)	ACLR + LET (n=10)	Fully Repaired LET→LMPR (n=7)
0°	3.8 ± 2.3	7.1 ± 4.1[a]	2.5 ± 4.0[a,b]	3.7 ± 2.00[a,b]	3.3 ± 1.3[b]	-0.5 ± 2.7[b]	0.8 ± 3.5[b]
15°	3.3 ± 1.4	6.9 ± 3.5[a]	2.8 ± 4.5[a,b]	4.6 ± 2.3[a,b]	4.0 ± 1.84[b]	-0.6 ± 2.7[b]	0.9 ± 3.6[b]
30°	3.0 ± 1.6	6.4 ± 3.1[a]	2.8 ± 5.0[a,b]	4.4 ± 2.3[a,b]	3.7 ± 1.6[a,d]	-0.1 ± 3.1[b]	1.0 ± 3.5[e]
45°	2.7 ± 1.4	5.4 ± 3.1[a]	2.4 ± 5.4[a]	3.6 ± 2.2[a]	2.9 ± 1.9[a,d]	0.0 ± 3.6[b]	1.4 ± 3.4
60°	2.3 ± 1.4	4.7 ± 2.8[a]	1.8 ± 6.0[b]	3.0 ± 2.1[a]	2.3 ± 1.9[a,d]	-0.2 ± 4.1[b]	1.5 ± 3.4
75°	2.0 ± 1.3	4.2 ± 2.6[a]	1.2 ± 6.5[b]	2.4 ± 2.1	1.9 ± 1.7	-0.6 ± 4.6[b]	1.3 ± 3.1[e]
90°	2.0 ± 1.0	3.9 ± 2.5[a]	0.6 ± 7.0[b]	1.9 ± 2.1	1.4 ± 1.5	-0.9 ± 5.2[b]	1.2 ± 3.2

a = significantly different from intact state, b = significantly different from fully cut state, e = significantly different from ACLR with LET first.

Coupled Valgus rotation During a Pivot Shift

After ACLR, valgus rotation during pivot shift remained increased at all flexion angles (all *P* < .003) except at 0° (*P* = .145) (n=20). Adding LMPR repair first (to the ACL-reconstructed and Kaplan fiber injured knee) (n=5) resulted in valgus rotation during pivot shift comparable to the intact knee at 0° (*P* = .193), 15° (*P* = .070), 30° (*P* = .057), 45° (*P* = .071), and 60° (*P* = .053). Subsequent LET resulted in valgus rotation during pivot shift comparable to the intact knee at all flexion angles (all *P* > .147).

Adding LET first (to the ACL-reconstructed and LMPR injured knee) (n=10), resulted in a significantly increased valgus rotation during pivot shift at all flexion angles except at 90° (*P* = .080). Subsequent LMPR repair (n=7) resulted in valgus rotation during pivot shift comparable to the intact knee state at 0° (*P* = .053) and 90° (*P* = .109) (Table 8).

Table 8. Coupled valgus rotation during a pivot shift seen after anterior cruciate ligament reconstruction (ACLR), lateral meniscus posterior root (LMPR) repair, and lateral extra-articular tenodesis (LET)

Coupled Valgus Rotation during a Pivot Shift							
Flexion Angle	Rotation at Intact State (n=20)	Difference from Intact, deg					
		Fully Cut (n=20)	ACLR (n=20)	ACLR + LMPR repair (n=5)	Fully Repaired LMPR→LET (n=5)	ACLR + LET (n=10)	Fully Repaired LET→LMPR (n=7)
0°	1.6 ± 1.7	2.3 ± 1.5[a]	0.6 ± 1.5[b]	0.9 ± 1.3	1.2 ± 0.9[b]	1.0 ± 0.5[a,b,c]	0.5 ± 0.6[b,e]
15°	2.1 ± 1.7	3.2 ± 1.9[a]	1.3 ± 2.0[a,b]	1.8 ± 1.6[b]	1.8 ± 1.0[b]	1.2 ± 0.5[a,b]	1.0 ± 0.8[a]
30°	2.5 ± 1.7	3.5 ± 2.5[a]	1.8 ± 2.2[a,b]	2.0 ± 1.7[b]	1.7 ± 1.1[b]	1.2 ± 0.7[a,b]	1.1 ± 1.1[a]
45°	2.9 ± 1.8	3.3 ± 2.5[a]	2.1 ± 2.1[a,b]	2.0 ± 1.8	1.5 ± 1.3	1.3 ± 1.0[a,b]	1.3 ± 1.3[a]
60°	3.2 ± 1.8	3.2 ± 2.5[a]	2.4 ± 2.1[a]	1.9 ± 1.5	1.4 ± 1.4	1.3 ± 1.2[a,b,c]	1.5 ± 1.5[a,c]
75°	3.4 ± 1.8	3.3 ± 2.6[a]	2.6 ± 2.2[a]	1.8 ± 1.3[a]	1.3 ± 1.3	1.3 ± 1.5[a,b,c]	1.6 ± 1.7[a]
90°	3.8 ± 1.9	3.3 ± 2.6[a]	2.7 ± 2.5[a]	1.7 ± 0.9[a]	1.1 ± 1.3	1.2 ± 1.9[b]	1.5 ± 2.1

Deg = degrees, a = significantly different from intact state, b = significantly different from fully cut state, c = significantly different from ACLR, e = significantly different from ACLR with LET first.

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DISCUSSION

The most important finding of our study was that both the LMPR and Kaplan fibers act as secondary stabilizers to isolated IR and overall pivot shift loading in the ACL-deficient knee, and that Kaplan fiber tears have an additive biomechanical effect to the ACL-deficient and LMPR tear knee state for isolated IR as well as for coupled IR and ATT during pivot shift, confirming our first hypothesis. Furthermore, adding a LET to the ACLR and LMPR deficient knee state restored knee stability for isolated IR, coupled IR during pivot shift, and coupled ATT during pivot shift, but not for coupled valgus rotation during pivot shift compared to the intact knee state. Adding LMPR repair to the ACLR and Kaplan fiber deficient knee state restored coupled valgus rotation and IR during pivot shift at most flexion angles, and coupled IR and ATT during pivot shift at certain flexion angles compared to the intact knee state. These findings confirm our second hypothesis that both LMPR repair and LET are needed to restore knee kinematics comparable to the intact knee state.

We found that both increased isolated IR and increased coupled IR during pivot shift in various testing states that were present after sectioning the ACL, LMPR, and Kaplan fibers were not fully restored by ACLR alone. The addition of a LMPR repair to ACLR resulted in a significant decrease in IR at higher flexion angles that was not significantly different to the ACL intact state. The addition of LET to ACLR resulted in a significant decrease in

IR at all flexion angles that was not significantly different to the ACL-intact state. Overall, comparing our findings for the ACL, LMPR, and Kaplan fiber cut states found increased IR values near full extension (0° and 15°) for the ACL sectioned state. A previous study reported no increase in IR with ACL sectioning at all flexion angles.[21] The different findings at 0° and 15° can possibly be explained by the different testing method of kinematic rig testing in a smaller group of 10 knees, compared to robotic testing in 20 knees in our study. Furthermore, although statistically significant increased IR values were found at 0° and 15°, the increased values in degrees were small (1.9° and 1.6°, respectively).

Further, our finding of no further significant increase in isolated IR with the addition of a LMPR tear to the ACL tear state was also similar to other studies where either a nonsignificant increase in IR was found[10] or a significant increase in IR was only found at high flexion angles (75° and 90°).[9] Additionally, we found a significant increase in IR with combined sectioning of the Kaplan fibers and ACL at all knee flexion angles compared to the intact knee state and we also found that cutting the Kaplan fibers in addition to the LMPR resulted in a further significant increase in IR at 30°, 45°, 60° and 75°. This latter finding compares similarly to the Geeslin et al.[20] study where the additional cutting of the Kaplan fibers in the ACL-deficient knee led to a further significant increase in IR at 60°, 75°, and 90°.

We also found that there was a significant increase in coupled ATT during pivot shift in several ACL, LMPR, and Kaplan fiber cut states that were not addressed by ACLR alone at lower flexion angles (0-45°). In general, adding LET to the ACLR (with LMPR cut) knee and to the ACLR and LMPR repaired knee resulted in similar ATT to the ACL intact state. In this study, ATT was significantly increased between 0° and 45° when just the ACL was cut compared to the intact state; however, the additive effects of cutting the LMPR and Kaplan fibers resulted in significant increases in ATT compared to the intact state at all flexion angles. It appears that the LMPR was important at lower flexion angles, the Kaplan fibers were important at higher flexion angles, and the additive effect was significant in the midranges of flexion. The findings from this study align with a previous study from Willinger et al.[21] who tested a similar protocol but transected the anterolateral structures versus the LMPR and Kaplan fibers. In their study, they found significantly increased ATT from 0 to 50° in 10° increments between the ACL cut and intact states, with no significant difference at higher flexion angles. Once they cut the anterolateral structures along with the ACL, they found significant increases in ATT at all flexion angles but 0°.[21] In our study, when reconstructing the ACL, increased ATT during pivot shift could not be fully restored to near intact values between 0° and 45°. In the group of 5 knees in which LMPR repair was added first after ACLR, ATT was restored at higher flexion angles (75°-90°) compared with the intact state. In the group of 10 knees in which LET was added first after ACLR, ATT was restored at all flexion angles. Overall, the sectioning of the ACL, LMPR, and Kaplan fibers results in significant increases in ATT during a simulated pivot shift that can only be restored to near native values at all flexion angles by the addition of LET.

Furthermore, we found a significant increase in coupled valgus rotation during pivot shift after cutting the ACL at lower flexion angles, and at 90° after cutting both the ACL and the LMPR, and at all flexion angles after cutting both the ACL and Kaplan fibers. An ACLR in the fully cut knee state was insufficient to restore valgus stability at all flexion angles. Adding a LMPR repair to the ACLR knee restored stability at most flexion angles (0-60°), as did adding LET for all flexion angles. We are not aware of other studies which have investigated the biomechanical effects on valgus rotation during pivot shift after adding LMPR repair and/or LET to the ACLR knee.

After completing the study, we performed post-testing arthroscopic evaluations to verify our data and we found a high rate of LMPR repairs failed during robotic testing, although while performing the repairs these all felt very solid both during the fixation and when testing the repair with a probe. We believe that the failed repairs are similar to the clinical scenario where LMPR repairs are felt to be relatively fragile repairs at time zero and that the harsh testing conditions of the robotic testing led to loosening and failure of some specimens which in clinical cases relies on the ability of biological healing to occur. We would recommend immediate post-testing arthroscopic or open assessments of the integrity of meniscal root repairs after robotic testing in future studies. The SutureLoc adjustable suture anchor root repair technique is a relatively new technique. The technique has been tested in two human cadaveric biomechanical studies, reporting a stiffer fixation with less cyclic displacement than conventional transtibial pull-out repairs,[30] and lower medial meniscal extrusion and reduced medial compartment contact pressures,[31] in both studies after time-zero cyclic loading. No biomechanical studies investigated this repair technique undergoing comparable testing conditions as in our study. Future biomechanical and clinical studies should further evaluate the biomechanical strength and validate the effect on root healing of this specific repair technique. We also advise to be cautious on implementing this repair technique in clinical practice until more studies become available.

Due to the smaller sample sizes in some groups after excluding the failed LMPR repairs some of the repair/reconstruction findings need to be interpreted with caution. The smaller sample sizes in these groups also explain some of the contradictory findings in the results. In addition, while our repair and reconstruction results have no known comparisons in the literature, it is difficult to compare our sectioning results to other results in the literature because most other studies assessed different testing conditions or structure sectioning protocols.

Overall, in this study, we found that the most important reconstruction state which best restored stability comparable to the ACL intact state for isolated IR and coupled IR and ATT during pivot shift was the addition of LET to either the ACLR alone or to ACLR with LMPR repaired state. Adding LET to the ACLR alone was insufficient to restore stability comparable to the intact knee state for coupled valgus rotation during pivot shift, while adding LMPR to the ACLR knee state was sufficient to restore valgus rotation during the pivot shift at most flexion angles. These results suggest that there is a specific role of the LMPR for coupled valgus rotation during pivot shift.

Limitations

We recognize that our study has some limitations. First, our average patient age was high, which can affect the amount of translation and rotatory instability seen with sectioning of the structures in older knees. Second, regarding injury of the anterolateral corner we focused specifically on complete injury to the Kaplan fibers, and did not investigate the influence of other structures of the anterolateral corner, especially the ALL, reducing the external validity of the study. Third, in vivo conditions as muscle contraction and dynamic loading cannot be fully reproduced in a biomechanical cadaveric study.

CONCLUSIONS

Both the LMPR and Kaplan fibers act as secondary stabilizers to IR and pivot shift loading in the ACL-deficient knee, with an additive biomechanical effect of the Kaplan fibers to the ACL with LMPR deficient knee for isolated IR and for coupled IR and ATT during pivot shift. Furthermore, the most important reconstruction state which best restored stability comparable to the ACL intact state was the addition of LET to either the ACLR alone or ACLR with LMPR repair state, except for valgus rotation during pivot shift, where LMPR repair contributes most.

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REFERENCES

1. Horvath A, Meredith SJ, Nishida K, Hoshino Y, Musahl V. **Objectifying the Pivot Shift Test**. *Sports Med Arthrosc Rev*. 2020;28(2):36-40. doi:10.1097/jsa.0000000000000260
2. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **Meniscal Tears, Posterolateral and Posteromedial Corner Injuries, Increased Coronal Plane, and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament–Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**. *Arthroscopy*. 2022;38(5):1664-1688.e1. doi:10.1016/j.arthro.2021.11.044
3. Ciatti R, Gabrielli A, Iannella G, Mariani PP. **Arthroscopic incidence of lateral meniscal root avulsion in patients with anterior cruciate ligament injury**. *J Orthop Traumatol*. 2021;22(1):30. doi:10.1186/s10195-021-00591-x
4. Praz C, Vieira TD, Saithna A, et al. **Risk Factors for Lateral Meniscus Posterior Root Tears in the Anterior Cruciate Ligament–Injured Knee: An Epidemiological Analysis of 3956 Patients From the SANTI Study Group**. *Am J Sports Med*. 2019;47(3):598-605. doi:10.1177/0363546518818820
5. Lambrey PJ, Fayard JM, Graveleau N, et al. **Male sex, revision surgery, low volume of anterior cruciate ligament remnant, and significant instability are risk factors for Posterior Root Tear of the Lateral Meniscus in patients undergoing Anterior Cruciate Ligament Reconstruction**. *Arthroscopy*. Published online 2024. doi:10.1016/j.arthro.2024.05.028
6. Bernholt D, DePhillipo NN, Aman ZS, Samuelsen BT, Kennedy MI, LaPrade RF. **Increased posterior tibial slope results in increased incidence of posterior lateral meniscal root tears in ACL reconstruction patients**. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(11):3883-3891. doi:10.1007/s00167-021-06456-4
7. Magosch A, Mouton C, Nührenbörger C, Seil R. **Medial meniscus ramp and lateral meniscus posterior root lesions are present in more than a third of primary and revision ACL reconstructions**. *Knee Surg Sports Traumatol Arthrosc*. 2021;29(9):3059-3067. doi:10.1007/s00167-020-06352-3
8. Shybut TB, Vega CE, Haddad J, et al. **Effect of Lateral Meniscal Root Tear on the Stability of the Anterior Cruciate Ligament–Deficient Knee**. *Am J Sports Med*. 2015;43(4):905-911. doi:10.1177/0363546514563910
9. Frank JM, Moatshe G, Brady AW, et al. **Lateral Meniscus Posterior Root and Meniscofemoral Ligaments as Stabilizing Structures in the ACL-Deficient Knee: A Biomechanical Study**. *Orthop J Sports Med*. 2017;5(6):2325967117695756. doi:10.1177/2325967117695756
10. Forkel P, Deimling C von, Lacheta L, et al. **Repair of the lateral posterior meniscal root improves stability in an ACL-deficient knee**. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(8):2302-2309. doi:10.1007/s00167-018-4949-8
11. Tang X, Marshall B, Wang JH, et al. **Lateral Meniscal Posterior Root Repair With Anterior Cruciate Ligament Reconstruction Better Restores Knee Stability**. *Am J Sports Med*. 2019;47(1):59-65. doi:10.1177/0363546518808004
12. Balendra G, Willinger L, Pai V, et al. **Anterolateral complex injuries occur in the majority of 'isolated' anterior cruciate ligament ruptures**. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(1):176-183. doi:10.1007/s00167-021-06543-6
13. Firoozabadi MA, Mortazavi SMJ, Shakiba M, et al. **Investigating Injuries to the Anterolateral Corner of the Knee: Imaging Insights Into Kaplan Fibers and the Anterolateral Ligament in Anterior Cruciate Ligament Tears**. *Orthop J Sports Med*. 2025;13(3):23259671251319504. doi:10.1177/23259671251319504

4

14. Leao RV, Helito PVP, Saithna A, Correa MF de P, Helito CP. **Anterolateral Ligament and Kaplan Fiber Injury Both Occur Frequently in Acute Anterior Cruciate Ligament-Injured Knees**. *J Clin Med*. 2024;13(4):946. doi:10.3390/jcm13040946
15. Runer A, Dammerer D, Kranewitter C, et al. **Injuries to the anterolateral ligament are observed more frequently compared to lesions to the deep iliotibial tract (Kaplan fibers) in anterior cruciate ligament deficient knees using magnetic resonance imaging**. *Knee Surg Sports Traumatol Arthrosc*. 2022;30(1):309-318. doi:10.1007/s00167-021-06535-6
16. Dyck PV, Smet ED, Roelant E, Parizel PM, Heusdens CHW. **Assessment of Anterolateral Complex Injuries by Magnetic Resonance Imaging in Patients With Acute Rupture of the Anterior Cruciate Ligament**. *Arthroscopy*. 2019;35(2):521-527. doi:10.1016/j.arthro.2018.08.032
17. Watanabe S, Nagai K, Hoshino Y, et al. **Influence of Injury to the Kaplan Fibers of the Iliotibial Band on Anterolateral Rotatory Knee Laxity in Anterior Cruciate Ligament Injury: A Retrospective Cohort Study**. *Am J Sports Med*. 2022;50(12):3265-3272. doi:10.1177/03635465221116097
18. Puzzitiello RN, Agarwalla A, Zuke WA, Garcia GH, Forsythe B. **Imaging Diagnosis of Injury to the Anterolateral Ligament in Patients With Anterior Cruciate Ligaments: Association of Anterolateral Ligament Injury With Other Types of Knee Pathology and Grade of Pivot-Shift Examination: A Systematic Review**. *Arthroscopy*. 2018;34(9):2728-2738. doi:10.1016/j.arthro.2018.04.025
19. Terry GC, Norwood LA, Hughston JC, Caldwell KM. **How iliotibial tract injuries of the knee combine with acute anterior cruciate ligament tears to influence abnormal anterior tibial displacement**. *Am J Sports Med*. 1993;21(1):55-60. doi:10.1177/036354659302100110
20. Geeslin AG, Moatshe G, Chahla J, et al. **Anterolateral Knee Extra-articular Stabilizers: A Robotic Study Comparing Anterolateral Ligament Reconstruction and Modified Lemaire Lateral Extra-articular Tenodesis**. *Am J Sports Med*. 2018;46(3):607-616. doi:10.1177/0363546517745268
21. Willinger L, Athwal KK, Holthof S, Imhoff AB, Williams A, Amis AA. **Role of the Anterior Cruciate Ligament, Anterolateral Complex, and Lateral Meniscus Posterior Root in Anterolateral Rotatory Knee Instability: A Biomechanical Study**. *Am J Sports Med*. 2023;51(5):1136-1145. doi:10.1177/03635465231161071
22. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction Can Restore Native Knee Kinematics in the Anterior Cruciate Ligament Reconstructed Knee: A Systematic Review of Biomechanical Cadaveric Studies**. *Arthroscopy*. 2024;40(2):632-647.e1. doi:10.1016/j.arthro.2023.05.005
23. Lording T, Corbo G, Bryant D, Burkhart TA, Getgood A. **Rotational Laxity Control by the Anterolateral Ligament and the Lateral Meniscus Is Dependent on Knee Flexion Angle: A Cadaveric Biomechanical Study**. *Clin Orthop Relat Res*. 2017;475(10):2401-2408. doi:10.1007/s11999-017-5364-z
24. Geeslin AG, Chahla J, Moatshe G, et al. **Anterolateral Knee Extra-articular Stabilizers: A Robotic Sectioning Study of the Anterolateral Ligament and Distal Iliotibial Band Kaplan Fibers**. *Am J Sports Med*. 2018;46(6):1352-1361. doi:10.1177/0363546518759053
25. Godin JA, Chahla J, Moatshe G, et al. **A Comprehensive Reanalysis of the Distal Iliotibial Band: Quantitative Anatomy, Radiographic Markers, and Biomechanical Properties**. *Am J Sports Med*. 2017;45(11):2595-2603. doi:10.1177/0363546517707961
26. Kaplan EB. **The iliotibial tract; clinical and morphological significance**. *J bone Joint Surg Am Vol*. 1958;40-A(4):817-832.

27. Lubowitz JH. **All-Inside Anterior Cruciate Ligament Graft Link: Graft Preparation Technique**. *Arthrosc Tech*. 2012;1(2):e165-e168. doi:10.1016/j.eats.2012.06.002
28. Lubowitz JH, Ahmad CS, Amhad CH, Anderson K. **All-Inside Anterior Cruciate Ligament Graft-Link Technique: Second-Generation, No-Incision Anterior Cruciate Ligament Reconstruction**. *Arthroscopy*. 2011;27(5):717-727. doi:10.1016/j.arthro.2011.02.008
29. Williams A, Ball S, Stephen J, White N, Jones M, Amis A. **The scientific rationale for lateral tenodesis augmentation of intra-articular ACL reconstruction using a modified 'Lemaire' procedure**. *Knee Surg, Sports Traumatol Arthrosc*. 2017;25(4):1339-1344. doi:10.1007/s00167-017-4537-3
30. Bachmaier S, Krych AJ, Smith PA, et al. **Primary Fixation and Cyclic Performance of Posterior Horn Medial Meniscus Root Repair With Knotless Adjustable Suture Anchor–Based Fixation: A Human Biomechanical Evaluation Over 100,000 Loading Cycles**. *Am J Sports Med*. 2024;53(5):1093-1100. doi:10.1177/03635465251317210
31. Cinque ME, Hinz M, Sidrak J, et al. **Biomechanical Comparison of Transtibial Pull-out Fixation Versus Suture Anchor Fixation for Repair of Medial Meniscus Posterior Root Tears**. *Am J Sports Med*. 2025;53(9):2128-2135. doi:10.1177/03635465251342267

chapter 5

Modified Lemaire Anterolateral Corner Reconstruction Does Not Impact Forgotten Joint Score-12 at 2 Years in Hamstring Graft Anterior Cruciate Ligament Reconstructions in High-Risk Patients.

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ABSTRACT

Purpose

To compare Forgotten Joint Score-12 (FJS-12) at 2-year follow-up in patients younger than 25 years, with a preoperative Tegner score ≥ 7 and intent to return to competitive sports, undergoing either isolated single-bundle hamstring autograft anterior cruciate ligament reconstruction (ACLR) or hamstring autograft ACLR with modified Lemaire anterolateral corner (ALC) reconstruction.

Methods

This single-center retrospective comparative cohort study included patients aged 16 to 25 years with a preoperative Tegner score ≥ 7 who underwent hamstring autograft ACLR, with or without a modified lateral extra-articular Lemaire tenodesis, between January 2019 and December 2022. Patients completed questionnaires preoperatively and at 6 weeks, 6, 12, and 24 months postoperatively. The primary outcome was FJS-12 at 24-months. Secondary outcomes included other patient recorded outcome measures (PROMs) and re-rupture rates at 24-months.

Results

Of 245 included patients, 122 (49.8%) underwent ACLR with a Lemaire ALC reconstruction. The 24-month follow-up rate was 88% (216/245). At 12 months, the FJS-12 was higher in the non-Lemaire group (88.0 ± 15.2 vs 75.0 ± 18.1, p = 0.003). At 24 months, FJS-12 scores were similar between groups (70.8 ± 21.7 vs 70.9 ± 20.6, p = 0.96). Within the non-Lemaire group, the FJS-12 declined significantly between 12 and 24 months (79.9 ± 17.9 vs 70.9 ± 20.6, p = 0.006). No significant differences were found in other PROMs at 24 months. Re-ruptures occurred in 18 patients (14.6%) in the non-Lemaire group and 9 (7.4%) in the Lemaire group (p = 0.11).

Conclusion

At 12 months, isolated ACLR resulted in higher FJS-12 scores compared with ACLR combined with modified Lemaire ALC reconstruction. However, this difference did not exceed the MCID and had disappeared by 24 months, suggesting no clinically meaningful difference associated with adding a Lemaire ALC reconstruction at 24-month follow-up.

Level of Evidence

Level III, retrospective comparative study.

INTRODUCTION

In recent years, injury to the anterolateral corner (ALC) structures of the knee, in combination with anterior cruciate ligament (ACL) tears, has regained considerable attention. Cadaveric and clinical studies have reported that isolated ACL reconstruction (ACLR) without surgical treatment of the ALC may lead to residual anterolateral rotatory instability.[1–3] A recent biomechanical systematic review reported that an ALC reconstruction (ALCR), using either a modified Lemaire lateral extra-articular tenodesis (LET) or an anterolateral ligament (ALL) reconstruction can improve residual knee rotatory stability after an ACLR[4], thereby reducing graft load.[5]

A systematic review of predominantly isolated ACLR studies, reported pooled ipsilateral re-injury rates of 7%, with athletes younger than 25 years having the highest secondary ACL injury rates of 10%.[6] Another review of clinical studies concluded that adding a lateral extra-articular procedure, regardless of technique, reduced ACLR re-injury rates without increasing complications at follow-up of at least 12 months.[7]

Although graft failure and revision rates are important, they do not fully capture patient's perceived functional recovery. Patient-reported outcome measures (PROMs) have therefore become essential in evaluating ACLR success. The Forgotten Joint Score-12 (FJS-12), a 12-question patient-reported outcome measure originally developed for arthroplasty outcomes, is designed to assess the extent of patient's awareness of their joint in daily life. It is valued for its low ceiling effect and ability to detect subtle differences, making it particularly useful in high-functioning patients.[8,9] Previous work on FJS-12 use in postoperative ACLR outcomes has shown normally distributed results, facilitating parametric analyses.[8] However, few studies have reported FJS-12 outcomes after ACLR, and none have compared patients undergoing ACLR with versus without ALCR.

The purpose of this study was to compare FJS-12 scores at 2-year follow-up in patients younger than 25 years, with a preoperative Tegner score ≥ 7 and intent to return to competitive sports, undergoing either isolated single-bundle hamstring autograft ACLR or hamstring autograft ACLR with modified Lemaire ALCR. We hypothesized that adding a modified Lemaire ALCR to an ACLR would result in higher FJS-12 and other PROMs scores, and lower ACLR re-rupture rates at a minimum of 2-year follow-up.

METHODS

Study design and participants

This single institution, multiple-surgeon, retrospective comparative cohort study was approved by our Institutional Review Board (IRB no. 2206-037). Patients aged 16-25 years, with a preoperative Tegner score ≥ 7 and intent to return to competitive sports, who underwent a primary hamstring autograft ACLR with or without a modified Lemaire ALCR between January 1, 2019 and December 31, 2022, were reviewed. Competitive sports were defined as soccer, rugby, field hockey, basketball, volleyball, netball, handball, tennis, squash, badminton, track and field athletics, downhill skiing, and gymnastics. The inclusion period from January 2019 to December 2022 reflects our institution's transition toward routinely adding a modified Lemaire ALCR in patients considered at high risk for graft failure, primarily based on young age and intention to return to pivoting or contact sports. This time frame resulted in an approximately equal distribution between the isolated ACLR and ACLR + Lemaire groups. All procedures were performed by four board-certified orthopedic surgeons, with 4, 5, 5 (W.A.W.), and 12 years of post-certification experience at the start of the study period. The majority of cases were treated by a single surgeon (72.1%, W.A.W.). All available PROM data up to 1-year postoperatively were collected. Patients were invited by email to complete the questionnaires preoperatively and at 6 weeks, 6 months, and 12 months, supported by automated app and email reminders. If questionnaires were not completed, patients were reminded during their outpatient visit, where they could fill them in digitally or on paper, after which clinic staff digitized the responses. At 2 years, eligible patients were contacted to complete PROMs via Castor Electronic Data Capture (Castor EDC, Amsterdam, The Netherlands), with automated email reminders sent after 2 weeks and phone contact at 4 weeks if no response was received.

Exclusion criteria were: 1) lack of response at 2-year follow-up, 2) age < 16 or ≥ 25 years, 3) skeletal immaturity requiring a different surgical technique; 4) primary bone-patellar-tendon-bone (BPTB) or quadriceps graft ACLR; 5) multi-ligament injury requiring repair or reconstruction of more than one ligament; or 6) revision ACLR. The study followed the STROBE guidelines.[10]

Outcome Measures

The primary outcome of this study was the Forgotten Joint Score-12 (FJS-12), assessed preoperatively and at 6 weeks, 6 months, 12 months, and 24 months postoperatively. Secondary outcomes included other patient-reported outcome measures: the International Knee Documentation Committee (IKDC), Lysholm, and Tegner scores were collected preoperatively and at all follow-up timepoints; the ACL-Return to Sport after Injury Scale (ACL-RSI) was collected from 6 months onward; and the Visual Analogue Scale (VAS) for pain was collected from 6 weeks onward. In addition, complication rates and graft re-ruptures were evaluated as secondary outcomes. As part of routine care, patients were also assessed clinically at 2 and 6 weeks, 6 months, and 12 months. These were in-office visits; the 2-week assessment was conducted by a junior doctor, while all subsequent assessments (6 weeks, 6 months, and 12 months) were performed by one of the four orthopedic surgeons involved in the study, including author W.A.W. For this study, 24-month follow-up was conducted online. Clinical visits included patient interviews, knee examination (range of motion (ROM), Lachman-, pivot-shift-, anterior drawer-testing), and documentation of complications. MRI was obtained to confirm re-rupture in cases of recurrent instability or pathological graft laxity. The FJS-12 consists of 12 questions to investigate the extent to which patients "forget" their knee joint during daily activities, that has been validated to evaluate outcomes after ACL-reconstruction.[11] A higher score (closer to 100) indicates better outcome, meaning the patient is less aware of their knee. A lower score (closer to 0) indicates a less favorable outcome, meaning the patient is more aware of their knee (Figure 1).[9] The IKDC questionnaire is a 19-point survey investigating a patient's symptoms, sports activity, and knee function. A higher score indicates less pain and fewer limitations during daily activities.[12] The Lysholm questionnaire was designed to assess the degree of knee instability at both the level of impairment and the level of impediment. A high score corresponds to a low level of knee instability.[13] The Tegner activity scale contains 1 item in which the patient self-reports the severity of his/her work and sports activities. The score ranges from 0 to 10. A high score corresponds to a high level of activity.[14] The ACL-RSI consists of 12 questions developed to assess psychological readiness for return to sport, with a higher score indicating more psychological readiness.[15] The Visual Analogue Scale (VAS) is a scale for pain intensity. The score ranges from 0 to 10, with 0 representing no pain and 10 indicating the worst imaginable pain.

Forgotten Joint Score-12 items
1. Awareness in bed at night?
2. Awareness sitting on a chari for more than 1h?
3. Awareness when you are walking for more than 15min?
4. Awareness taking a bath/shower?
5. Awareness traveling in a car?
6. Awareness climbing stairs?
7. Awareness walking on uneven ground?
8. Awareness when standing up from a low sitting position?
9. Awareness standing for long periods of time?
10. Awareness doing housework or gardening?
11. Awareness taking a walk/hiking?
12. Awareness when you are doing your favorite sport?

Never, 0; Almost never, 1; Seldom, 2; Sometimes, 3; Mostly, 4

Figure 1. The Forgotten Joint Score-12 For calculation of the Forgotten Joint Score-12 the raw scores for all 12 items are averaged. This average is multiplied by 25. The result is then subtracted from 100 to get the final score. A higher score (closer to 100) indicates better outcome, meaning the patient is less aware of their knee. A lower score (closer to 0) indicates a less favorable outcome, meaning the patient is more aware of their knee.

At 24 months, patients reported any re-ruptures (including date of re-injury), postoperative knee infections, and consultations with other physicians related to the involved knee. Additional information was obtained for events not already documented. Complications were categorized as wound healing problems, infections (superficial or deep requiring debridement and antibiotics), venous thromboembolism (VTE), and cyclops/ arthrofibrosis formation. Demographics included age, sex, body mass index (BMI), graft details, associated knee pathologies, and additional surgical procedures.

Surgical techniques

Graft harvesting and preparation

The semitendinosus graft was harvested posteriorly[16] by three of four surgeons, including author W.A.W., using an atraumatic closed tendon harvester proximally and a closed harvester distally (Arthrex, Naples, FL, USA). One surgeon used an anterior approach with an oblique incision above the pes and an open tendon harvester. Grafts were quadrupled and fixed with adjustable cortical suspensory fixation (Femoral and Tibial TightRope, Arthrex). If the graft diameter was lower than 8mm, the gracilis tendon was harvested and tendons were tripled or quadrupled.

ACL Reconstruction

Anatomic, single-bundle, all-inside ACLRs were performed as described by Lubowitz et al.[17] Femoral and tibial aimers were positioned at the center of the anteromedial femoral ACL attachment site, and at the center of the tibial ACL attachment site, tunnels drilled retrograde, and the graft was tensioned in full extension.

Modified Lemaire ALC Reconstruction

The ALCR was performed with the modified Lemaire technique as described by Williams et al.[18] A 1 x 10 cm iliotibial band strip was harvested, left attached to Gerdy's tubercle, whip-stitched proximally, passed deep to the lateral collateral ligament, and fixed in a 4.5mm socket just proximal and posterior to the lateral epicondyle, with a non-absorbable Poly-Ether-Ether-Ketone (PEEK) tenodesis interference screw (Arthrex) at 30° of flexion and neutral rotation with about 20N tension (by feel). The ITB defect was closed with a continuous Vicryl suture.

Postoperative rehabilitation

Postoperative rehabilitation was identical for both groups and followed the evidence-based guideline by the Royal Dutch Society for Physical Therapy. Bracing was not used. Weight-bearing was generally allowed from the first postoperative day with crutches, progressing to full weight-bearing without crutches only if patients showed a normal gait pattern and did not experience pain or swelling during or shortly after walking. In cases of concomitant meniscal repair or cartilage treatment, an initial period of non-weight-bearing mobilization was prescribed, followed by gradual loading. Rehabilitation included a prehabilitation phase and three criterion-based postoperative phases: (1) impairment-based rehabilitation, (2) sport-specific training, and (3) return-to-play preparation. Return to sport was typically allowed after 9–12 months, depending on functional performance and criteria-based testing.[19]

Statistical Analysis

Continuous variables were tested for normality using the Shapiro–Wilk test. Normally distributed data were presented as mean ± SD and compared with t-tests, and non-normal data as median (IQR) and compared using the Mann–Whitney U test. Categorical variables were presented as counts and percentages. Group differences were assessed using the Chi-square test of independence or Fisher's exact test.

All PROMs were compared across five predefined time points: T0 (preoperative), T1 (6 weeks postoperative), T2 (6 months postoperative), T3 (1 year postoperative), and T4 (2 years postoperative). The VAS was assessed only up to T3 (1 year postoperative). In addition to comparisons between Lemaire and non-Lemaire groups at each time point, within-group comparisons between T3 and T4 were made for all PROMs except the VAS-score, for which T2 and T3 were compared. For these comparisons, the paired t-test was applied for normally distributed outcomes, while the Wilcoxon signed-rank test was used for non-normally distributed variables. Boxplots were created for each PROM at every time point (Figures 2-7) Missing data were handled using pairwise deletion, meaning that patients with missing values were excluded only from the specific analysis involving that variable. The percentage of missing data varied across PROMs (Supplementary Table 1).

For the primary outcome (FJS-12), we defined a cohort-specific MCID as ½ SD of the within-patient change in FJS-12 from T0 to T4 (ΔFJS-12). We then calculated, for each group, the proportion of patients achieving this MCID and compared these proportions using a χ^2 test. The distribution of ΔFJS-12 between groups was compared using a Mann–Whitney U test. All analyses were performed in Python V3.13 (Python Software Foundation, Wilmington, DE, USA) using the Anaconda Distribution (Anaconda, Inc., Austin, TX, USA). The packages pandas, NumPy, SciPy, and statsmodels were used for analysis, and figures were created with Matplotlib. All analyses were run in Spyder, environment details and code can be made available on reasonable request. A two-sided p-value < 0.05 was considered statistically significant.

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RESULTS

Baseline and Preoperative Characteristics

Of the 262 patients who met the inclusion criteria, 17 did not respond at T4, leaving 245 available for analysis (94%) (Figure 2). Of these, the completed forms per timepoint were: ACL-RSI—T2: 174, T3: 186, T4: 216 (not collected at T0–T1); FJS-12—T0: 150, T2: 164, T3: 157, T4: 224 (not collected at T1); IKDC—T0: 147, T3: 145, T4: 218 (not collected at T1–T2); Lysholm—T0: 150, T1: 160, T2: 157, T3: 150, T4: 217; Tegner—T1: 165, T2: 178, T3: 189, T4: 217 (not collected at T0); VAS—T1: 164, T2: 178, T3: 189 (not collected at T0 and T4). Full per-timepoint counts and completeness breakdowns are provided in Supplementary Table S1. Out of the 245 included patients, 122 (49.8%) underwent an ACLR with a Lemaire ALCR. This group had a median age of 19.0 years, median BMI of 22.6, preoperative Tegner score of 9, and included 73 male patients (59.8%). The 123 patients (50.2%) who underwent an isolated ACLR had a median age of 21.0 years, median BMI of 23.2, preoperative Tegner score of 8, and included 72 male patients (58.5%) (Table 1). Preoperatively, the Lemaire group had significantly higher Tegner scores (9 vs. 8, $p < 0.01$), were younger (19 versus 21 years, $p = 0.03$) and had lower BMI (22.6 versus 23.2, $p = 0.047$). At 24-month follow-up, 216 of 245 patients (88%) completed at least one of the questionnaires. The last date of follow-up was May 2, 2025. Follow-up duration was calculated as the time interval between the date of surgery and the date the questionnaire was completed. Mean follow-up was 863 days for the Lemaire-group (95%CI 703-1329 days) and 1150 days for the non-Lemaire group (95%CI 731-1550 days.)

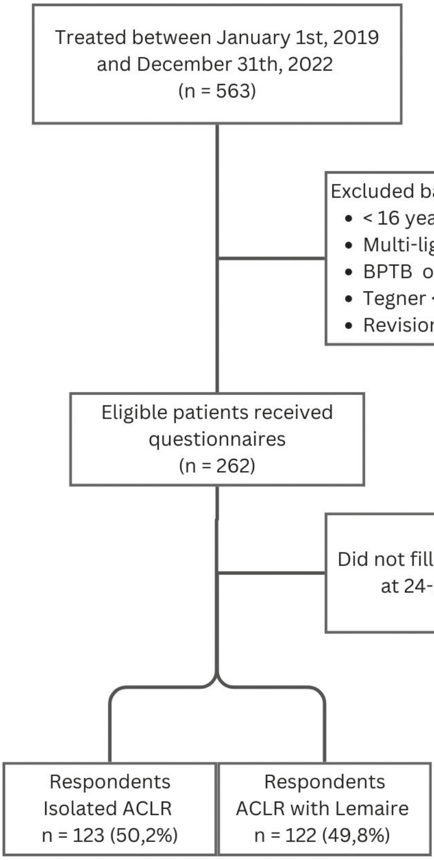

Figure 2. Flowchart of the included patients.

Table 1. Baseline Characteristics

	Lemaire (n= 122)	Non-Lemaire (n= 123)	p-value
Age (yr)	19.0 [17.0 - 22.0]	21.0 [18.0 - 23.0]	**.03**
Male sex	72 (58.5%)	73 (59.8%)	.99
BMI	22.6 [21.2 - 24.1]	23.2 [21.6 - 25.5]	**.047**
Laterality			.37
Right	61 (50.0%)	69 (56.1%)	
Left	61 (50.0%)	53 (43.1%)	
Bilateral	0 (0%)	1 (0.8%)	
Concomitant procedures			
Meniscus repair			.84
Lateral	20 (15%)	19 (15%)	
Medial	22 (18%)	16 (13%)	
Both	10 (8%)	9 (7%)	
Meniscectomy			.09
Lateral	4 (3%)	7 (6%)	
Medial	3 (2%)	7 (6%)	
Both	3 (2%)	0 (0%)	
Root repair	6 (5%)	9 (7%)	.44
Graft type			.87
Semitendinosis	100 (82.0%)	102 (82.9%)	
Semitendinosis + Gracilis	22 (18.0%)	20 (16.3%)	
Complications			
Re-rupture	9 (7.4%)	18 (14.6%)	.11
Superficial wound infection	3 (3%)	1 (1%)	.37
Deep wound infection	2 (2%)	2 (2%)	.99
Wound dehiscence	3 (3%)	4 (4%)	.99
Re-operations			.54
0	105 (86%)	105 (85%)	
1	15 (12%)	12 (10%)	
2	1 (0.8 %)	3 (2.4%)	
3	0 (0%)	2 (2%)	
4	1 (0.8 %)	1 (1%)	

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Table 1. Baseline Characteristics

	Lemaire (n= 122)	Non-Lemaire (n= 123)	p-value
Cyclops laesion required surgical treatment	6 (4.9%)	2 (1.6%)	.15
Graft diameter	8.5 [8.0 - 9.0]	8.5 [8.0 - 9.0]	.72
Time to re-rupture (d)	453.89 ± 267.47	698.71 ± 489.71	.11
Tegner preoperatively	9.0 [8.0 - 9.0]	8.0 [7.0 - 9.0]	**<.01**
Tegner postoperatively	7.0 [5.0 - 9.0]	7.0 [5.0 - 7.0]	.1

Note: Values are presented as number and percentage for categorical variables, median with interquartile range for non-normally distributed continuous variables, and mean with standard deviation for normally distributed variables. Statistical comparisons between the Lemaire and non-Lemaire groups were performed using the chi-square test or Fisher's exact test for categorical data, and the Mann–Whitney U test for continuous variables unless normally distributed, in which case the t-test was used. Significant values are highlighted in bold.
BMI, body mass index; d, day; yr, year

Primary Outcome: Forgotten Joint Score-12
No significant differences were found in FJS-12 scores between groups at baseline, 6 months, and 24 months. At 12 months, the non-Lemaire group reported significantly higher scores compared with the Lemaire group (88.0 versus 75.0, $p < 0.01$). At 24-months, scores were not significantly different (70.83 versus 70.83, $p = 0.51$) (Table 2). Analysis of within-group comparisons showed a significant decrease in FJS-12 scores from 12 to 24 months in the group that underwent isolated ACLR (79.9 versus 70.9, $p<0.01$), whereas no significant changes occurred in this time period in the ACL + Lemaire group (70.8 [IQR 52.1 – 87.5] versus 70.8 [IQR 56.3 – 88.5]; $p<0.01$) (Figure 3, Table 3). We defined a cohort-specific MCID as ½ SD of within-patient ΔFJS-12 from T0 to T4 (14.75 points). Among complete T0–T4 pairs, 54.5% of Lemaire patients (48/88) and 60.9% of non-Lemaire patients (28/46) achieved the MCID (risk difference −6.3 percentage points; χ^2 p=0.483). The distribution of change (ΔFJS-12 = T4–T0) did not differ meaningfully between groups (Mann–Whitney p=0.260; Cliff's δ −0.12, small). At final follow-up, the between-group difference in FJS-12 was smaller than the MCID, indicating no clinically important difference (Table 4).

Table 2 Patient-reported outcome measurements

Questionnaire	**Lemaire (N)**	**Non-Lemaire (N)**	**Lemaire**	**Non-Lemaire**	**p-value**
Forgotten Joint Score-12					
*Preoperatively**	95	55	42.0 (IQR 26.0–70.0)	42.0 (IQR 23.0–59.5)	.59
*6 mo postoperatively**	95	69	66.7 (IQR 52.0–81.33)	69.0 (IQR 46.0–90.0)	.42
*12 mo postoperatively**	84	73	75.0 (IQR 31.5–92.0)	88.0 (IQR 67.0–96.0)	**.0005**
*24 mo postoperatively**	113	111	70.8 (IQR 52.08–87.5)	70.8 (IQR 56.25–88.54)	.50
IKDC					
*Preoperatively**	93	54	66.7 (IQR 60.9–74.7)	64.4 (IQR 54.3–71.0)	.11
*12 mo postoperatively**	58	87	85.1 (IQR 81.6–87.4)	85.1 (IQR 79.3–88.5)	.64
*24 mo postoperatively**	109	109	82.8 (IQR 75.9–87.4)	83.9 (IQR 78.2–88.5)	.46
Lysholm					
*Preoperatively**	96	54	64.5 (IQR 50.8–79.0)	63.5 (IQR 51.3–73.8)	.40
*6 wk postoperatively^*	99	61	57.1 ± 19.7	59.4 ± 21.5	.50
*6 mo postoperatively**	93	64	85.0 (IQR 77.0–91.0)	84.0 (IQR 74.75–90.0)	.48
*12 mo postoperatively**	87	63	94.0 (IQR 88.0–95.5)	91.0 (IQR 86.0–95.5)	.67
*24 mo postoperatively**	108	109	89.0 (IQR 81.8–95.0)	86.0 (IQR 80.0–94.0)	.62
Tegner					
*Preoperatively**	122	123	9 (IQR 8–9)	8 (IQR 7–9)	**.0009**
*6 wk postoperatively**	101	64	2 (IQR 1–2)	2 (IQR 0–2)	.52
*6 mo postoperatively**	100	78	4 (IQR 4–5)	4 (IQR 3.3–5.0)	.39

Table 2 Patient-reported outcome measurements (continued)

Questionnaire	**Lemaire (N)**	**Non-Lemaire (N)**	**Lemaire**	**Non-Lemaire**	**p-value**
*12 mo postoperatively**	98	91	7 (IQR 6–9)	7 (IQR 6–8)	.14
*24 mo postoperatively**	108	109	7 (IQR 5–9)	7 (IQR 5–7)	.10
ACL-RSI					
*6 mo postoperatively^*	97	77	55.2 ± 20.8	54.6 ± 22.8	.84
*12 mo postoperatively**	96	90	67.9 (IQR 53.5–85.0)	70.4 (IQR 51.9–84.8)	.82
*24 mo postoperatively**	107	109	62.5 (IQR 47.1–80.8)	65.8 (IQR 49.2–83.3)	.73
VAS					
*6 wk postoperatively**	101	63	1.6 (IQR 1.0–2.4)	1.5 (IQR 0.8–2.8)	.74
*6 mo postoperatively**	100	78	0.8 (IQR 0.1–1.5)	0.7 (IQR 0.2–1.5)	.71
*12 mo postoperatively**	99	90	0.3 (IQR 0.0–0.88)	0.3 (IQR 0.0–1.12)	.68

Note: Values are presented as median with interquartile range for non-normally distributed continuous variables, and mean with standard deviation for normally distributed variables. Statistical comparisons between the Lemaire and non-Lemaire groups were performed using the chi-square test or Fisher's exact test for categorical data, and the Mann–Whitney U (*) test for continuous variables unless normally distributed, in which case the t-test (^) was used. Other complications included one case of symptomatic bone cyst formation, one case of scar irritation, and one cyclops lesion.

Significant values are highlighted in bold.

ACL-RSI, Anterior Cruciate Ligament - Return to Sport after Injury Scale; IKDC, International Knee Documentation Committee; IQR, interquartile range; mo, month; VAS, Visual Analogue Scale; wk, week

Table 3 Patient-Reported Outcome Measurements – Intra group analyses

PROM	Group	N	Test	p-value	T3 (12 months)	T4 (24 months)
Forgotten Joint Score-12	Lemaire	77	Wilcoxon	.31	75.0 (IQR 31.0–92.0)	72.9 (IQR 56.3–89.6)
	Non-Lemaire	61	Paired t-test	.0005	79.9 ± 20.2	71.0 ± 21.0
IKDC	Lemaire	51	Paired t-test	.06	84.4 ± 5.2	82.2 ± 7.4
	Non-Lemaire	75	Wilcoxon	.72	85.1 (IQR 79.3–88.5)	85.1 (IQR 79.3–89.7
Lysholm	Lemaire	75	Paired t-test	.01	90.4 ± 9.8	87.7 ± 11.4
	Non-Lemaire	52	Paired t-test	.02	90.8 ± 8.0	87.6 ± 9.3
Tegner	Lemaire	86	Wilcoxon	.05	7 (IQR 6–9)	7 (IQR 5.3–9)
	Non-Lemaire	78	Wilcoxon	.0479	7 (IQR 6–8)	7 (IQR 5–7)
ACL-RSI	Lemaire	82	Wilcoxon	.94	67.1 (IQR 54.37–83.33)	65.8 (IQR 50.8–80.8)
	Non-Lemaire	77	Paired t-test	.48	65.8 ± 24.5	67.4 ± 22.1
VAS	Lemaire	87	Wilcoxon	.0001	0.8 (IQR 0.2–1.5)	0.4 (IQR 0.0–0.9)
	Non-Lemaire	70	Wilcoxon	.0005	0.6 (IQR 0.2–1.5)	0.2 (IQR 0.0–1.1)

Note:Values are presented as median with interquartile range for non-normally distributed continuous variables, and mean with standard deviation for normally distributed variables. Statistical comparisons between the Lemaire and non-Lemaire groups were performed using the chi-square test or Fisher's exact test for categorical data, and the Mann–Whitney U test for continuous variables unless normally distributed, in which case the t-test was used. Other complications included one case of symptomatic bone cyst formation, one case of scar irritation, and one cyclops lesion.
Significant values are highlighted in bold.
ACL-RSI: Anterior Cruciate Ligament - Return to Sport after Injury Scale IKDC: International Knee Documentation Committee; IQR, interquartile range; mo, month; PROM, patient-recorded outcome measure; VAS, Visual Analogue Scale

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Table 4. FJS MCID and Change (Complete-Case T0–T4 Pairs)

Outcome / Measure	Lemaire (n=88)	Non-Lemaire (n=46)	Effect / Statistic	p-value
MCID achieved	48/88 (54.5%)	28/46 (60.9%)	RD −6.3 pp; RR 0.90; OR 0.77	.48 (χ^2)
ΔFJS (T4–T0)	17.9 (-0.75 42.4)	21.1 (7.9 – 52.5)	Cliff's δ = −0.12	.26 (Mann–Whitney U)

Note: MCID defined as ½ SD of within-patient ΔFJS (threshold = 14.75 points). Analysis uses complete T0–T4 pairs with known group. RD = risk difference (Lemaire − Non-Lemaire, percentage points); CIs for proportions are Wilson. ΔFJS is summarized as median (IQR).
CI, confidence interval; FJS, Forgotten Joint Score; IQR, interquartile range; MCID, minimal clinically important difference; OR, odds ratio; RD, risk difference; RR, risk ratio; SD, standard deviation.

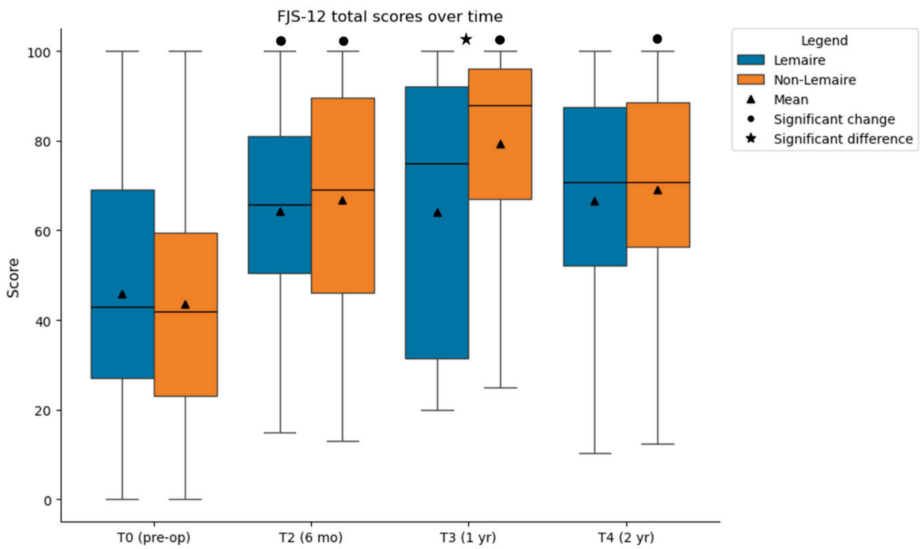

Figure 3. Development of FJS-12 scores over time in patients treated with and without a Lemaire procedure. Boxplots represent median and interquartile range of FJS-12 scores at preoperative (T0), 6 months (T2), 1 year (T3), and 2 years (T4) follow-up. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous time-point, * denotes a significant difference between the Lemaire and non-Lemaire group at a timepoint.

Secondary Outcomes: Other PROMs and re-rupture Rates

There were no significant between-group differences at any time point for the IKDC scores, (p = 0.11 at baseline, p = .64 at 12 months and p = .46 at 24 months. The non-Lemaire group improved from 64.4 preoperatively to 85.1 at 12 months and 83.9 at 24 months; The Lemaire group improved from 66.7 to 85.1 and 82.7, respectively. No significant changes occurred between 12- and 24-months within either group, (p = .06 and p = .72) (Figure 4, Table 2).

The Lysholm scores did not differ significantly between groups at any time point. Preoperatively, scores were 63.5 in the non-Lemaire and 64.5 in the Lemaire group (p = .40); at 6 weeks, 59.4 and 57.1 (p = .49), at 6 months 84.0 and 85.0 (p = .49), at 12 months 91.0 and 94.0 (p = .67), and at 24 months 86.0 and 89.0 (p = .62). Scores declined significantly between 12 and 24 months within both groups (non-Lemaire 90.8 to 87.6, p = .02; Lemaire: 90.4 to 87.7 p = .02) (Figure 5, Table 2).

Preoperatively, the Lemaire group had higher Tegner scores than the non-Lemaire group (9 vs. 8, p < .001). At 6 weeks, both groups scored 2 (p= .52); at 6 months, 4 (p= .39); at 12 months, 7 (p= .14); and at 24 months, 7, (p= .09). Between 12- and 24-months, no significant change was observed within the Lemaire group, whereas in the non-Lemaire group there was a significant decrease (p = .04) (Figure 6, Table 2).

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The ACL-RSI scores showed no significant between-group differences at any time point. At 6 months, scores were 54.6 in the non-Lemaire and 55.2 in the Lemaire group, (p = .84); at 12 months, 70.4 and 67.9, (p = .82); and at 24 months, 65.8 and 62.5 (p = .73). No significant changes occurred between 12- and 24-months within both groups, (p = .48 and p = .94) (Figure 7, Table 2).

Postoperative pain scores (VAS) were low in both groups with no significant differences at 6 weeks, 6 months, or 12 months (Figure 7). At 12 months, median VAS was 0.3 in both groups (p = .68). Significant decreases occurred from 12 to 24 months in both groups (non-Lemaire: 0.6 to 0.2 (p < .01), Lemaire 0.8 to 0.4 (p = .01) (Figure 8, Table 2).

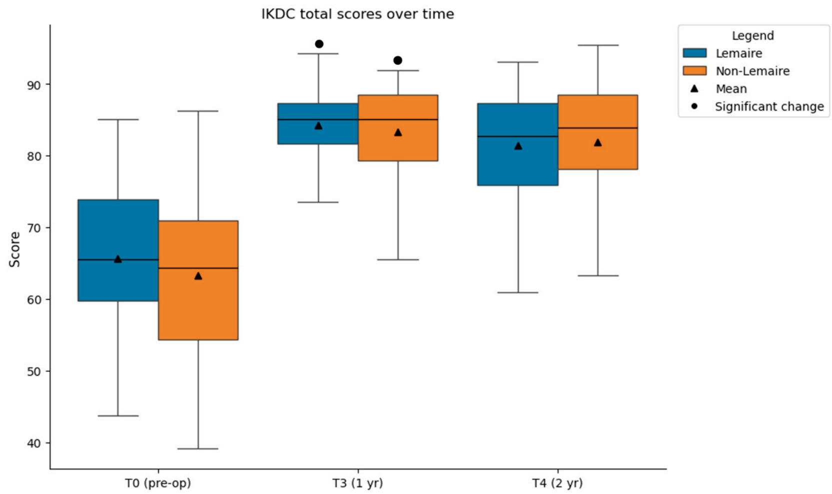

Figure 4. Development of IKDC scores over time in patients treated with and without a Lemaire procedure. Timepoints shown are preoperative (T0), 1 year (T3), and 2 years (T4) postoperatively. Boxplots represent median and interquartile range. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous timepoint.

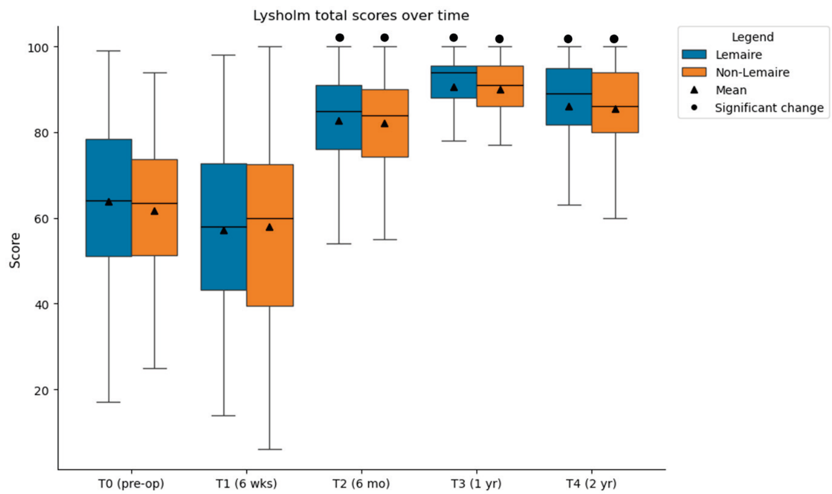

Figure 5. Development of Lysholm scores over time in patients treated with and without a Lemaire procedure. Lysholm scores are plotted for T0 (pre-op), T1 (6 weeks), T2 (6 months), T3 (1 year), and T4 (2 years). Boxplots represent median and interquartile range. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous timepoint.

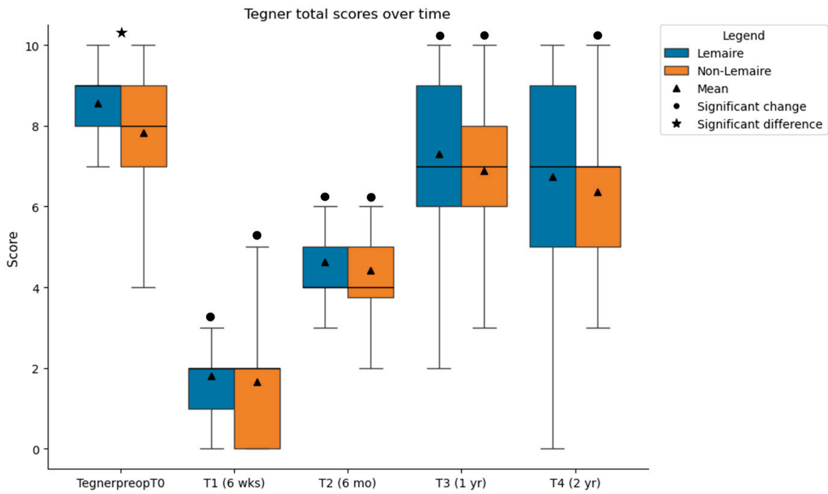

Figure 6. Development of Tegner activity scores over time in patients treated with and without a Lemaire procedure. Scores are reported for preoperative activity (T0) and postoperative activity at 6 weeks (T1), 6 months (T2), 1 year (T3), and 2 years (T4). Boxplots represent median and interquartile range. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous timepoint, asterix denotes a significant difference between the Lemaire and non-Lemaire group at a timepoint.

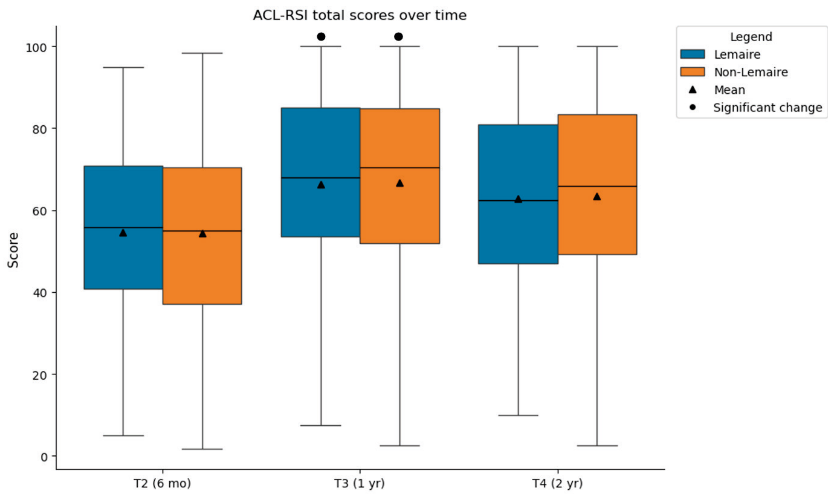

Figure 7. Development of ACL-RSI scores over time in patients treated with and without a Lemaire procedure. Timepoints shown are 6 months (T2), 1 year (T3), and 2 years (T4) postoperatively. Boxplots represent median and interquartile range. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous timepoint.

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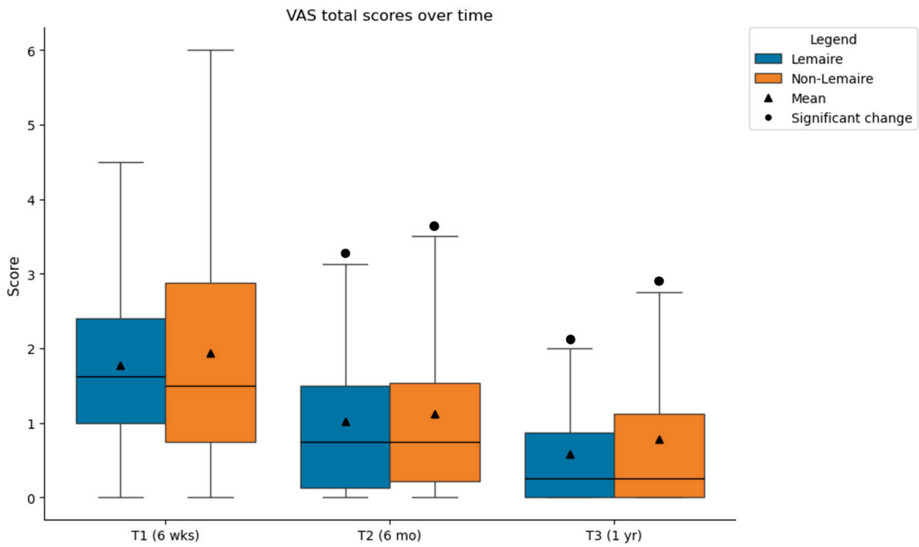

Figure 8. Development of VAS pain scores over time in patients treated with and without a Lemaire procedure. VAS scores are reported for T1 (6 weeks), T2 (6 months), and T3 (1 year) postoperatively. Boxplots represent median and interquartile range. Black triangles indicate the group mean, dots denote a significant change within the Lemaire or non-Lemaire group compared with the previous timepoint.

A total of 27 re-ruptures (11.0%) occurred. There were 18 re-ruptures (14.6%) in the non-Lemaire group and 9 re-ruptures (7.4%) in the Lemaire group (p = .11). In the non-Lemaire group, re-ruptures occurred during soccer (9), netball (1), (on-field) rehabilitation (3), a jump from height (1), due to infection (1), or during an unspecified activity (3). In the Lemaire group re-ruptures occurred during soccer (5), handball (1), netball (1), (on-field) rehabilitation (1), or an unspecified activity (1).

Complications

Over the 24-month follow-up, 26 complications, excluding graft failures, were recorded. Eight infections occurred—four superficial (1.6%) – of whom 1 was in the non-Lemaire group and 3 in the Lemaire group-, treated with oral antibiotics, and four deep (1.6%) of whom 2 in both groups-, requiring irrigation and debridement. Wound dehiscence occurred in seven patients (2.9%) -of whom 4 were in the non-Lemaire group and 3 in the Lemaire group-, while three patients (1.2%) experienced transient sensory disturbance or scar irritation -of whom 2 were in the non-Lemaire group and 1 was in the Lemaire group-. Two wound-related complications (1.6%) occurred at the lateral extra-articular tenodesis (LET) site in the Lemaire group. No symptomatic deep venous thrombosis events were observed. Eight patients experienced extension deficit due to cyclops formation – of whom 2 were in the non-Lemaire group and 6 in the Lemaire group. Thirty-five patients (14.2%) underwent 49 reoperations: 16 for ACL graft rupture, (12 non-Lemaire, 4 Lemaire), 12 for meniscus (re)tears

(5 non-Lemaire, 7 Lemaire), 8 cyclops lesions (2 non-Lemaire, 6 Lemaire). All patients who underwent meniscal reoperation were followed for a minimum of 6 months post-revision, or longer if clinically indicated. No statistically significant differences in complication or reoperation rates were found between groups (Table 1).

DISCUSSION

The most important finding of this study was that adding a modified Lemaire ALCR to hamstring autograft ACLR in patients between 16 – 25 years, with a preoperative Tegner score ≥ 7 and the intent to return to competitive sports, did not result in a statistically significant difference in FJS-12 outcomes at 24-months compared with an isolated hamstring autograft ACLR. Similarly, no differences were observed in IKDC, Lysholm, Tegner, or ACL-RSI scores at 24 months. These results contradict our first hypothesis that a Lemaire tenodesis would improve subjective PROMs. In line with our second hypothesis, the Lemaire group exhibited a numerically lower overall graft re-rupture rate. However, the study was underpowered to demonstrate a statistically significant difference.

Interestingly, at 12 months, FJS-12 scores were significantly higher in the non-Lemaire group, but at 24 months scores converged (70.8 in both groups), indicating a moderate level of joint awareness.[20] However, these differences did not meet the MCID. Although a statistically significant difference in FJS-12 scores was found at one-year follow-up, the clinical relevance of this difference warrants caution. Reported minimal clinically important differences (MCID) for the FJS-12 vary by context and procedure. Clement et al. suggested an MCID of 16.6 and a minimal important change of 17.7 for total knee arthroplasty cohorts, with a minimal important change of 10 for individuals.[21] For total hip arthroplasty, a similar minimal important change of 18 was reported[22] while for unicompartmental knee arthroplasty, the MCID may be as high as 19.8.[23] In our study, the between-group difference in FJS-12 at one year approached but did not clearly exceed these thresholds, and nearly disappeared at two years. This may reflect true convergence over time, but the potential for early measurement bias should also be considered. Differences in incision location and scarring between groups—specifically the lateral incision associated with the Lemaire procedure—could have influenced early FJS responses, as has been observed following total knee arthroplasty.[24] Baseline differences in age, BMI, and Tegner score were noted, with the Lemaire group being younger (19.0 versus 21.0 years, p = 0.03), having a lower BMI (22.6 vs. 23.2, p <0.047), and a higher pre-operative Tegner score (9.0 vs. 8.0, p<0.01). It is possible that the patients in the Lemaire group were more active and more cognitively engaged with their knee, explaining the difference in FJS-12 scores at 12 months. Furthermore, these intrinsic baseline cohort differences reflect a deliberate selection of high-risk, high-demand patients for additional ALCR, based on factors such as age and return-to-sport goals. This may have introduced differences in rehabilitation expectations and subjective knee perception between groups. More active patients may be more aware of minor limitations, which could temporarily lower their FJS-12 scores. In contrast, the slightly older and potentially less demanding non-Lemaire group may have had more modest expectations regarding knee performance, influencing their perception of joint awareness. These psychological and functional differences between cohorts, rather than the surgical procedure alone, may thus have contributed to the transient difference observed in joint awareness at one year. The small BMI difference, with both medians within the normal range, is unlikely to have affected outcomes. Given that younger age is a well-established risk factor for graft failure[25] this variable likely played a role in the clinical decision to add a modified Lemaire ALCR in patients deemed at elevated risk, particularly during the transitional period in our clinic toward more routine implementation of this procedure. Few studies have evaluated the FJS-12 in the ACLR setting. Ferreira et al. reported scores of 74.2 at 30 months for an isolated ACLR group[26] , comparable to the 70.8 in our study. Lee et al. also found comparable scores (71.4) at ≥ 24 months[8], while Ferretti et al. reported 91.4 at 24-months in an ACLR with ALCR cohort of 47 patients.[27] Their exclusive inclusion of acute injuries (<15 days) contrasts with our cohort's variable chronicity, potentially influencing tissue quality, rehabilitation, and subjective recovery. Our cohort's higher preoperative Tegner scores (9 versus 7) also suggest a more demanding athletic population, in whom even subtle joint awareness may be perceived.[8] Sakamoto et al. reported exceptionally high scores in a double-bundle, isolated hamstring ACLR group (95.8 at 24 months) - the highest reported – raising questions about ceiling effects, despite claims of resistance to such bias. Cultural or psychological factors may have influenced scores, particularly as the Japanese version was validated in arthroplasty patients rather than in young ACL-injured athletes.[28] Age may influence FJS-12 scores, as younger individuals may have higher physical expectations and greater sensitivity to subtle functional deficits, leading to lower joint awareness thresholds and potentially lower FJS-12 scores despite good objective outcomes.

The IKDC scores improved from 64.4 preoperatively to 83.9 at 24 months in the non-Lemaire group and from 66.6 to 82.8 in the Lemaire group, with no significant differences between them ($p = 0.46$ and $p = 0.16$, respectively). These findings are consistent with current literature. Getgood et al. reported an IKDC score of 87.3 for ACLR + LET patients at 24 months, which was not statistically different from the isolated ACLR group[29], while Sonnery-Cottet et al. reported scores of 85.4 and 81.8 for isolated ACLR and ACLR with ALL reconstruction, respectively.[30] These results suggest that adding an ALCR does not compromise patient-reported knee function and may yield comparable, if not slightly improved, outcomes up to 24 months postoperatively.

The Lysholm scores in our study improved from 63.5 preoperatively to 86.0 at 24 months in the non-Lemaire group and from 64.5 to 89.0 in the Lemaire group, with no significant differences between them ($p = 0.62$ and $p = 0.40$, respectively). While these results are favorable, they are slightly lower than those reported by Sonnery-Cottet et al., who observed Lysholm scores of 91.3 and 91.9 at 24-month in isolated ACLR and ACLR with ALL reconstruction groups, respectively.[30] Rowan et al. reported even higher scores of 98 and 90 in a cohort comparing isolated ACLR to ACLR with ALCR, however their lack of pre-operative Lysholm scores makes direct comparison difficult.[31]

Preoperatively, the Lemaire group had a significantly higher Tegner score than the non-Lemaire group (9 versus 8, $p< 0.001$), reflecting a greater level of sports participation. This likely mirrors our evolving clinical practice, in which patients deemed at highest risk for graft failure—often highly active athletes—were more frequently selected for a concomitant Lemaire tenodesis. At 24 months, both groups had a mean score of 7 (p = 0.09), indicating that patients did not regain their preinjury activity level.

The ACL-RSI scores in our cohort were consistent with the prior literature, with no significant difference between groups (65.8 in the non-Lemaire group versus 62.5 in the Lemaire group at 24 months; $p = 0.72$. Thomas et al. reported scores of 72 versus 62; ($p = 0.15$) at 7 months, which are higher than our 6 month scores (55.2 versus 54.6; p = 0.84).[32] Their older mean patient age may explain this difference, as a recent systematic review associated older age with higher early postoperative ACL-RSI scores, possibly due to more mature coping skills and a perception of being further along the recovery pathway.[33] Joseph et al. at reported 8 month postoperative results of 78.7 versus 77.1,[34] and Ferretti et al. found a notably higher score of 85.4 in their ACLR with ALCR group at 25.2 months -one of the highest reported.[27] Their inclusion of only patients operated within 15 days of injury contrasts with our cohort's longer interval time from injury to surgery, which may account for lower ACL-RSI outcomes[33]. A prolonged preoperative period with recurrent instability may negatively influence psychological readiness to return to sport. Overall, our findings suggest that the addition of a Lemaire ALCR does not adversely affect psychological readiness, and may provide reassurance in high-risk patients without compromising subjective outcomes. Pain scores are rarely reported in comparable studies. One might expect that an additional procedure, such as a modified Lemaire ALC with an extra incision, could increase early postoperative pain. In our study, pain scores were similar between groups at 6 weeks, 6 months, and 12 months, suggesting that adding a modified Lemaire ALCR does not increase mid-term pain. Interestingly, Getgood et al. reported higher pain scores in the ACLR with LET group at 3 and 6 months[29]. Future studies should assess early postoperative pain (≤ 6 weeks) to further investigate potential short-term differences associated with ALCR.

A systematic review of predominantly isolated ACLR studies reported pooled ipsilateral re-injury rates of 7%, with athletes younger than 25 years having the highest secondary ACL injury rates of 10%.[35] Our study recorded 27 re-ruptures overall (11.0%), with 18 re-ruptures (14.6%) in the non-Lemaire group versus 9 in Lemaire group (7.4%) -a 49% relative reduction. Although not statistically significant, these results align with previous literature suggesting that a concomitant ALCR can reduce ACLR re-rupture risk in high-demanding athletes. Getgood et al., in a randomized controlled trial of 618 patients, found significantly lower graft failure rates in ACLR with ALCR compared with isolated ACLRs (4% versus 11%). The higher re-rupture rates in our cohort may relate to higher baseline activity levels, as reflected by preoperative Tegner scores. In the study of Getgood et al. no Tegner scores were reported but patients that aimed to return to high-risk pivoting sports were selected.[29] Mahmoud et al. reported a non-significant reduction in re-ruptures after adding an ALCR (5% vs. 11%, $p = 0.09$) at 10 year follow-up, but their lower preoperative Tegner score (5) and higher mean age (25 years) may explain the difference from our results.[36] Sonnery-Cottet et al. also found reduced graft failure rates in their prospective randomized study at 38 months in ACLR hamstring grafts with ALL reconstruction (mean age 21.8 years) compared with isolated ACLR hamstring grafts (mean age 23.5 years) (4.1% versus 10.8%)[30], although preoperative Tegner scores were not reported. Overall, these findings support the protective effect of ALCR on graft integrity in high-risk patients.

Limitations

This study has several limitations. The retrospective design may have introduced selection bias and limits control over confounding variables. Although follow-up at 24 months was high (94%), missing data for PROMs at earlier timepoints could have affected comparisons across time. Surgeries were performed by multiple surgeons, which may have led to variability in surgical execution. Furthermore, the majority of surgeries (72.1%) were performed by a single surgeon, reflecting natural variation in staff availability and team composition over the study period. The decision to perform a Lemaire procedure was not randomized but evolved over time based on patient risk factors, which may have introduced selection bias and time-dependent confounding. Furthermore, the findings of this study apply specifically to four-strand semitendinosus/gracilis grafts with suspensory fixation, and may not be generalizable to other graft types or fixation techniques. Additional considerations include the fact that clinical assessments were performed by members of the surgical team rather than independent observers, which may have introduced assessment bias. In addition, although the study included a substantial number of patients, it may still have been underpowered to detect smaller but potentially clinically relevant between-group differences, and therefore the possibility of a type II error cannot be excluded. No patient acceptable symptom state has yet been defined for ACL-reconstructed patients, limiting interpretation of absolute scores. Lastly, while 2-year follow-up provides valuable insight into mid-term outcomes, it may be insufficient to determine whether the Lemaire procedure has lasting effects on joint awareness or rotational stability.

CONCLUSION

At 12 months, isolated ACLR resulted in higher FJS-12 scores compared with ACLR combined with modified Lemaire ALC reconstruction. However, this difference did not exceed the MCID and had disappeared by 24 months, suggesting no clinically meaningful difference associated with adding a Lemaire ALC reconstruction at 24-month follow-up.

REFERENCES

1. Lie DTT, Bull AMJ, Amis AA. **Persistence of the Mini Pivot Shift after Anatomically Placed Anterior Cruciate Ligament Reconstruction**. *Clin Orthop Relat Res*. 2007;457(NA;):203-209. doi:10.1097/blo.0b013e3180314b01
2. Georgoulis AD, Ristanis S, Chouliaras V, Moraiti C, Stergiou N. **Tibial Rotation is Not Restored after ACL Reconstruction with a Hamstring Graft**. *Clin Orthop Relat Res*. 2007;454(NA;):89-94. doi:10.1097/blo.0b013e31802b4a0a
3. Logan MC, Williams A, Lavelle J, Gedroyc W, Freeman M. **Tibiofemoral Kinematics following Successful Anterior Cruciate Ligament Reconstruction Using Dynamic Multiple Resonance Imaging**. *Am J Sports Med*. 2004;32(4):984-992. doi:10.1177/0363546503261702
4. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction can Restore Native Knee Kinematics in the ACL Reconstructed Knee. A Systematic Review of Biomechanical Cadaveric Studies**. *Arthroscopy*. 2024;40(2):632-647. doi:10.1016/j.arthro.2023.05.005
5. Marom N, Ouanezar H, Jahandar H, et al. **Lateral Extra-articular Tenodesis Reduces Anterior Cruciate Ligament Graft Force and Anterior Tibial Translation in Response to Applied Pivoting and Anterior Drawer Loads**. *Am J Sports Med*. 2020;48(13):3183-3193. doi:10.1177/0363546520959322
6. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
7. D'Ambrosi R, Corona K, Cerciello S, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces Graft Reinjury Without Increasing the Rate of Complications: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J sports Med*. Published online 2025:3635465241285887. doi:10.1177/03635465241285887
8. Lee JY, Low YM, Jiang L, et al. **The Forgotten Joint Score-12 in Anterior Cruciate Ligament injuries**. *J Orthop*. 2020;21:117-121. doi:10.1016/j.jor.2020.03.029
9. Behrend H, Giesinger K, Giesinger JM, Kuster MS. **The "Forgotten Joint" as the Ultimate Goal in Joint Arthroplasty Validation of a New Patient-Reported Outcome Measure**. *J Arthroplast*. 2012;27(3):430-436.e1. doi:10.1016/j.arth.2011.06.035
10. Vandenbroucke JP, Elm E von, Altman DG, et al. **Strengthening the Reporting of Observational Studies in Epidemiology (STROBE): Explanation and Elaboration**. *PLoS Med*. 2007;4(10):e297. doi:10.1371/journal.pmed.0040297
11. Behrend H, Giesinger K, Zdravkovic V, Giesinger JM. **Validating the forgotten joint score-12 in patients after ACL reconstruction**. *Knee*. 2017;24(4):768-774. doi:10.1016/j.knee.2017.05.007
12. Irrgang JJ, Anderson AF, Boland AL, et al. **Development and Validation of the International Knee Documentation Committee Subjective Knee Form***. *Am J Sports Med*. 2001;29(5):600-613. doi:10.1177/03635465010290051301
13. Lysholm J, Gillquist J. **Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale**. *Am J Sports Med*. 1982;10(3):150-154. doi:10.1177/036354658201000306
14. Tegner Y, Lysholm J. **Rating Systems in the Evaluation of Knee Ligament Injuries**. *Clin Orthop Relat Res*. 1985;198(NA;):42-49. doi:10.1097/00003086-198509000-00007

15. Webster KE, Feller JA, Lambros C. **Development and preliminary validation of a scale to measure the psychological impact of returning to sport following anterior cruciate ligament reconstruction surgery**. *Phys Ther Sport*. 2008;9(1):9-15. doi:10.1016/j.ptsp.2007.09.003
16. Wilson TJ, Lubowitz JH. **Minimally Invasive Posterior Hamstring Harvest**. *Arthrosc Tech*. 2013;2(3):e299-e301. doi:10.1016/j.eats.2013.04.008
17. Lubowitz JH, Ahmad CS, Amhad CH, Anderson K. **All-Inside Anterior Cruciate Ligament Graft-Link Technique: Second-Generation, No-Incision Anterior Cruciate Ligament Reconstruction**. *Arthroscopy*. 2011;27(5):717-727. doi:10.1016/j.arthro.2011.02.008
18. Williams A, Ball S, Stephen J, White N, Jones M, Amis A. **The scientific rationale for lateral tenodesis augmentation of intra-articular ACL reconstruction using a modified 'Lemaire' procedure**. *Knee Surg, Sports Traumatol, Arthrosc*. 2017;25(4):1339-1344. doi:10.1007/s00167-017-4537-3
19. Melick N van, Cingel REH van, Brooijmans F, et al. **Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus**. *Br J Sports Med*. 2016;50(24):1506. doi:10.1136/bjsports-2015-095898
20. Giesinger JM, Behrend H, Hamilton DF, Kuster MS, Giesinger K. **Normative Values for the Forgotten Joint Score-12 for the US General Population**. *J Arthroplast*. 2019;34(4):650-655. doi:10.1016/j.arth.2018.12.011
21. Clement ND, Scott CEH, Hamilton DF, MacDonald D, Howie CR. **Meaningful values in the Forgotten Joint Score after total knee arthroplasty**. *Bone Jt J*. 2021;103-B(5):846-854. doi:10.1302/0301-620x.103b5.bjj-2020-0396.r1
22. Robinson PG, MacDonald DJ, Macpherson GJ, Patton JT, Clement ND. **Changes and thresholds in the Forgotten Joint Score after total hip arthroplasty: minimal clinically important difference, minimal important and detectable changes, and patient-acceptable symptom state**. *Bone Jt J*. 2021;103-B(12):1759-1765. doi:10.1302/0301-620x.103b12.bjj-2021-0384.r1
23. Longo UG, Salvatore SD, Candela V, et al. **Unicompartmental Knee Arthroplasty: Minimal Important Difference and Patient Acceptable Symptom State for the Forgotten Joint Score**. *Medicina*. 2021;57(4):324. doi:10.3390/medicina57040324
24. Kulshrestha V, Sood M, Kumar S, et al. **Numbness Following Total Knee Arthroplasty: Role of Incision Length And Position - A Randomized Study**. *Clin Orthop Surg*. 2022;14(1):59-70. doi:10.4055/cios21140
25. Cristiani R, Forssblad M, Edman G, Eriksson K, Stålman A. **Age, time from injury to surgery and quadriceps strength affect the risk of revision surgery after primary ACL reconstruction**. *Knee Surg, Sports Traumatol, Arthrosc*. 2021;29(12):4154-4162. doi:10.1007/s00167-021-06517-8
26. Ferreira A, Saithna A, Carrozzo A, et al. **The Minimal Clinically Important Difference, Patient Acceptable Symptom State, and Clinical Outcomes of Anterior Cruciate Ligament Repair Versus Reconstruction: A Matched-Pair Analysis From the SANTI Study Group**. *Am J Sports Med*. 2022;50(13):3522-3532. doi:10.1177/03635465221126171
27. Ferretti A, Carrozzo A, Saithna A, et al. **Comparison of Primary Repair of the Anterior Cruciate Ligament and Anterolateral Structures to Reconstruction and Lateral Extra-articular Tenodesis at 2-Year Follow-up**. *Am J Sports Med*. 2023;51(9):2300-2312. doi:10.1177/03635465231178301
28. Sakamoto T, Watanabe S, Horii M, et al. **Longitudinal Evaluation Using the Forgotten Joint Score-12 for Double-Bundle Primary Anterior Cruciate Ligament Reconstruction: A Retrospective Observational Study**. *Cureus*. 2024;16(9):e70547. doi:10.7759/cureus.70547

29. Getgood AMJ, Bryant DM, Litchfield R, et al. **Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2-Year Outcomes From the STABILITY Study Randomized Clinical Trial**. *Am J Sports Med*. 2019;48(2):285-297. doi:10.1177/0363546519896333
30. Sonnery-Cottet B, Saithna A, Cavalier M, et al. **Anterolateral Ligament Reconstruction Is Associated With Significantly Reduced ACL Graft Rupture Rates at a Minimum Follow-up of 2 Years: A Prospective Comparative Study of 502 Patients From the SANTI Study Group**. *Am J Sports Med*. 2017;45(7):1547-1557. doi:10.1177/0363546516686057
31. Rowan FE, Huq SS, Haddad FS. **Lateral extra-articular tenodesis with ACL reconstruction demonstrates better patient-reported outcomes compared to ACL reconstruction alone at 2 years minimum follow-up**. *Arch Orthop Trauma Surg*. 2019;139(10):1425-1433. doi:10.1007/s00402-019-03218-3
32. Thomas L, Zhishen W, Louis K, Thomas T, Jos V, Kurt C. **Lateral extra-articular tenodesis improves functional movement outcomes in ACL reconstruction patients**. *J Exp Orthop*. 2025;12(2):e70269. doi:10.1002/jeo2.70269
33. Sell TC, Zerega R, King V, et al. **Anterior Cruciate Ligament Return to Sport after Injury Scale (ACL-RSI) Scores over Time After Anterior Cruciate Ligament Reconstruction: A Systematic Review with Meta-analysis**. *Sports Med - Open*. 2024;10(1):49. doi:10.1186/s40798-024-00712-w
34. Joseph L, Demey G, Chamu T, et al. **Adding a modified Lemaire procedure to ACLR in knees with severe rotational knee instability does not compromise isokinetic muscle recovery at the time of return-to-play**. *J Exp Orthop*. 2020;7(1):84. doi:10.1186/s40634-020-00302-1
35. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
36. Mahmoud A, Torbey S, Honeywill C, Myers P. **Lateral Extra-Articular Tenodesis Combined With Anterior Cruciate Ligament Reconstruction Is Effective in Knees With Additional Features of Lateral, Hyperextension, or Increased Rotational Laxity: A Matched Cohort Study**. *Arthroscopy*. 2022;38(1):119-124. doi:10.1016/j.arthro.2021.04.068

Supplementary Table 1. Missing data across PROMs

Score	Test	Total	N Lemaire	N non-Lemaire	Lemaire	non-Lemaire	p-value	% Missing
FJS-12 T0	Mann–Whitney U	150	95	55	42.0 (IQR 26.0–70.0)	42.0 (IQR 23.0–59.5)	.60	38.8%
FJS-12 T2	Mann–Whitney U	164	95	69	66.7 (IQR 52.0–81.3)	69.0 (IQR 46.0–90.0)	.42	33.1%
FJS-12 T3	Mann–Whitney U	157	84	73	75.0 (IQR 31.5–92.0)	88.0 (IQR 67.0–96.0)	.0005	35.9%
FJS-12 T4	Mann–Whitney U	224	113	111	70.83 (IQR 52.1–87.5)	70.83 (IQR 56.3–88.5)	.50	8.6%
FJS-12 All timepoints		92	57	35				62.4%
ACL-RSI T2	t-test	174	97	77	55.2 ± 20.8	54.6 ± 22.8	.84	29.0%
ACL-RSI T3	Mann–Whitney U	186	96	90	67.9 (IQR 53.5–85.0)	70.4 (IQR 51.9–84.8)	.82	24.1%
ACL-RSI T4	Mann–Whitney U	216	107	109	62.5 (IQR 47.1–80.8)	65.8 (IQR 49.2–83.3)	.73	11.8%
ACL-RSI all timepoints		132	73	59				46.1%
IKDC T0	Mann–Whitney U	147	93	54	66.67 (IQR 60.9–74.7)	64.4 (IQR 54.3–71.0)	.11	40.0%
IKDC T3	Mann–Whitney U	145	58	87	85.1 (IQR 81.6–87.4)	85.06 (IQR 79.3–88.5)	.64	40.8%
IKDC T4	Mann–Whitney U	218	109	109	82.8 (IQR 75.9–87.4)	83.91 (IQR 78.2–88.5)	.46	11.0%
IKDC all timepoints		75	40	35				67.3%
Lysholm T0	Mann–Whitney U	150	96	54	64.5 (IQR 50.8–79.0)	63.5 (IQR 51.2–73.8)	.40	38.8%
Lysholm T1	t-test	160	99	61	57.1 ± 19.7	59.4 ± 21.5	.50	34.7%
Lysholm T2	Mann–Whitney U	157	93	64	85.0 (IQR 77.0–91.0)	84.0 (IQR 74.8–90.0)	.49	35.9%
Lysholm T3	Mann–Whitney U	150	87	63	94.0 (IQR 88.0–95.5)	91.0 (IQR 86.0–95.5)	.67	38.8%
Lysholm T4	Mann–Whitney U	217	108	109	89.0 (IQR 81.8–95.0)	86.0 (IQR 80.0–94.0)	.62	11.4%

Supplementary Table 1. Missing data across PROMs

Score	Test	Total	N Lemaire	N non-Lemaire	Lemaire	non-Lemaire	p-value	% Missing
Lysholm all timepoints		80	58	22				67.3%
Tegner T0	Mann–Whitney U	245	122	123	9 (IQR 8–9)	8 (IQR 7–9)	.0009	0.0%
Tegner T1	Mann–Whitney U	165	101	64	2 (IQR 1–2)	2 (IQR 0–2)	.52	32.7%
Tegner T2	Mann–Whitney U	178	100	78	4 (IQR 4–5)	4 (IQR 3.3–5)	.39	27.3%
Tegner T3	Mann–Whitney U	189	98	91	7 (IQR 6–9)	7.0 (IQR 6–8)	.14	22.9%
Tegner T4	Mann–Whitney U	217	108	109	7.0 (IQR 5–9)	7.0 (IQR 5–7)	.10	11.4%
Tegner all timepoints		118	72	46				51.8%
VAS T1	Mann–Whitney U	164	101	63	1.6(IQR 1.0–2.4)	1.5 (IQR 0.8–2.8)	.74	33.1%
VAS T2	Mann–Whitney U	178	100	78	0.8 (IQR 0.1–1.5)	0.69 (IQR 0.2–1.5)	.71	27.3%
VAS T3	Mann–Whitney U	189	99	90	0.3 (IQR 0.0–0.9)	0.3 (IQR 0.0–1.1)	.68	22.9%
VAS all timepoints		132	78	54				46.1%

Note: Missing PROMs at different time points for Lemaire and non-Lemaire groups. Values are presented as median with interquartile range for non-normally distributed continuous variables, and mean with standard deviation for normally distributed variables. Statistical comparisons between the Lemaire and non-Lemaire groups were performed using the Mann–Whitney U test for continuous variables unless normally distributed, in which case the t-test was used. % Missing is the proportion of the full cohort (N=245) without a valid response for that PROM at that timepoint. Rows labeled "all timepoints" give the number of patients per group who provided complete data across all collected visits for that instrument (complete-case count); no test is shown for these rows. P-values are two-sided and unadjusted for multiplicity. T0 (preoperative); T1 (6 weeks postoperative); T2 (6 months postoperative); T3 (1 year postoperative); T4 (2 years postoperative); ACL-RSI, Anterior Cruciate Ligament - Return to Sport after Injury Scale; IKDC, International Knee Documentation Committee; IQR, interquartile range; VAS, Visual Analogue Scale.

chapter 6

Editorial Commentary: The Anterolateral Ligament is Only Part of the Puzzle of Anterolateral Corner Injury in Anterior Cruciate Ligament Disruption and Reconstruction

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ABSTRACT

Over the past decade, there has been an increased awareness of the role of the anterolateral corner (ALC) in the setting of anterior cruciate ligament (ACL) injury and ACL reconstruction. Although several studies have debated the existence, exact anatomy and function of the ALC, the role in clinical practice is well recognized. Biomechanical studies have assessed the role of the anterolateral ligament (ALL), superficial and deep Kaplan fiber layers of the iliotibial band, the anterolateral capsule with the ALL, and the capsulo-osseous layer within the ALC. Furthermore, both biomechanical and clinical studies support the role of either ALL reconstruction or lateral extra-articular tenodesis such as the modified Lemaire or Arnold-Coker Modification of the McIntosh technique in the setting of ACL reconstruction. Not only have many randomized controlled trials shown decreased failure or re-rupture rates with adding these procedures, but they also show minimal complication rates, equivalent to superior patient-reported outcome measures and decreased presence of persisting rotatory instability or positive pivot shift. These developments have caused a major shift in the treatment of young patients with ACL injuries, especially those who have ligamentous laxity, hyperextension, involvement in pivoting sports, or contralateral injuries. The next steps should focus on which patients require ALC procedures, the role of ALC procedures with hamstring versus quadriceps or bone-patellar tendon-bone autograft, and the development of post-traumatic osteoarthritis.

In recent years, renewed anatomic interest[1] in the anterolateral corner (ALC) of the knee has led to extensive research in its components, particularly the anterolateral ligament (ALL). There has been considerable discussion about the existence, precise anatomy, and function of the ALL, particularly in the context of residual anterolateral rotatory instability (ALRI) after anterior cruciate ligament (ACL) injury and ACL re-rupture rates.[2,3]

In the recent study titled "The Anterolateral Ligament Complex has Limited Impact on Anterior Tibial Translation or Internal Rotation Stability in ACL-Deficient and ACL-Reconstructed Knees. A Systematic Review of Biomechanical Cadaver Studies," by Hohmann, Keough, Molepo, Arciero, and Imhoff[4], the biomechanical role of the ALL is further investigated. The authors performed a thorough search, appropriately assessed the quality of the included studies and applied multiple statistical tests to evaluate heterogeneity between the studies. A pooled meta-analysis of the data was not deemed feasible. Ultimately, 22 studies involving 284 specimens were included. Their systematic review concluded that there is no conclusive evidence that the ALL significantly limits anterior tibial translation or internal rotation stability in either ACL-intact or ACL-reconstructed knees under time-zero cadaveric biomechanical testing.

Although this systematic review provides additional insight into the role of the ALL, it addresses only part of the story. The ALC is a complex anatomic region, and its contribution to rotatory stability cannot be attributed solely to the ALL. Numerous studies have described the ALC as comprising the superficial and deep (Kaplan fiber) layers of the iliotibial band, the anterolateral capsule (including the ALL), and the capsulo-osseous layer.[5,6] All of these structures may be injured in conjunction with the ACL, as shown in various imaging studies, although the reported incidence of injury to individual components varied significantly.[7–10]

In our view, ALC injury encompasses a broad range of full or partial injuries to different anatomic structures, each contributing variably to ALRI after ACL injury. An ALC injury may consist of a partial tear of the anterolateral capsule, with or without involvement of the ALL, proximal and/or distal Kaplan fiber disruption, and/or injury to the capsulo-osseous layer. The cumulative effect of these injuries - alongside other concomitant injuries and individual knee characteristics[11] - determines the overall degree of ALRI in the ACL-injured knee.

It is, therefore, an oversimplification to focus solely on the ALL in the setting of ACL injury. The statements in the systematic review by Hohmann et al.[4] - that isolated ALL reconstruction or lateral extra-articular tenodesis may not be necessary in the management of ACL-deficient knees or may not provide biomechanical benefit when added to ACL reconstruction (ACLR)- should be interpreted with caution. A recent systematic review of biomechanical studies showed that all 6 included sectioning studies reported the iliotibial band to function as a secondary stabilizer to the ACL and to resist internal rotation. In contrast, only 2 of 6 sectioning studies found the ALL to contribute significantly to tibial internal rotation control.[12] Furthermore, this same study concluded that both a modified

Lemaire tenodesis and an ALL reconstruction significantly reduce residual ALRI in isolated ACL-reconstructed knees, restoring internal rotation stability and internal rotation stability during pivot shift testing.[9]

Clinically, the biomechanical relevance of combining ALC reconstruction with ACLR has been supported in high-risk, young patient populations. In the prospective study by the SANTI group, it was shown that adding ALL reconstruction to hamstring tendon graft ACLR resulted in a 3.1-fold reduction in ACL graft failure.[13] Furthermore, the STABILITY trial reported a statistically significant and clinically relevant reduction in graft rupture and persistent rotatory laxity two years postoperatively after adding a lateral extra-articular tenodesis to hamstring tendon ACLR.[14] More recently, several randomized controlled trials have shown similar dramatic reduction in failure rates, which further support treatment of the ALC in high-risk patients.[15,16]

In our clinical practices, we maintain a low threshold for adding ALC reconstruction to ACLR, particularly in high-risk patients. Since implementing this approach, we have observed a substantial reduction in ACL re-rupture rates. The procedure is relatively straightforward and, when routinely performed, adds minimal time to the surgery without significant morbidity.[17]

Consequently, in our opinion, biomechanical analysis of injury to only 1 component of the ALC (i.e. the ALL) cannot and should not be directly translated to clinical practice.

REFERENCES

1. Claes S, Vereecke E, Maes M, Victor J, Verdonk P, Bellemans J. **Anatomy of the anterolateral ligament of the knee**. *J Anat*. 2013;223(4):321-328. doi:10.1111/joa.12087
2. List JP van der. **Editorial Commentary: Anterolateral Reconstruction Versus Lateral Extra-Articular Tenodesis—Six of One and Half a Dozen of the Other**? *Arthrosc: J Arthrosc Relat Surg*. 2020;36(7):1951-1952. doi:10.1016/j.arthro.2020.04.037
3. Kent RN, Boorman-Padgett JF, Thein R, et al. **High Interspecimen Variability in Engagement of the Anterolateral Ligament: An In Vitro Cadaveric Study**. *Clin Orthop Relat Res*. 2017;475(10):2438-2444. doi:10.1007/s11999-017-5375-9
4. Hohmann E, Keough N, Molepo M, Arciero R, Imhoff A. **The anterolateral ligament complex has limited impact on anterior tibial translation or internal rotational stability in ACL-deficient and ACL-reconstructed knees. A systematic review of biomechanical cadaver studies**. *Arthrosc: J Arthrosc Relat Surg*. Published online 2025. doi:10.1016/j.arthro.2025.04.043
5. Godin JA, Chahla J, Moatshe G, et al. **A Comprehensive Reanalysis of the Distal Iliotibial Band: Quantitative Anatomy, Radiographic Markers, and Biomechanical Properties**. *Am J Sports Med*. 2017;45(11):2595-2603. doi:10.1177/0363546517707961
6. Meena A, Attri M, Farinelli L, et al. **Anterolateral corner of knee: Current concepts**. *J Exp Orthop*. 2025;12(1):e70172. doi:10.1002/jeo2.70172
7. Balendra G, Willinger L, Pai V, et al. **Anterolateral complex injuries occur in the majority of 'isolated' anterior cruciate ligament ruptures**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(1):176-183. doi:10.1007/s00167-021-06543-6
8. Marom N, Greditzer HG, Roux M, et al. **The Incidence of Kaplan Fiber Injury Associated With Acute Anterior Cruciate Ligament Tear Based on Magnetic Resonance Imaging**. *Am J Sports Med*. 2020;48(13):3194-3199. doi:10.1177/0363546520956302
9. Guruprasad A, Sinha U, Kumar S, et al. **Utility of three-dimensional proton density-weighted sequence MRI in knee for the assessment of Anterolateral complex in Anterior cruciate ligament injury**. *Br J Radiol*. 2024;97(1155):583-593. doi:10.1093/bjr/tqae003
10. Firoozabadi MA, Mortazavi SMJ, Shakiba M, et al. **Investigating Injuries to the Anterolateral Corner of the Knee: Imaging Insights Into Kaplan Fibers and the Anterolateral Ligament in Anterior Cruciate Ligament Tears**. *Orthop J Sports Med*. 2025;13(3):23259671251319504. doi:10.1177/23259671251319504
11. Wal WA van der, Meijer DT, Hoogeslag RAG, LaPrade RF. **Meniscal Tears, Posterolateral and Posteromedial Corner injuries, Increased Coronal Plane and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament-Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**. *Arthrosc J Arthrosc Relat Surg*. 2021;38(5):1664-1688.e1. doi:10.1016/j.arthro.2021.11.044
12. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction can Restore Native Knee Kinematics in the ACL Reconstructed Knee. A Systematic Review of Biomechanical Cadaveric Studies**. *Arthrosc: J Arthrosc Relat Surg*. Published online 2023. doi:10.1016/j.arthro.2023.05.005

13. Sonnery-Cottet B, Saithna A, Cavalier M, et al. **Anterolateral Ligament Reconstruction Is Associated With Significantly Reduced ACL Graft Rupture Rates at a Minimum Follow-up of 2 Years: A Prospective Comparative Study of 502 Patients From the SANTI Study Group**. *Am J Sports Med*. 2017;45(7):1547-1557. doi:10.1177/0363546516686057
14. Getgood AMJ, Bryant DM, Litchfield R, et al. **Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2-Year Outcomes From the STABILITY Study Randomized Clinical Trial**. *Am J Sports Med*. 2019;48(2):285-297. doi:10.1177/0363546519896333
15. D'Ambrosi R, Corona K, Cerciello S, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces Graft Reinjury Without Increasing the Rate of Complications: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J sports Med*. Published online 2025:3635465241285887. doi:10.1177/03635465241285887
16. Bosco F, Giustra F, Masoni V, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces the Graft Reinjury Rate and Improves Clinical Outcomes: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J Sports Med*. 2023;52(8):2129-2147. doi:10.1177/03635465231198494
17. Heard M, Marmura H, Bryant D, et al. **No increase in adverse events with lateral extra-articular tenodesis augmentation of anterior cruciate ligament reconstruction – Results from the stability randomized trial**. *J ISAKOS*. 2023;8(4):246-254. doi:10.1016/j.jisako.2022.12.001

chapter 7

Increased Posterior Tibial Slope and Lateral Extra-Articular Tenodesis Are Associated with Revision Anterior Cruciate Ligament Reconstruction in a Young High-Risk Population.

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ABSTRACT

Background

Increased posterior tibial slope (PTS) has been associated with higher revision rates after anterior cruciate ligament reconstruction (ACLR). Whether addition of lateral extra-articular tenodesis (LET) mitigates the risk associated with increased PTS is unclear.

Purpose

To determine the prevalence of increased PTS (≥12°) in young high-risk primary ACLR patients and evaluate whether LET is associated with lower revision rates in patients with increased PTS.

Study Design

Retrospective comparative cohort study.

Methods

Patients ≤25 years undergoing primary ACLR across three high-volume centers with ≥2 years between surgery and data collection were included. PTS was measured on lateral radiographs for both medial and lateral plateaus. Primary analyses consisted of four pre-specified multivariable logistic regression models with different PTS operationalizations as continuous predictors per 1° increase (medial PTS, lateral PTS, the maximum [PTSmax], and the lateral–medial difference [ΔPTS]), adjusted for patient and surgical covariates including graft type, with surgical center as a fixed effect. Secondary analyses used PTS dichotomized at 12°; revision rates between isolated ACLR and ACLR with LET were compared, with the treatment effect quantified as absolute risk reduction (ARR) and number needed to treat (NNT).

Results

A total of 780 patients were included; 84 (10.8%) underwent revision ACLR. Increased PTS (≥12°) was present in 28.2% of patients and more common in those requiring revision (38.6% vs 27.0%, p=0.03). In patients with PTSmax ≥12°, revision occurred in 21.0% without and 9.2% with LET (ARR 11.8% [95% CI 2.3–21.3%], NNT 9); in patients with PTSmax <12°, revision occurred in 13.2% without and 5.4% with LET (ARR 7.8% [95% CI 3.0–12.6%], NNT 13). In the four pre-specified multivariable models with PTS as a continuous predictor, LET was independently associated with substantially lower odds of revision ACLR (OR 0.37, 95% CI 0.22–0.62, p<0.001). Lateral PTS (OR 1.09 per 1° increase, 95% CI 1.00–1.18, p=0.04) and PTSmax (OR 1.09, 95% CI 1.00–1.19, p=0.04) were independently associated with revision ACLR, while medial PTS showed a similar effect size that did not reach conventional statistical significance (OR 1.07, 95% CI 0.99–1.16, p=0.10). The lateral–medial PTS difference was not associated with revision ACLR.

Conclusion

In a young high-risk primary ACLR population, increased PTS was present in nearly thirty percent of patients. LET was associated with a lower risk of revision irrespective of PTS, while increased PTS was independently associated with revision ACLR.

Clinical Relevance

In high-risk patients with increased PTS undergoing primary ACLR, addition of LET may serve as an initial risk-reduction strategy. As increasing PTS remained independently associated with revision ACLR, slope-reducing osteotomy may be considered in selected primary cases, particularly in patients with substantially increased PTS.

INTRODUCTION

Young athletes undergoing ACLR face a substantial risk of graft rupture, with reported secondary injury rates up to 10% in patients younger than 25 years.[12,18,36] Two modifiable surgical factors have emerged as key determinants of graft survival: anterolateral rotatory instability and increased posterior tibial slope (PTS). Addition of an anterolateral corner (ALC) reconstruction – either a modified Lemaire lateral extra-articular tenodesis (LET) or an anterolateral ligament (ALL) reconstruction – has been shown to reduce residual rotatory laxity, offload the ACL graft, and lower revision rates in high-risk populations.[10,19,27,32]

Increased PTS increases anterior tibial translation and ACL graft force under axial loading, and is associated with higher graft rupture rates after ACLR, particularly in adolescents and young adults.[2,8,9,11,14,15,17,20,24,25,31,34] Although the risk associated with PTS likely exists along a continuum, a threshold of 12° is most commonly applied in the literature and clinical practice to define a clinically relevant increase;[24,34] however, no universally accepted cutoff has been established. Furthermore, current evidence remains inconsistent regarding whether the medial or the lateral PTS is the more relevant predictor of graft failure, with studies supporting either compartment.[2,8,24] ALC reconstruction and increased PTS affect different biomechanical mechanisms: ALC reconstruction primarily reduces tibial internal rotation, whereas increased PTS primarily increases anterior tibial translation and graft loading. To date, no clinical study has evaluated whether the addition of an ALC reconstruction during primary ACLR is sufficient to mitigate the increased risk associated with an elevated PTS.

Therefore, the purpose of this study was to determine the prevalence of increased PTS in a young high-risk primary ACLR population and to evaluate whether LET is associated with lower revision rates in patients with increased PTS. We hypothesized that the prevalence of increased PTS would be approximately 30% and that, within the increased PTS subgroup, LET would be independently associated with a lower risk of revision ACLR compared with isolated ACLR.

METHODS

This retrospective multicenter comparative cohort study was approved by the Institutional Review Board (2409-053) and conducted across three high-volume ACLR centers. This study is reported in accordance with the STROBE guidelines for observational studies.

Patient Selection

During the study years, all three centers gradually adopted the addition of a modified Lemaire LET into routine clinical practice for patients considered at higher risk of revision, in line with emerging international evidence on ALC reconstruction in high-risk ACLR populations.[10,19,27] Within this evidence base, LET was considered indicated when one or more of the following risk factors were present: high-grade preoperative pivot shift, young age (≤ 25 years), the intention to return to pivoting or contact sport, generalized hyperlaxity, and physiological knee hyperextension. There was no formal institutional protocol; however, all participating surgeons were high-volume ACL surgeons working in accordance with the published evidence base, and the indication was applied consistently among surgeons within each center. The center-specific inclusion periods were deliberately defined to span this gradual transition in clinical practice, and to yield, within each center, approximately balanced numbers of patients treated with isolated ACLR versus ACLR combined with LET. Because allocation to LET was non-randomized and the proportion of patients receiving LET increased gradually over time, treatment groups were not strictly contemporaneous within centers.

All consecutive patients aged 25 years or younger who underwent primary ACLR during the center-specific inclusion periods (December 2017 through December 2023) were screened for eligibility. Within this overall window, the exact start and end dates differed by center; end dates were chosen at each center to ensure a minimum postoperative observation of 2 years. Patients were eligible if they presented with a primary ACL rupture accompanied by instability complaints and/or the intention to return to their preinjury level of sports participation, and if at least two years had elapsed between primary ACLR and the date of data collection. The observation period was defined as the time interval between primary ACLR and the date of data collection at each center. Surgical procedures were performed by ten orthopedic surgeons specialized in knee surgery.

Patients were excluded if they (I) were skeletally immature, defined as either radiographs demonstrating open physes or treatment with an epiphyseal-sparing ACLR technique, (II) had no lateral knee radiograph available (IIa) or an inadequate lateral radiograph, defined as >6 mm posterior femoral condyle overlap (IIb), (III) had a multiligament knee injury, (IV) had revision ACLR attributable to a technical cause, defined as non-anatomic tunnel placement according to the Staubli method (tibial tunnel)[28] and the Bernard and Hertel grid method (femoral tunnel)[1], or significant tunnel widening (>12mm) on postoperative imaging, or (V) had a history of ipsilateral infection.

Baseline demographics

Demographic and patient characteristic data included age at time of injuries and surgeries, sex, BMI, primary and secondary trauma mechanism, type of activity during primary and secondary injury (sports/non-sports, pivoting/non-pivoting), time to failure after primary surgery, pre- and postoperative Tegner scores, graft types and diameters, prior knee surgical procedures and knee injury treatments, additional knee pathologies, and additional knee surgical treatments. Furthermore, the ACL and LET surgical techniques, time to return to sports (RTS) after primary ACLR, additional surgeries after primary ACLR, and contralateral ACL injury and/or surgery were recorded. These variables were recorded to characterize the study population and to allow adjustment for known risk factors associated with ACL graft failure in the statistical analysis (Table 1).

Table 1. Baseline characteristics of the study population

Variable	Overall	Center 1	Center 2	Center 3
Age at injury	18 [16–20]	19 [17–22]	17 [16–18]	19 [17–22]
Age at surgery	19 [17–21]	20 [18–22]	18 [17–19]	20 [17–23]
BMI	22.7 [21.3–24.5]	23.0 [21.1–24.4]	22.6 [21.3–24.3]	22.8 [21.5–24.7]
Male sex	433 (55.5%)	128 (55.4%)	167 (53.7%)	138 (58.0%)
Preoperative Tegner score	7 [7–9]	9 [7–9]	7 [7–7]	7 [5–9]
Medial posterior tibial slope	9.41 (2.96)	9.88 (3.26)	8.95 (2.80)	9.55 (2.77)
Lateral posterior tibial slope	9.51 (3.03)	9.59 (3.38)	9.38 (2.92)	9.60 (2.81)
Posterior tibial slope >= 12	220/780 (28.2%)	87/231 (37.7%)	72/311 (23.2%)	61/228 (25.6%)
Sports during primary injury	713 (91.4%)	224 (97.0%)	278 (89.4%)	211 (88.7%)
Prior knee surgery	55 (7.1%)	13 (5.2%)	33 (10.6%)	9 (3.8%)
Pivoting sports				
Yes, level 1 pivoting	583 (74.7%)	188 (81.4%)	219 (70.4%)	176 (73.9%)
Yes, level 2 some pivoting	94 (12.1%)	30 (13.0%)	38 (12.2%)	26 (10.9%)
No, level 3 pivoting	56 (7.2%)	4 (1.7%)	38 (12.2%)	14 (5.9%)
Not applicable	47 (6.0%)	9 (3.9%)	16 (5.1%)	22 (9.2%)
Primary ACLR graft type				
Autograft HS: semitendinosus	581 (74.6%)	162 (70.1%)	231 (74.3%)	188 (79.3%)
Autograft BPTB	74 (9.5%)	5 (2.2%)	69 (22.2%)	0 (0.0%)
Autograft QT: no bone block	63 (8.1%)	55 (23.8%)	8 (2.6%)	0 (0.0%)
Autograft HS: semi + graci	58 (7.4%)	8 (3.5%)	1 (0.3%)	49 (20.7%)
Other (<5%)	3 (0.4%)	1 (0.4%)	2 (0.6%)	0 (0.0%)
Primary ACLR graft diameter	8.5 [8-9]	8.5 [8-9]	8.5 [8-9]	8.5 [8-9]

Table 1. Baseline characteristics of the study population

Variable	Overall	Center 1	Center 2	Center 3
Primary ACLR technique				
All-inside: fem+ tib button	702 (90.0%)	222 (96.1%)	242 (77.8%)	238 (100.0%)
Anteromedial technique	65 (8.3%)	0 (0.0%)	65 (20.9%)	0 (0.0%)
Other	13 (1.7%)	9 (3.9%)	4 (1.3%)	0 (0.0%)
ACL fixation technique				
Not performed	364 (46.7%)	105 (45.5%)	156 (50.2%)	103 (43.3%)
Interference screw	303 (38.8%)	13 (5.6%)	155 (49.8%)	135 (56.7%)
Corkscrew	66 (8.5%)	66 (28.6%)	0 (0.0%)	0 (0.0%)
Other	47 (6.0%)	47 (20.3%)	0 (0.0%)	0 (0.0%)
Medial meniscus surgery during ACLR				
Meniscal repair	175 (22.5%)	69 (29.9%)	39 (12.5%)	67 (28.3%)
Partial meniscectomy	61 (7.8%)	12 (5.2%)	33 (10.6%)	16 (6.8%)
Other	14 (1.8%)	7 (3.0%)	4 (1.3%)	3 (1.3%)
Lateral meniscus surgery during ACLR				
Partial meniscectomy	116 (14.9%)	37 (16.0%)	58 (18.6%)	21 (8.9%)
Meniscal repair	99 (12.7%)	34 (14.7%)	8 (2.6%)	57 (24.1%)
Other	17 (2.2%)	6 (2.6%)	2 (0.6%)	9 (3.8%)
Cartilage surgery during ACLR	9 (1.2%)	1 (0.4%)	1 (0.3%)	7 (2.9%)
Revision ACLR	84 (10.8%)	32 (13.9%)	18 (5.8%)	34 (14.3%)

Continuous variables are reported as mean (SD) and median [IQR], with the number of missing values shown ("missing="). Categorical variables are reported as n (%), calculated among non-missing observations. Between-center differences were assessed using Kruskal–Wallis tests for non-normally distributed continuous variables, one-way ANOVA/Welch ANOVA for approximately normally distributed continuous variables (Welch when variances were unequal), and Pearson's chi-square tests for categorical variables; statistical tests were performed across centers only (Center 1, Center 2, Center 3).

Radiographic Measurements

A true lateral radiograph was defined as a measured distance of < 6mm of overlap between the posterior halves of the medial and lateral femoral condyles.[13,23] When multiple radiographs were available, the image best fulfilling this criterion was used.

Measurement was performed using a previously described cortical-referenced technique based on the posterior tibial cortex (PTC) and the anterior tibial cortex (ATC).[29] The ATC was defined at the line connecting two points on the anterior cortex of the proximal tibia at 5 and 15 cm distal to the knee joint line; if tibial length on the radiograph was less than 15cm, the most distal visible cortex point was used. The PTC was defined analogously for the posterior cortex. PTS was defined as the angle between the posterior inclination of the medial or lateral tibial plateau tangent and a line perpendicular to the tibial axis. The final PTS value was computed as the mean of PTC- and ATC-referenced measurements (MPA).[29] On a true lateral radiograph, the medial tibial plateau was identified as the more concave plateau and the lateral tibial plateau as the more convex plateau, consistent with established conventions.[3]

All radiographic measurements were performed by the first author using digital PACS software according to the predefined measurement protocol. Although interobserver reliability was not formally re-assessed within the current study, the cortical-referenced technique applied here has demonstrated excellent inter- and intra-observer reliability in a previous published validation study.[29]

Outcomes

The primary clinical outcome was revision ACLR of the index knee during the observation period. Suspected graft insufficiency was assessed clinically (positive Lachman and pivot-shift test) and confirmed on magnetic resonance imaging.

PTS was measured for both the medial and lateral tibial plateaus. Because current evidence remains inconsistent regarding which compartment is the more relevant predictor of graft failure — with studies supporting medial slope, lateral slope, or both as risk factors[2,8,24], we did not select a single compartment a priori. Instead, four pre-specified operationalizations of PTS were defined as primary continuous predictors: medial PTS, lateral PTS, the maximum of medial and lateral PTS (PTSmax), and the lateral–medial PTS difference (ΔPTS). The primary descriptive outcome was the prevalence of increased PTS, defined as PTSmax ≥12°. Secondary outcomes consisted of the unadjusted association between LET and revision ACLR stratified by medial PTS, lateral PTS, and PTSmax dichotomized at 12°, expressed as absolute risk reduction (ARR) and number needed to treat (NNT); and the shape of the dose–response relationship between PTS and revision ACLR.

Statistical Analysis

Continuous variables were summarized as median (interquartile range, IQR) or mean (standard deviation), and categorical variables as counts and percentages. Between group comparisons were performed using Welch t-test for approximately normally distributed continuous variables, the Mann–Whitney U test for skewed continuous variables, and the χ^2 test or Fisher's exact test for categorical variables, as appropriate.

The primary outcome, revision ACLR, was analyzed as a binary outcome using logistic regression (binomial generalized linear model with logit link).

The primary analyses consisted of four pre-specified multivariable logistic regression models, each with a different PTS operationalization (medial, lateral, PTSmax, and ΔPTS) as a continuous predictor (per 1° increase). All models included LET as the principal exposure of interest and were adjusted for sex, age at surgery, BMI, primary ACL graft diameter, lateral meniscectomy, graft type (hamstring autograft, bone–patellar tendon–bone, and quadriceps tendon), and surgical center as a fixed effect. Covariates were selected by center-adjusted univariate logistic regression; variables with a p value <0.20 were retained for the multivariable models. Associations were reported as adjusted odds ratios (OR) with 95% confidence intervals.

As secondary analyses to contextualize the findings against the existing literature, PTS was dichotomized at 12° (medial, lateral, and PTSmax, each <12° vs. ≥12°). Revision ACLR rates were compared between patients treated with isolated ACLR and those treated with ACLR combined with LET, both overall and stratified by PTS category. The treatment effect of LET was quantified as the absolute risk reduction (ARR) with 95% confidence intervals (derived from the standard error of the difference in proportions) and the corresponding number needed to treat (NNT). An interaction term between LET and PTS category was included to test for effect modification. To characterize the shape of the dose–response relationship between PTS and the probability of revision ACLR, restricted cubic splines (4 knots) were incorporated into the multivariable logistic regression models. Predicted probabilities with 95% confidence intervals were estimated across the observed range of medial and lateral PTS values, separately for patients with and without LET, with all other covariates fixed at their median values.

Given the low proportion of missing data, missing values in continuous covariates were imputed using the within-center median, with fallback to the overall median. Results of the primary analyses were verified in a complete-case sensitivity analysis. All analyses were performed in Python (V3.9) using the statsmodels and patsy libraries. No formal a priori power analysis was performed; the cohort size was determined by the available eligible patients within the predefined center-specific inclusion windows. Statistical significance was defined as $p<0.05$; all tests were two-sided.

RESULTS

A total of 881 patients were screened; after applying the predefined exclusion criteria (n=101), 780 patients were included in the final analysis (Figure 1). The mean observation period was 52 months (range 28 – 92 months). The included cohort had a median age at injury of 18 years (IQR 16–20) and a median age at surgery of 19 years (IQR 17–21).

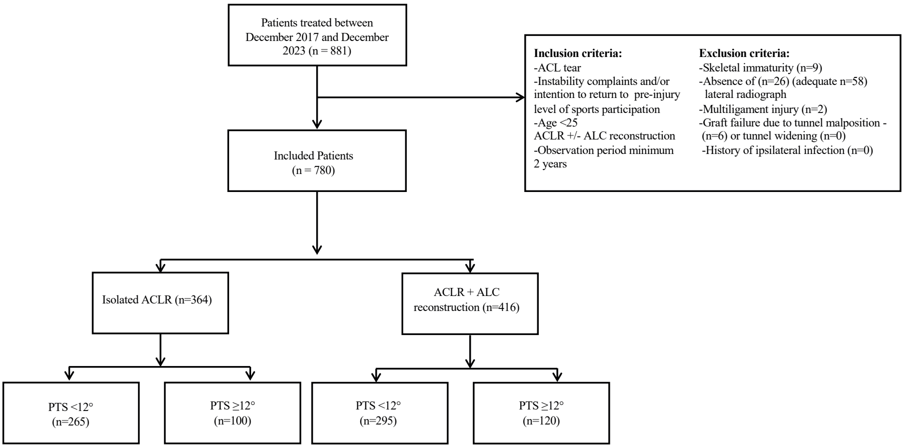


Figure 1. Flowchart of patient inclusion and exclusion

Baseline characteristics are presented in Table 1 and showed variation between centers, notably in graft type, surgical technique, and LET method. The overall prevalence of increased PTS was 28.2% and varied across centers (Center 1: 37.7%, Center 2: 23.2%; Center 3, 25.6%); The prevalence of medial PTS ≥12° was 20.5% and of lateral PTS ≥12° was 21.4%.

Overall, 84 patients underwent revision ACLR (10.8%). Revision rates differed across centers (Center 1: 32 revisions (13.9%), Center 2: 18 revisions (5.8%); Center 3: 34 revisions (14.3%). Patients requiring revision had significantly higher PTS measurements (maximum slope 11.03±2.94 vs 10.21±2.87, p=.02; medial slope 10.15±2.98 vs 9.32±2.95, p=.02; lateral slope 10.22±2.85 vs 9.43±3.04, p=.02), while age, sex, and BMI did not differ significantly between groups (Table 2).

Table 2. Comparison of patient characteristics and posterior tibial slope between patients with and without revision ACLR

Variable	No revision ACLR (n=696)	Revision ACLR (n=84)	p
Age	19 [17–21]	18.5 [16.3–21]	.29
Male sex	381 (54.6%)	52 (62.7%)	.20
BMI	22.8 [21.3–24.6]	22.7 [21.1–23.9]	.32
Time to failure	NA	17 [11–31]	NA
Maximum posterior tibial slope	10.21 (2.87)	11.03 (2.94)	**.02**
Medial posterior tibial slope (degrees)	9.32 (2.95)	10.15 (2.98)	**.02**
Lateral posterior tibial slope (degrees)	9.43 (3.04)	10.22 (2.85)	**.02**

Data are presented as median [IQR] for non-normally distributed continuous variables and as mean (SD) for approximately normally distributed variables; categorical variables are shown as n (%). Between-group comparisons were performed using the Mann–Whitney U test for skewed continuous variables, Welch's t-test for continuous variables with unequal variances, and the Chi-square test for categorical variables. Maximum posterior tibial slope was defined as the larger value of the medial and lateral posterior tibial slope measurements (degrees). Time to failure is only defined among patients with a revision; therefore, no statistical comparison with the non-revision group was performed and values are reported descriptively only.

In the four pre-specified primary multivariable models with PTS analyzed as a continuous predictor, each PTS measure showed an independent association with revision ACLR with effect estimates of comparable magnitude (Table 3). Each additional degree of medial PTS was associated with a 7% increase in adjusted odds of revision (OR 1.07 per 1°, 95% CI 0.99–1.16, p=.10); each additional degree of lateral PTS with a 9% increase (OR 1.09 per 1°, 95% CI 1.00–1.18, p=.04); and each additional degree of PTSmax with a 9% increase (OR 1.09 per 1°, 95% CI 1.00–1.19, p=.04). The lateral–medial PTS difference (ΔPTS) was not independently associated with revision ACLR (OR 1.03 per 1°, 95% CI 0.93–1.15, p=.53), indicating that the absolute slope, rather than the asymmetry between compartments, drives the association.

Across all models, LET was independently associated with substantially lower odds of revision ACLR (OR 0.37, 95% CI 0.22-0.62, p<.001). Younger age at surgery was also independently associated with revision ACLR (OR 0.91 per year, p=.03-.04). After adjustment, surgical center remained independently associated with revision ACLR, with Centers 2 and 3 showing lower odds compared with Center 1 (Table 3).

Table 3. Multivariable logistic regression — main analysis (N = 780, 84 events)

	Medial PTS		**Lateral PTS**		**Max PTS**		Δ PTS (lat–med)	
	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p
Medial PTS (per 1°)	1.07 (0.99–1.16)	.105	1.09 (1.00–1.18)	**.041**	1.09 (1.00–1.19)	**.041**	1.04 (0.93–1.15)	.525
LET	0.37 (0.22–0.61)	**<.001**	0.37 (0.23–0.62)	**<.001**	0.37 (0.22–0.61)	**<.001**	0.37 (0.23–0.61)	**<.001**
Sex (male)	1.69 (0.99–2.89)	.06	1.66 (0.97–2.84)	.07	1.68 (0.98–2.87)	.06	1.67 (0.98–2.86)	.06
Age (per year)	0.91 (0.83–0.99)	**.04**	0.91 (0.83–0.99)	**.033**	0.91 (0.83–0.99)	**.04**	0.91 (0.83–0.99)	**.04**
BMI (per unit)	0.95 (0.87–1.04)	.25	0.95 (0.87–1.04)	.27	0.95 (0.87–1.04)	.28	0.94 (0.87–1.03)	.18
Graft type (ref = Hamstring)								
BTB	0.50 (0.10–2.42)	.39	0.50 (0.10–2.41)	.38	0.49 (0.10–2.37)	.38	0.52 (0.11–2.54)	.42
Quadriceps tendon	0.42 (0.12–1.46)	.17	0.41 (0.12–1.43)	.16	0.42 (0.12–1.47)	.17	0.40 (0.11–1.39)	.15
Graft diameter (per mm)	0.82 (0.55–1.21)	.31	0.81 (0.55–1.20)	.30	0.81 (0.55–1.20)	.30	0.81 (0.55–1.21)	.307
Lateral meniscectomy	0.46 (0.20–1.05)	.07	0.44 (0.19–1.01)	.05	0.45 (0.20–1.02)	.06	0.46 (0.20–1.06)	.07
Study center (ref = Center 1)								
Center 2	0.30 (0.15–0.60)	**<.001**	0.29 (0.14–0.57)	**<.001**	0.30 (0.15–0.60)	**<.001**	0.27 (0.14–0.54)	**<.001**
Center 3	0.91 (0.52–1.59)	.75	0.87 (0.50–1.53)	.64	0.92 (0.53–1.61)	.77	0.86 (0.49–1.50)	.60

OR = odds ratio; CI = confidence interval; BTB = bone-patellar tendon-bone; BMI = body mass index; LET = lateral extra-articular tenodesis. All PTS modeled as continuous predictors (OR per 1° increase. Bold rows indicate $p < 0.05$ in at least one model. Covariates selected by univariate screening ($p < 0.20$): graft type ($p = 0.123$), sex ($p = 0.189$), age ($p = 0.056$), BMI ($p = 0.127$), graft diameter ($p = 0.014$), lateral meniscectomy ($p = 0.067$). Tegner score and medial meniscectomy were excluded. LET and surgical center were forced into all models. Unknown LET technique and lateral meniscectomy imputed with mode; graft diameter imputed with median.

The dose–response analysis using restricted cubic splines showed an approximately linear increase in the probability of revision ACLR across the observed range of both medial and lateral PTS values, with no evidence of a threshold effect or inflection point (Supplementary Figure 1). In secondary analyses using the 12° threshold, increased PTSmax was more common among patients requiring revision than among those who did not (38.6% vs 27.0%, p=.03). Stratified by LET, the protective association of LET was observed across all PTS categories (Table 4).

Table 4. Graft failure rates stratified by PTS (medial and lateral) and LET status, with absolute risk reduction and number needed to treat.

PTS-stratum	N	No LET, n/N (%)	LET, n/N (%)	ARR (95%-BI)	NNT
Lateral PTS ≥12°	166	13/77 (16.9%)	10/89 (11.2%)	5.6% (−5.0%–16.3%)	18
Lateral PTS <12°	610	42/285 (14.7%)	17/325 (5.2%)	9.5% (4.7%–14.3%)	11
Medial PTS ≥12°	159	17/77 (22.1%)	6/82 (7.3%)	14.8% (3.9%–25.6%)	7
Medial PTS <12°	617	38/285 (13.3%)	21/332 (6.3%)	7.0% (2.3%–11.7%)	14

ARR = absolute risk reduction; LET = lateral extra-articular tenodesis; NNT = number needed to treat; 95% CIs: standard error of the difference in proportions. NNTs rounded to nearest whole number.

In the medial PTS ≥12° stratum, the revision rate was 22.1% without versus 7.3% with LET (ARR 14.8% [95% CI 3.9%–25.6%], NNT 7); in the medial PTS <12° stratum, 13.3% versus 6.3% (ARR 7.0% [95% CI 2.3%–11.7%], NNT 14). In the lateral PTS ≥12° stratum, the revision rate was 16.9% without versus 11.2% with LET (ARR 5.6% [95% CI −5.0%–16.3%], NNT 18); in the lateral PTS <12° stratum, 14.7% versus 5.2% (ARR 9.5% [95% CI 4.7%–14.3%], NNT 11). For PTSmax ≥12°, the revision rate was 21.0% (21/100) without and 9.2% (11/120) with LET (ARR 11.8% [95% CI 2.3%–21.3%], NNT 9); for PTSmax <12°, 13.2% (35/265) without and 5.4% (16/296) with LET (ARR 7.8% [95% CI 3.0%–12.6%], NNT 13). There was no evidence that the protective association of LET differed by PTSmax category (interaction p=.97).

In the complete-case sensitivity analysis (n=752, events=80), lateral PTS remained independently associated with revision ACLR (OR 1.09, 95% CI 1.01–1.19, p=.031), while the association for medial PTS was attenuated (OR 1.07, 95% CI 0.99–1.17, p=.10) (Supplementary Table 1).

DISCUSSION

In this multicenter cohort of young high-risk primary ACLR patients, increased PTS (≥12°) was present in 28.2% of patients, confirming our first hypothesis. Increased PTS was independently associated with a higher risk of revision ACLR, while LET was associated with lower revision rates across the full range of PTS values, including patients with increased PTS. The protective association of LET did not differ between PTS strata (interaction p=0.97). However, LET did not fully eliminate the excess risk associated with increased PTS: the revision rate in patients with PTS ≥12° and LET (9.2%) remained numerically higher than in patients with PTS <12° and LET (5.4%). These findings partially confirm our second hypothesis — LET reduced revision risk in the increased PTS subgroup, but did not neutralize the independent effect of elevated PTS.

Both increased PTS and LET influence anterior tibial translation, although through partially overlapping mechanisms. LET primarily reduces tibial internal rotation laxity and residual anterolateral rotatory instability, [19,32] with cadaveric studies indicating that the iliotibial band also acts as a secondary stabilizer to anterior tibial translation.[32] Increased PTS, in contrast, primarily increases anterior tibial translation and graft loading under axial load.[2,9,11,14,15,20,31] Rather than mitigating the slope itself, LET therefore appears to provide a slope-independent reduction in revision risk that is additive to the slope effect. This may explain why the protective association of LET was observed consistently across the full range of PTS values in our cohort.[19,32]

Our findings support a stepwise approach to risk reduction in high-risk primary ACLR patients. LET was associated with substantially lower odds of revision ACLR across all PTS values, supporting its consideration as an initial risk-reduction strategy. Because increasing PTS remained independently associated with revision ACLR despite LET, slope reducing osteotomy may be considered as an additional step in selected primary cases, particularly in patients with PTS substantially above 12°. This concept is supported by recent literature reporting improved graft stability and reduced failure rates after combining slope-reducing osteotomy with primary ACLR in patients with elevated PTS and excessive anterior tibial subluxation[26,33] and by a recent editorial advocating consideration of slope correction in primary ACLR when PTS exceeds approximately 12–14°.[7] The role of slope-reducing osteotomy in primary ACLR remains debated, and a recent international Delphi consensus supports its consideration only in highly selected presentations.[30] The decision to perform a slope reducing osteotomy should integrate multiple patient-specific factors, including activity level and return-to-sport goals, cause of any prior graft failure, details of previous ACLR, coronal alignment, meniscal and cartilage status, and relevant physical examination findings such as generalized laxity or knee hyperextension.

As our data are observational and do not directly evaluate slope-reducing osteotomy, this stepwise concept should be interpreted as hypothesis-generating; prospective studies are needed to determine whether the addition of slope correction in primary ACLR further reduces revision risk in patients with substantially elevated PTS already receiving LET.

Recent biomechanical studies support these findings. Pearce et al. demonstrated that increasing PTS linearly increases ACL graft forces, and that LET reduces graft force compared with isolated ACLR; although slope reduction had a larger effect.[22] Lemme et al found that LET performed comparably to or better than slope reducing osteotomy under simulated pivot-shift conditions in the presence of increased PTS.[16] From a clinical perspective, Mazy et al reported substantially higher graft rupture rates in patients with PTS ≥12° (19.4%) compared with PTS <12° (2.7%) in a single-center, single-surgeon cohort of hamstring ACLR combined with LET and a minimum follow-up of 6 years.[21] Direct comparisons between studies in this field are limited by substantial heterogeneity in follow-up duration, graft choice, uniformity of technique, degree of surgical standardization, and risk stratification criteria, all of which influence reported revision rates; our findings should therefore be interpreted as complementary rather than directly comparable to single-surgeon series. Our findings do not directly compare LET with slope reducing osteotomy, but demonstrate that LET is associated with reduced revision risk across the full range of PTS values, including in patients with increased PTS.

Several methodologic considerations deserve discussion. There is ongoing debate regarding whether medial or lateral PTS is the more relevant predictor to graft loading and failure risk. Recent evidence suggests that lateral PTS may have a larger effect on ACL graft forces and anterior tibial translation,[35] and one clinical study identified lateral PTS as an independent predictor of ACL graft failure while medial PTS did not reach statistical significance.[4] Conversely, a meta-analysis found both compartments to be increased in patients with failed grafts compared with primary tears or intact ACLs.[6] An international Delphi consensus reached agreement on using the medial plateau as the reference point for PTS measurement on lateral knee radiographs but did not reach consensus on a cutoff value for pathological PTS or an absolute indication for slope reducing osteotomy.[30] Rather than selecting one compartment a priori, we analyzed four pre-specified operationalizations of PTS as continuous predictors in parallel multivariable models. The medial, lateral, and maximum PTS measures yielded near-identical adjusted odds ratios (approximately 1.07–1.09 per 1° increase), whereas the lateral–medial PTS difference was not independently associated with revision ACLR. This convergence indicates that the absolute slope, rather than the compartment chosen for measurement or the asymmetry between compartments, drives the association with revision risk.

Several PTS measurement techniques have been described[30] and yield systematically different PTS values[3] , which limits direct comparison of absolute threshold studies.[5] Although full-length lateral tibial radiographs allow a variety of measurements and the complete mechanical axis of the tibia to be measured, such imaging is not routinely available in clinical practice and many patients only have standard lateral knee radiographs available. Moreover, even when lateral knee radiographs are obtained, the proximal tibia is frequently not visualized over a sufficient length to reliably determine the anatomic axis. We therefore used a previously described cortical-referenced measurement technique that allows PTS determination on standard lateral knee radiographs.[29] This approach has demonstrated high inter- and intra-observer reliability[29] and reflects real-world clinical decision-making, where treatment planning often relies on routinely available imaging rather than dedicated long-leg lateral radiographs.

Revision rates differed substantially between surgical centers (5.8% to 14.3%), with overall rates at the upper end of those reported in the literature for young high-risk ACLR populations.[10,27] The persistence of a significant center effect in the multivariable analysis, even after adjustment for patient and surgical covariates including graft type, suggests that the observed between-center differences cannot be fully attributed to case-mix or graft choice alone. Center 2 had the lowest revision rate and was notable for substantial use of bone-patellar tendon-bone autograft (22%) and the anteromedial portal drilling technique (21%); however, neither graft type nor surgical technique was independently associated with revision risk in the multivariable model. Plausible additional contributors to the residual center effect include differences in ACL fixation technique, rehabilitation protocols, return-to-sport criteria, patient selection at the indication phase, and local thresholds for performing revision surgery, none of which were uniformly captured in our retrospective dataset. These findings underscore the relevance of multicenter designs in this field but also highlight residual confounding that observational data alone cannot fully resolve.

LIMITATIONS

This study has several limitations. Its retrospective design introduces the possibility of selection bias and limits control over confounding variables. In particular, the adoption of LET evolved over time based on patient risk factors, and was not randomized, introducing potential confounding by indication and temporal bias. Although surgical center was included as a fixed effect and we adjusted for known confounders, unmeasured factors such as rehabilitation adherence and return-to-sport criteria may have influenced revision risk. Because treatment strategies evolved over time during the inclusion period, patients undergoing isolated ACLR and those undergoing LET were not always treated contemporaneously in all centers, which may introduce allocation bias.

All PTS measurements were performed by a single observer using a previously validated cortical-referenced technique, and interobserver reliability was not formally reassessed within the current study. Furthermore, 84 of the 881 screened patients (9.5%) were excluded due to absent or inadequate lateral radiographs, which may have introduced a degree of selection bias and limits the applicability of the present findings to patients with adequate imaging. No formal a priori power analysis was performed; the cohort size was determined by the available eligible patients within the predefined center-specific inclusion windows, and the study may have been underpowered to detect subtler associations. Specific meniscal tear patterns (e.g., root, body, bucket-handle, or ramp lesions) were not consistently recorded and therefore could not be incorporated into the analysis, despite their known relevance to ACLR outcomes. In addition, although graft type was included as a covariate, residual heterogeneity in surgical technique and rehabilitation across centers cannot be fully captured, and a significant between-center difference in revision rates persisted after multivariable adjustment, indicating residual confounding.

The primary outcome was revision ACLR, which may underestimate the true rate of functional graft insufficiency, as some patients with clinical instability may not undergo revision surgery, and thresholds for revision surgery may have differed between centers. The majority of patients in our cohort underwent hamstring autograft ACLR using an all-inside technique, which may limit generalizability of our findings to other graft types and surgical approaches. Finally, the observation period may not capture all late revisions, particularly those treated outside the participating centers. However, most ACL graft ruptures in young athletic populations occur within the first postoperative years, making the available observation period clinically relevant for the primary study objective.

CONCLUSION

In a young high-risk primary ACLR population, increased PTS was present in nearly thirty percent of patients. LET was associated with a lower risk of revision irrespective of PTS, while increased PTS was independently associated with revision ACLR.

REFERENCES

1. Bernard M, Hertel P, Hornung H, Cierpinski T. **Femoral insertion of the ACL. Radiographic quadrant method**. *Am J knee Surg*. 1997;10(1):14-21; discussion 21-2.
2. Bernhardson AS, Aman ZS, Dornan GJ, et al. **Tibial Slope and Its Effect on Force in Anterior Cruciate Ligament Grafts: Anterior Cruciate Ligament Force Increases Linearly as Posterior Tibial Slope Increases**. *Am J Sports Med*. 2019;47(2):296-302.
3. Boer BC, Veerman QWT, Brouwer RW, et al. **Proximal anatomical axes show bidirectional variability: Accurate tibial slope requires mechanical axis measurement**. *Knee Surg, Sports Traumatol, Arthrosc*. Published online 2025.
4. Buyukkuscu MO, Kulduk A, Sencan K, Yavuz U, Albayrak K, Karslioglu B. **Increased lateral, but not medial, posterior tibial slope is associated with early graft failure following anterior cruciate ligament reconstruction**. *BMC Musculoskelet Disord*. 2025;26(1):1024.
5. Dean RS, DePhillipo NN, Chahla J, Larson CM, LaPrade RF. **Posterior Tibial Slope Measurements Using the Anatomic Axis Are Significantly Increased Compared With Those That Use the Mechanical Axis**. *Arthroscopy*. 2021;37(1):243-249.
6. Dean RS, DePhillipo NN, LaPrade RF. **Posterior Tibial Slope in Patients With Torn ACL Reconstruction Grafts Compared With Primary Tear or Native ACL: A Systematic Review and Meta-analysis**. *Orthop J Sports Med*. 2022;10(4):23259671221079380.
7. Dejour DH, Dan MJ, Cance N. **Editorial Commentary: Posterior Tibial Slope-Reducing Osteotomy Should Be Considered in Patients Having Primary Anterior Cruciate Ligament Reconstruction if Posterior Tibial Slope Is Greater Than 12° to 14°**. *Arthrosc: J Arthrosc Relat Surg*. 2025;41(8):3196-3199.
8. Duerr R, Ormseth B, Adelstein J, et al. **Elevated Posterior Tibial Slope Is Associated With Anterior Cruciate Ligament Reconstruction Failures: A Systematic Review and Meta-analysis**. *Arthrosc: J Arthrosc Relat Surg*. 2023;39(5):1299-1309.e6.
9. Fening S, Kovacic J, Kambic H, McLean S, Scott J, Miniaci A. **The Effects of Modified Posterior Tibial Slope on Anterior Cruciate Ligament Strain and Knee Kinematics – A Human Cadaveric Study**. *J Knee Surg*. 2008;21(03):205-211.
10. Getgood AMJ, Bryant DM, Litchfield R, et al. **Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2-Year Outcomes From the STABILITY Study Randomized Clinical Trial**. *Am J Sports Med*. 2019;48(2):285-297.
11. Giffin JR, Vogrin TM, Zantop T, Woo SLY, Harner CD. **Effects of Increasing Tibial Slope on the Biomechanics of the Knee**. *Am J Sports Med*. 2004;32(2):376-382.
12. Grassi A, Kim C, Muccioli GMM, Zaffagnini S, Amendola A. **What Is the Mid-term Failure Rate of Revision ACL Reconstruction? A Systematic Review**. *Clin Orthop Relat R*. 2017;475(10):2484-2499.
13. Gwinner C, Fuchs M, Sentuerk U, et al. **Assessment of the tibial slope is highly dependent on the type and accuracy of the preceding acquisition**. *Arch Orthop Trauma Surg*. 2019;139(12):1691-1697.
14. Imhoff FB, Comer B, Obopilwe E, Beitzel K, Arciero RA, Mehl JT. **Effect of Slope and Varus Correction High Tibial Osteotomy in the ACL-Deficient and ACL-Reconstructed Knee on Kinematics and ACL Graft Force: A Biomechanical Analysis**. *Am J Sports Med*. 2020;49(2):410-416.
15. Imhoff FB, Mehl J, Comer BJ, et al. **Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load**. *Knee Surg, Sports Traumatol, Arthrosc*. 2019;27(10):3381-3389.

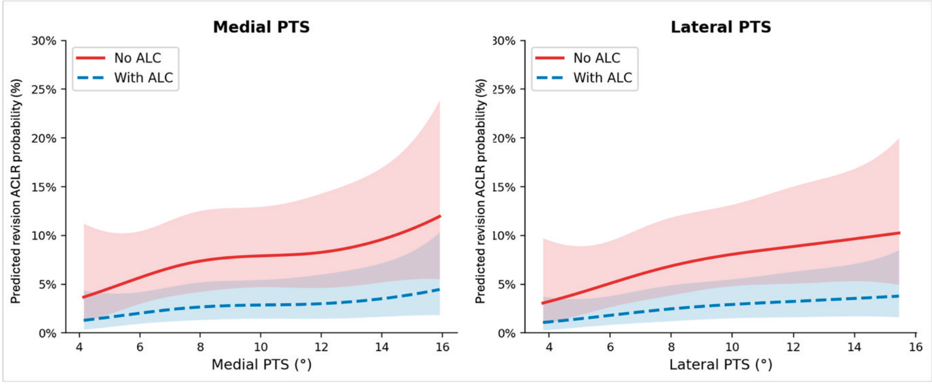
16. Lemme NJ, Badida R, Molino J, et al. **The Effect of Lateral Extra-articular Tenodesis on Anterior Cruciate Ligament Graft Forces and Knee Stability Compared With Slope Reduction Osteotomy in the Setting of Increased Posterior Tibial Slope**. *Am J Sports Med*. 2025;53(8):1912-1920.
17. Liu Z, Jiang J, Yi Q, et al. **An increased posterior tibial slope is associated with a higher risk of graft failure following ACL reconstruction: a systematic review**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(7):2377-2387.
18. Magnussen RA, Meschbach NT, Kaeding CC, Wright RW, Spindler KP. **ACL Graft and Contralateral ACL Tear Risk within Ten Years Following Reconstruction**. *Jbjs Rev*. 2015;3(1):NA;
19. Marom N, Ouanezar H, Jahandar H, et al. **Lateral Extra-articular Tenodesis Reduces Anterior Cruciate Ligament Graft Force and Anterior Tibial Translation in Response to Applied Pivoting and Anterior Drawer Loads**. *Am J Sports Med*. 2020;48(13):3183-3193.
20. Martineau PA, Fening SD, Miniaci A. **Anterior opening wedge high tibial osteotomy: the effect of increasing posterior tibial slope on ligament strain**. *Can J Surg J Can Chir*. 2010;53(4):261-267.
21. Mazy D, Cance N, Favroul C, et al. **The Impact of Posterior Tibial Slope and Static Anterior Tibial Translation on ACL Graft Rupture Rates After Hamstring Autograft Reconstruction With Lateral Extra-articular Tenodesis**. *Am J Sports Med*. 2025;53(10):2379-2386.
22. Pearce SL, Bryniarski AR, Brown JR, et al. **Biomechanical Analysis of Tibial Motion and ACL Graft Forces After ACLR With and Without LET at Varying Tibial Slopes**. *Am J Sports Med*. 2023;51(10):2583-2588.
23. Pfeiffer TR, Burnham JM, Hughes JD, et al. **An Increased Lateral Femoral Condyle Ratio Is a Risk Factor for Anterior Cruciate Ligament Injury**. *J Bone Jt Surg*. 2018;100(10):857-864.
24. Salmon LJ, Heath E, Akrawi H, Roe JP, Linklater J, Pinczewski LA. **20-Year Outcomes of Anterior Cruciate Ligament Reconstruction With Hamstring Tendon Autograft: The Catastrophic Effect of Age and Posterior Tibial Slope**. *Am J Sports Med*. 2018;46(3):531-543.
25. Samuelsen BT, Aman ZS, Kennedy MI, et al. **Posterior Medial Meniscus Root Tears Potentiate the Effect of Increased Tibial Slope on Anterior Cruciate Ligament Graft Forces**. *Am J Sports Med*. 2019;48(2):334-340.
26. Song G yang, Ni Q kun, Zheng T, Zhang Z jun, Feng H, Zhang H. **Slope-Reducing Tibial Osteotomy Combined With Primary Anterior Cruciate Ligament Reconstruction Produces Improved Knee Stability in Patients With Steep Posterior Tibial Slope, Excessive Anterior Tibial Subluxation in Extension, and Chronic Meniscal Posterior Horn Tears**. *Am J Sports Med*. 2020;48(14):3486-3494.
27. Sonnery-Cottet B, Saithna A, Cavalier M, et al. **Anterolateral Ligament Reconstruction Is Associated With Significantly Reduced ACL Graft Rupture Rates at a Minimum Follow-up of 2 Years: A Prospective Comparative Study of 502 Patients From the SANTI Study Group**. *Am J Sports Med*. 2017;45(7):1547-1557.
28. Stubli HU, Rauschning W. **Tibial attachment area of the anterior cruciate ligament in the extended knee position: Anatomy and cryosections in vitro complemented by magnetic resonance arthrography in vivo**. *Knee Surg, Sports Traumatol, Arthrosc*. 1994;2(3):138-146.
29. Utzschneider S, Goettinger M, Weber P, et al. **Development and validation of a new method for the radiologic measurement of the tibial slope**. *Knee Surg, Sports Traumatol, Arthrosc*. 2011;19(10):1643-1648.

30. Wackerle AM, Marcaccio S, Apseloff N, et al. **Assessment and surgical correction of posterior tibial slope in revision anterior cruciate ligament surgery: An international expert Delphi consensus statement**. *J ISAKOS*. 2025;13:100900.
31. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **Meniscal Tears, Posterolateral and Posteromedial Corner injuries, Increased Coronal Plane and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament-Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**. *Arthrosc J Arthrosc Relat Surg*. 2021;38(5):1664-1688.e1.
32. van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction can Restore Native Knee Kinematics in the ACL Reconstructed Knee. A Systematic Review of Biomechanical Cadaveric Studies**. *Arthrosc: J Arthrosc Relat Surg*. Published online 2023.
33. Wang D, Di M, Zheng T, et al. **Effect of Slope-Reducing Tibial Osteotomy With Primary Anterior Cruciate Ligament Reconstruction on Clinical and Radiological Results in Patients With a Steep Posterior Tibial Slope and Excessive Anterior Tibial Subluxation: Propensity Score Matching With a Minimum 2-Year Follow-up**. *Am J Sports Med*. 2025;53(6):1381-1391.
34. Webb JM, Salmon LJ, Leclerc E, Pinczewski LA, Roe JP. **Posterior Tibial Slope and Further Anterior Cruciate Ligament Injuries in the Anterior Cruciate Ligament–Reconstructed Patient**. *Am J Sports Med*. 2013;41(12):2800-2804.
35. Whicker EA, Rizzo MG, Rothrauff BB, et al. **Does the Medial or Lateral Tibial Slope Have a Greater Effect on ACL Reconstruction Mechanics? A Biomechanical Analysis**. *Orthop J Sports Med*. 2026;14(1):23259671251405432.
36. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Medicine*. 2016;44(7):1861-1876.

Supplementary Table 1. Sensitivity analysis — complete case (N = 754, 82 events)

	Medial PTS		**Lateral PTS**		**Max PTS**		Δ PTS (lat–med)	
N = 754; events = 82	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p	OR (95% CI)	p
Medial PTS (per 1°)	1.06 (0.97–1.15)	.18	1.09 (1.00–1.18)	**.046**	1.08 (1.00–1.18)	.06	1.05 (0.95–1.18)	.34
LET	0.39 (0.24–0.65)	**<.001**	0.40 (0.24–0.65)	**<.001**	0.39 (0.24–0.65)	**<.001**	0.39 (0.24–0.65)	**<.001**
Sex (male)	1.67 (0.97–2.88)	.06	1.64 (0.95–2.83)	.08	1.66 (0.97–2.86)	.07	1.64 (0.95–2.83)	.07
Age (per year)	0.91 (0.83–0.99)	**.04**	0.91 (0.83–0.99)	**.03**	0.91 (0.83–0.99)	**.035**	0.91 (0.83–0.99)	**.04**
BMI (per unit)	0.95 (0.87–1.04)	.25	0.95 (0.87–1.04)	.27	0.95 (0.87–1.04)	.28	0.94 (0.87–1.03)	.18
Graft type								
BTB	0.60 (0.12–3.09)	.54	0.60 (0.12–3.11)	.54	0.59 (0.11–3.08)	.54	0.60 (0.12–3.09)	.54
Quadriceps tendon	0.42 (0.12–1.49)	.18	0.41 (0.12–1.45)	.17	0.43 (0.12–1.50)	.18	0.40 (0.11–1.41)	.16
Graft diameter (per mm)								
Lateral meniscectomy	0.41 (0.17–0.99)	**.048**	0.39 (0.16–0.95)	**.038**	0.40 (0.17–0.96)	**.041**	0.41 (0.17–0.99)	**.046**
Study center (ref = Center 1)								
Center 2	0.32 (0.16–0.64)	**<.01**	0.30 (0.15–0.62)	**<.001**	0.32 (0.16–0.65)	**<.01**	0.29 (0.14–0.59)	**<.001**
Center 3	0.92 (0.52–1.62)	.77	0.88 (0.50–1.56)	.67	0.93 (0.52–1.64)	.79	0.87 (0.49–1.53)	.62

Complete-case sensitivity analysis (N = 754, 82 events). Same model specification as main analysis. OR = odds ratio; CI = confidence interval. Max PTS is centered at 12°. Bold p-values indicate $p < 0.05$.



Supplementary Figure 1. Dose–response relationship between posterior tibial slope and revision ACLR. Predicted probability of revision ACLR as a function of medial (left panel) and lateral (right panel) posterior tibial slope (PTS), derived from multivariable logistic regression with restricted cubic splines. Lines show predictions for patients with LET (blue, dashed) and without (red, solid), adjusted for sex, age, BMI, graft diameter, graft type (hamstring reference), and pre-operative Tegner score. Note the continuous, approximately linear increase in revision ACLR risk with higher PTS values in both groups, with substantially lower predicted risk in the LET group across the entire range.

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chapter 8

Which Pain Management Protocol Is More Effective after Combined Anterior Cruciate Ligament and Anterolateral Corner Reconstruction? A Comparison Study Protocol of Adductor Canal Block with and without Anterolateral Genicular Nerve Block

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ABSTRACT

Background

Anterior cruciate ligament (ACL) reconstruction is one of the most frequently performed orthopedic procedures. In recent years, anterolateral corner (ALC) reconstruction has increasingly been added to ACL reconstruction to improve rotational stability and reduce failure rates. However, this additional procedure requires a lateral incision, which may contribute to increased postoperative pain. The adductor canal block (ACB) is widely used for postoperative analgesia after ACL reconstruction, but it does not provide sufficient coverage of the lateral femoral region affected by ALC reconstruction. An anterolateral genicular nerve block may add to the ACB by targeting lateral knee innervation. This study aims to compare the efficacy of ACB alone versus ACB combined with anterolateral genicular nerve block for postoperative pain control in patients undergoing combined ACL and ALC reconstruction.

Methods

This multicenter, double-blind, randomized controlled trial includes 80 patients aged 16 years or older undergoing primary quadriceps tendon autograft ACL reconstruction combined with modified Lemaire ALC reconstruction. Participants are randomized in a 1:1 ratio to receive either ACB alone or ACB with an anterolateral genicular nerve block using ropivacaine. The primary outcome measure is the Numeric Rating Scale (NRS) pain score during movement at 2 hours postoperatively. Secondary outcomes include NRS pain score at rest and during movement at 1, 4, 6, 24, 48 hours, and 1 week after surgery, cumulative opioid consumption, use of rescue analgesics, patient-reported outcomes (VAS-pain, IKDC-subjective, Tegner, Lysholm, ACL-RSI) at six weeks, and incidence of adverse events. The primary outcome will be analyzed using an Analysis of Covariance (ANCOVA) model; secondary longitudinal outcomes will be analyzed using linear mixed-effects models.

Discussion

The ACL-GAIN trial (Adductor CanaL block with Genicular block Added for Improved aNalgesia) is the first randomized controlled double-blind study to evaluate the combined use of ACB and anterolateral genicular nerve block for postoperative analgesia after ACL and ALC reconstruction. We hypothesize that the addition of the genicular block reduces postoperative pain and opioid use, thereby enhancing patient comfort and facilitating early rehabilitation. The results may contribute to optimizing multimodal pain management protocols for patients undergoing complex knee ligament reconstructions.

Trial registration:

Trial registration: registered in the Dutch Trial Register (OMON – Overview of Medical Research in the Netherlands), a WHO-recognized primary registry, via the CCMO Research Portal (registration number: NL010865/R034410), approved by the Medical Research Ethics Committee (METC) Oost-Nederland.

BACKGROUND

Anterior cruciate ligament (ACL) injuries occur at a high frequency worldwide. In the United States approximately 400,000 ACL reconstructions are performed each year. In recent years, anterolateral corner (ALC) reconstruction has increasingly been performed alongside ACL reconstruction, to address residual anterolateral rotatory instability, caused by injury to the ALC structures. Several recent systematic reviews and meta-analyses of high-level studies have reported that adding an ALC reconstruction during primary ACL reconstruction results in better rotational stability and a significant reduction in failure rates.[1–4] To perform an ALC reconstruction it is necessary to add an additional incision at the lateral side of the distal femur.

ACL reconstructions are typically performed as outpatient procedures[5], necessitating effective postoperative pain management to ensure patient comfort and facilitate early mobilization. Usually, a multimodal analgesia protocol is applied, including non-steroidal anti-inflammatory drugs, opioid analgesics, peripheral nerve blocks, and local infiltration anesthesia (LIA). Numerous studies have compared the efficacy of an adductor canal block (ACB) versus a femoral nerve block (FNB) for pain control after ACL reconstruction[6–9] . While no significant differences have been found in pain scores, opioid consumption[6,8,9] or duration of analgesia between ACB and FNB, ACB shows superior quadriceps strength in the early postoperative period,[6–8] whereas FNB carries a higher risk of (near) falls.[10] An ACB provides analgesia to the anteromedial aspect of the knee and distal lower leg but does not cover the distal lateral femur region where the ALC reconstruction is performed. In a randomized clinical trial comparing hamstring ACL reconstruction with versus without ALC reconstruction, patients in the ALC reconstruction group experienced more pain at three months follow-up. There is, however, a paucity of literature investigating the optimal pain management strategies after combined ACL and ALC reconstruction.

To address persistent postoperative pain, particularly on the lateral side of the knee, improving current pain management protocols is warranted. Adding an anterolateral genicular nerve block may be a sensible option.[11] Although the efficacy of ACB versus local nerve blocks or local infiltration anesthesia for pain management after ACL reconstruction has been investigated,[12–14] no studies to date have examined ACB with versus without anterolateral genicular nerve block for pain management following combined ACL and ALC reconstruction.

The aim of this multicenter, prospective randomized trial is to compare postoperative pain outcomes of ACB alone versus ACB with an anterolateral genicular nerve block in patients undergoing ACL reconstruction combined with ALC reconstruction. The primary outcome is the Numeric Rating Scale (NRS) pain score, while secondary outcomes include cumulative opioid consumption during hospital recovery and at 24 and 48 hours after surgery. We hypothesize that ACB combined with an anterolateral genicular nerve block provides superior postoperative analgesia compared to ACB alone.

METHODS

This study and manuscript were designed in accordance with the Standard Protocol Items: Recommendations for Interventional Trials (SPIRIT) guidelines. The trial was approved by the Medical Ethics Committee Oost-Nederland (Radboudumc), and registered in the Dutch Trial Register (OMON – Overview of Medical Research in the Netherlands), a WHO-recognized primary registry, via the CCMO Research Portal (registration number: NL010865/R034410).

Study design

This study is a two-center, double blinded, parallel arm, prospective randomized controlled trial (RCT) with a 1:1 allocation ratio, conducted at (blinded for submission). This protocol is reported in accordance with the SPIRIT 2013 guidelines. Patients undergoing quadriceps autograft ACL reconstruction in combination with ALC reconstruction are randomized into two treatment arms:

(I) ACB without anterolateral genicular nerve block, and
(II) ACB with anterolateral genicular nerve block.

The hypothesis is that anterolateral genicular nerve block provides superior postoperative analgesia compared to ACB alone. All patients aged 16 years or older undergoing primary quadriceps tendon autograft ACL reconstruction with a modified Lemaire ALC procedure are eligible to participate.

The quadriceps tendon graft is increasingly becoming our first graft choice, and multiple studies have shown comparable[15,16] or better[17,18] clinical functional outcomes and graft survival rate compared with bone patellar tendon bone autografts[15] and hamstring tendon autografts.[16–18]

Study sample

Potential participants will be recruited from the orthopedic surgery departments of two hospitals. Inclusion and exclusion criteria are summarized in Table 1. In general, inclusion involves patients with acute, isolated, or combined (meniscal and/or cartilage injury) ACL tears who wish to return to preinjury activity level. Exclusion criteria include unwillingness to undergo ACL with ALC reconstruction, multiligamentous injury, revision ACL surgery, contraindications to peripheral nerve blocks (e.g., local infection, significant hematological disorder, allergy to local anesthetics, relevant cardiovascular conditions), pre-existing neurological deficits, pre-existing chronic pain condition, a history of allergy to any study medication, no understanding of Dutch language, or pregnancy or breastfeeding during the perioperative study period. A flowchart is shown in Figure 1. Participants may withdraw from the study at any time. Withdrawal after randomization does not affect inclusion in the primary analysis, which will be performed according to the intention-to-treat principle.

Table 1. Inclusion and exclusion criteria for participating in this RCT

Inclusion criteria	Exclusion criteria
- Clinical indication and willingness to undergo combined ACL and ALC reconstruction - (Sub)total primary ACL tear on physical examination and MRI, with or without concomitant meniscal injury and/or cartilage injury and/or partial concomitant knee ligament injury not requiring surgery - Age 16 years and older - Preinjury Tegner score ≥ 6 and desire to return to preinjury level	- Multiligamentous knee injury requiring multiligamentous knee surgery - Patients undergoing ACL revision surgery - Contraindications to peripheral nerve blocks including but not limited to local infection at the injection site, significant hematological disease, allergy to local anesthetics, and relevant cardiovascular conditions (e.g. atrioventricular conduction disorders, use of anti-arrhythmic medication) - Pre-existing neurological deficits - Pre-existing chronic pain condition not related to ACL injury -History of allergy to drugs used in this study - No understanding of Dutch language or not capable of understanding the study and participation - Pregnancy or breastfeeding at the time of surgery or during the perioperative study period

Blinding and Randomization

All patients provide written informed consent. After induction of general or spinal anesthesia, patients are randomly allocated to either the ACB-only group or the ACB plus anterolateral genicular nerve block group. Randomization is performed using a computer-generated sequence, and allocation concealment is ensured by a sealed opaque-envelope technique. The anesthesia assistant opens the envelope only after consent and prepares either 20 mL of 3.75mg/mL ropivacaine or 20mL of 0.9% sodium chloride. The orthopedic surgeon performing the anterolateral genicular nerve block, the anesthetist, nursing staff, and research personnel collecting postoperative data remain blinded to group allocation. Participants are also blinded.

Anesthesia and Intraoperative Analgesia

All patients receive premedication with paracetamol (2 g p.o.), unless contraindicated. An intravenous cannula is inserted in the forearm and a 0.9% NaCl infusion is started. For general anesthesia, patients are induced with 2-4 mg/kg propofol, 0.1-0.3 µg/kg sufentanil, and 8 mg dexamethasone, followed by insertion of a laryngeal mask airway. Anesthesia is maintained with a propofol infusion (6 – 10 mg/kg/h).

For spinal anesthesia, 3-4 mL of hyperbaric prilocaine (20 mg/ml) is injected using a 27G pencil-point needle at the level L3-4 or L4-5 interspace after confirmation of free cerebrospinal

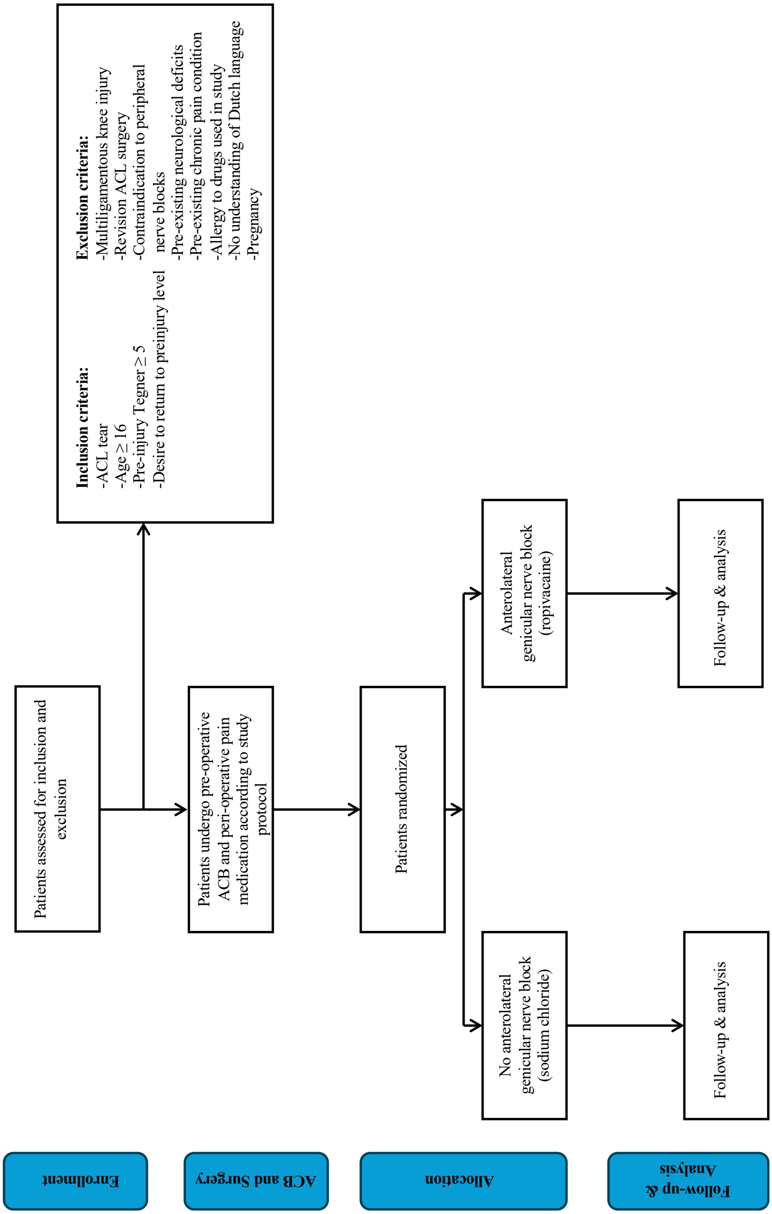

Figure 1. Flowchart of study

fluid flow. The anesthesia team avoids administering intraoperative analgesics other than opioids. All intraoperative opioid administration is recorded in the electronic health record.

Surgical techniques

Graft harvesting and preparation

For quadriceps tendon graft harvesting, a 2-3cm vertical incision is made just above the superior pole of the patella. Subcutaneous fat is dissected, the paratenon exposed, incised, and retracted to visualize the quadriceps tendon. A double-bladed knife (9-11mm) is used to obtain a full-thickness longitudinal graft. The distal end of the graft is sharply detached from the superior pole of the patella, and a Vicryl suture placed. The graft is then harvested using a quad tendon stripper cutter (Arthrex, Naples, USA), to a length of 6.5-7cm. Capsular defects are closed with continuous Vicryl sutures. For graft preparation, a FiberTag Tightrope II implant (Arthrex, Naples, USA) is secured to both graft ends.[19]

ACL Reconstruction

Anatomic single-bundle all-inside ACL reconstruction is performed as described by Lubowitz et al., using a quadriceps autograft.[20] Femoral and tibial aimers are positioned at the center of the anteromedial femoral and tibial ACL attachment sites. Tunnels are drilled retrograde, and the graft is tensioned in near extension.

Modified Lemaire ALC Reconstruction

The ALC reconstruction is performed using the modified Lemaire technique as described by Williams et al.[21] A 1 x 10 cm iliotibial band (ITB) strip is harvested, left attached to Gerdy's tubercle, whip-stitched proximally, passed deep to the lateral collateral ligament, and fixed in a 4.5mm socket just proximal and posterior to the lateral epicondyle with a non-absorbable Poly-Ether-Ether-Ketone (PEEK) tenodesis interference screw (Arthrex) at 30° of flexion and neutral rotation under 20N tension. The ITB defect is closed with a continuous Vicryl suture.

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Postoperative rehabilitation

Postoperative rehabilitation is identical for both groups and based on the evidence statement for rehabilitation after ACL reconstruction by the Royal Dutch Society for Physical Therapy. The program includes a prehabilitation phase followed by three criterion-based postoperative phases:

1) impairment-based rehabilitation,
2) sport-specific training, and
3) return to play.[22]

Anterolateral genicular nerve block

The anterolateral genicular nerve block or placebo injection is administered by the surgeon at the completion of the ACL reconstruction with modified Lemaire ALC reconstruction, as described by Gruskay et al.[11] The 2-step injection uses either 20mL of 0.9% sodium chloride solution or 20mL of 3.75mg/mL ropivacaine loaded into a syringe with an 18-gauge needle. Key anatomical landmarks include the superior edge of the patella and the lateral epicondyle.

First injection: positioned two fingerbreadths above the superolateral patella. The needle is inserted to the anterior femur, slightly retracted, and 10mL of solution is infiltrated into the surrounding tissue Figure 2.

Second injection: placed 2–3 fingerbreadths lateral to the first injection and 2–3 fingerbreadths proximal to the lateral epicondyle, aligned with the lateral femur. The needle is inserted until bone contact, then withdrawn 1–2 mm, and the remaining 10mL is administered Figure 2.

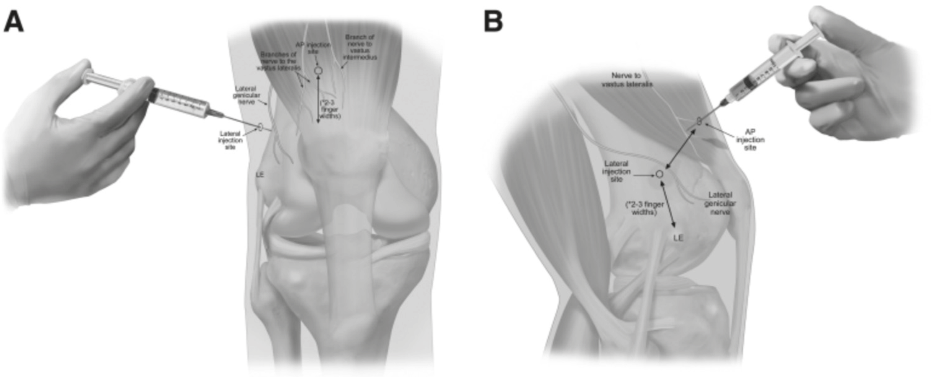

Figure 2. Drawing of the relevant neural anatomy as well as anatomic landmarks as viewed from anterior (A) and lateral (B). The anterior injection of the lateral genicular nerve block is placed 2 to 3 fingerbreadths above the superior pole of the patella in-line with the lateral one-third of the patella. This injection targets branches of the nerve to vastus lateralis as well as the nerve to vastus intermedius. The nerve to the vastus lateralis is a terminal branch of the femoral nerve that runs obliquely along the periosteum of the metaphysis at the anterolateral aspect of the knee. It gives off a transverse superficial retinacular branch as well as a longitudinal deep capsular branch. The articular branch of the nerve to the vastus intermedius runs along the anterior aspect of the distal femur towards the supra-patellar pouch of the knee capsule and is variably anesthetized by a typical adductor canal block. The lateral injection of the lateral genicular nerve block is placed 5 cm proximal to joint line, 2 to 3 fingerbreadths above the lateral epicondyle and 2 fingerbreadths lateral to the "anteroposterior injection site." This injection targets branches of the lateral genicular nerve as well as some variant branches of the nerve to vastus lateralis. Neither of these branches is anesthetized by the typical adductor canal block. Adapted with permission from Gruskay et al.[11]

Adductor Canal Block

Both groups undergo an ultrasound-guided saphenous nerve blockade prior to the induction of general or spinal anesthesia. The block is performed under aseptic conditions by an experienced anesthesiologist. The transducer is placed transversely over the medial mid-thigh and moved distally to identify the femoral artery and vein in the subsartorial space. The borders of the sartorius (anterolateral) and adductor longus (posterior) muscles are identified to define the apex of the femoral triangle. The injection target is distal to this apex, at the beginning of the adductor canal. Using a 50–80 mm echogenic needle, 15 mL of 3.75 mg/mL ropivacaine is administered using an in-plane technique.

Postoperative analgesia

After surgery, patients are transferred to the post-anesthesia care unit (PACU), where pain is assessed using the numeric rating scale (NRS). Intravenous morphine is administered if the NRS score is ≥ 4. Ketamine, magnesium sulphate, and clonidine are available as rescue analgesics when deemed necessary by the attending anesthesiologist.

Following PACU discharge, patients receive a standard analgesic regimen consisting of paracetamol 1 g every 6 hours, diclofenac 50 mg every 8 hours, and either tramadol 50 mg every 8 hours or oxycodone slow-release 10 mg every 12 hours, with oxycodone immediate-release 5 mg every 4 hours as needed, for 5 days.

As an escape strategy, patient-controlled analgesia (PCA) with intravenous morphine is provided for those not meeting discharge criteria on the same day due to pain. The PCA protocol consists of 1.5 mg morphine boluses available every 8 minutes, with a maximum of 30 mg per 4 hours.

All patients receive standardized instructions on NRS pain scoring, satisfaction assessment, and PCA use when applicable. Antiemetic medication is administered in the PACU as required, consisting of 4mg ondansetron i.v. and 0.625mg droperidol for ongoing nausea.

Data collection

Patient demographics (age, sex, height, body weight, and body mass index (BMI), pre-operative medication, medical history, and baseline PROMs (NRS pain score, Pain Catastrophizing Scale, Tegner, Lysholm, and International Knee Documentation Committee (IKDC)-subjective) are collected. Surgical data include operative side, graft diameter, type of meniscal treatment (partial medial and/or lateral meniscectomy, medial and/or lateral (including root) repair, and any cartilage procedures.

Resting and dynamic pain scores (NRS 0-10) at 1, 2, 4, and 6 hours postoperatively are recorded by nursing staff, as well as at 24 and 48 hours and at 1 week via telephone by a research assistant. All PROMs and pain data are recorded in the electronic patient files and stored in *Castor Electronic Data Capture*. The primary outcome measure is the NRS pain score during movement at 2 hours postoperatively. Secondary outcomes include NRS pain score at rest and during movement at 1, 4, 6, 24, 48 hours, and 1 week after surgery, cumulative dose of as-needed opioid medication administered during hospital recovery and at 24 and 48 hours postoperatively, as well as use of non-opioid rescue analgesics. Opioid doses are converted to milligram morphine equivalents for analysis. PROMs will also be collected at 6 weeks postoperatively. A timeline of the study is shown in figure 3. An overview of which outcomes are collected at the different follow-up visits are represented in table 2.

Any adverse effects such as nausea, vomiting, or procedure related complications are documented. Furthermore, any procedural related complications (hematoma, infection, new or persistent paresthesia or hypoesthesia) are recorded during follow-up.

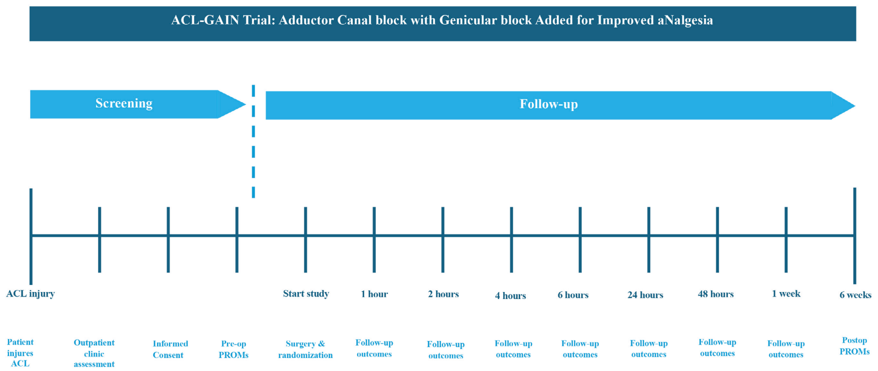

Figure 3. Timeline for patients in the ACL-GAIN trial

Table 2. Overview of which outcomes are collected at the different follow-up visits

	Pre	1 hrs	2 hrs	4 hrs	6 hrs	24 hrs	48 hrs	1 wk	6 wks
Primary Outcomes									
Dynamic NRS pain at 2 hours postoperatively		X	X	X	X	X	X		
Secondary Outcomes NRS pain (resting & dynamic)		X		X	X	X	X	X	
Cumulative opioids hospital		X	X	X	X				
Cumulative opioids home						X	X		
Rescue analgesics hospital		X	X	X	X				
PROMs: PCS	X								
PROMs: VAS pain, Tegner, Lysholm, IKDC	X								X

NRS: Numerical Rating Scale; PROMs: Patient Reported Outcome Measures; PCS: Pain Catastrophizing Scale; VAS: Visual Analogue Scale; IKDC: International Knee Documentation Committee

Statistical Analysis
All primary and secondary analyses will be conducted according to the intention-to-treat principle. All randomized participants will be analyzed in the treatment group to which they were allocated, regardless of protocol deviations, treatment received, or early withdrawal after randomization. All available outcome data collected up to the point of withdrawal will be included in the analyses. No replacement of participants after randomization will be performed. Categorical variables will be summarized as counts and percentages. Continuous variables will be summarized as mean (standard deviation) or median (interquartile range (IQR)), as appropriate.

The primary estimand is the adjusted between-group difference in NRS pain (0–10) during movement at 2 hours postoperatively. This estimand will be estimated using a prespecified linear regression model within an ANCOVA framework, with treatment group as the main predictor and adjustment for baseline NRS pain and study center as fixed effects. Adjustment for baseline NRS pain is prespecified and included solely to improve the precision of the treatment effect estimate; confounding is not expected due to randomization. The primary hypothesis will be tested using this model.

The intervention will be considered successful if the adjusted between-group difference at 2 hours postoperatively is at least 1.0 NRS point and statistically significant at a two-sided α level of 0.05. Based on previous literature, a 1-point change on the NRS pain scale is considered clinically meaningful.

Pain scores collected at 1, 2, 4, and 6 hours postoperatively, as well as at 24 and 48 hours and at 1 week, will be analyzed as secondary outcomes using a prespecified linear mixed-effects model. This model will include fixed effects for treatment group and categorical time, adjustment for baseline NRS pain and study center, and a random intercept for participant to account for within-subject correlation due to repeated measurements. No group-by-time interaction will be included in the primary mixed-effects model. These longitudinal analyses are considered secondary and exploratory.

Time-specific between-group differences at selected postoperative time points (including 24 and 48 hours and 1 week) will be reported as prespecified model-based contrasts with corresponding 95% confidence intervals.

Based on previous literature, including the study by Myles et al., a 1-point change on the NRS pain scale (equivalent to 10 mm on a 0–100 mm visual analogue scale) is considered clinically meaningful.[23]

With an alpha of 0.05, and a beta of 0.2 (80% power), assuming a mean difference of 1 and SD = 1.5, a sample size of 35 patients per group (70 in total) is required to detect a significant difference. Allowing for a 10% drop-out rate, the total planned enrollment is 80 patients. The assumed SD of 1.5 for the 0-10 pain scale is based on published postoperative pain data after arthroscopic ACL reconstruction. In these studies, the variability of VAS/NRS pain scores during the first 24 hours postoperatively is commonly reported with SDs ranging from approximately 0.7 to 1.1, while higher variability up to around 2.0 has been described at certain time points and depending on the analgesic regimen and study population.[13,24] Based on this reported range of variability, an SD of 1.5 was selected for the sample size calculation.

DISCUSSION

This study reports on the design of the ACL-GAIN trial (Adductor CanaL block with Genicular block Added for Improved aNalgesia). In the past decade, addressing injury to the ALC structures of the knee in combination with ACL tears has regained considerable attention. A systematic review of predominantly isolated ACLR studies, reported high re-injury rates exceeding 20%, with athletes younger than 25 years returning to pivoting sport having the highest risk of secondary ACL injury.[25] Another review of clinical studies concluded that adding a lateral extra-articular procedure, regardless of technique, reduced ACL reconstruction re-injury rates without increasing complications at mid-term follow-up.[26] There is growing consensus on specific indications for ALC reconstruction in ACL-reconstructed knees. In a recent international consensus statement, experts strongly recommended adding an ALC reconstruction in young, active patients undergoing hamstring autograft ACLR and in cases of high-grade rotational or anterior laxity, knee hyperextension, revision surgery, or returning to pivoting sports.[27]

Adding an ALC reconstruction procedure with an additional incision at the lateral side of the distal femur has implications for postoperative pain perception. Current multimodal analgesia -typically including non-steroidal anti-inflammatory drugs, opioid analgesics, and peripheral nerve blocks- may not adequately address pain related to the ALC procedure. Since postoperative pain is inversely associated with functional recovery at all stages of rehabilitation[28] there is a clear need for improved pain management strategies after combined ACL and ALC reconstruction.

Regarding peripheral nerve blocks, the ACB is preferred over the FNB, as ACB provides superior quadriceps strength in the early postoperative phase.[6–8] However, evidence regarding the analgesic effectiveness of ACB after ACL reconstruction is conflicting. A randomized controlled trial found only a minimal effect on postoperative pain management following isolated hamstring autograft ACL reconstruction in the context of multimodal analgesia and intra-articular local anesthesia.[29] A 2019 Cochrane review concluded that it remains uncertain whether patients treated with ACB experience lower pain intensity at rest or during movement, fewer opioid-related adverse events, or fewer accidental falls compared with those receiving placebo treatment.[30] One possible explanation for the limited efficacy of ACB is that it only targets the saphenous nerve distribution and does not anesthetize the genicular nerves on the lateral side of the knee. The anterolateral genicular nerve block, as described by Gruskay et al.,[11] targets three nerve branches that are not anesthetized by ACB: the transverse superficial and longitudinal deep capsular branches of the lateral genicular nerve, branches of the nerve to the vastus lateralis, and the articular branch of the nerve to the vastus intermedius.[11,31,32] Adding an anterolateral genicular nerve block postoperatively may therefore reduce lateral knee pain, which is particularly relevant when ALC reconstruction is combined with ACL reconstruction.

To our knowledge, no studies have investigated ACB with versus without anterolateral genicular nerve block for pain management after combined ACL and ALC reconstruction. Moreover, no randomized controlled trials have evaluated short-term postoperative pain outcomes specifically in this patient population. A recent systematic review investigating complications after lateral extra-articular tenodesis (LET) in ACL reconstruction identified pain at the LET site as a common long-term complaint.[33] This pain was reported in two of seven included studies; Imbert et al. found pain at the ALC site in 2.9% of patients after a minimum of three years follow-up, primarily attributed to fixation hardware;[34] whereas Eggeling et al. reported that 17.4% of patients who underwent combined LET and revision ACLR experienced pain in the LET region at rest or during movement at a minimum of two years' follow-up.[35] Similarly, Getgood et al. found higher pain scores at three and six months postoperatively in patients who underwent ACLR with LET compared to those with isolated ACLR in a randomized clinical trial.[36]

This study has been designed to assess short-term postoperative pain in patients undergoing ACL reconstruction combined with ALC reconstruction. We hypothesize that ACB with an anterolateral genicular nerve block provides superior analgesia compared with ACB alone. The outcomes of this study may contribute to optimizing peri-operative pain management protocols, improving patient comfort, and facilitating enhanced postoperative rehabilitation.

REFERENCES

1. D'Ambrosi R, Corona K, Cerciello S, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces Graft Reinjury Without Increasing the Rate of Complications: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J Sports Med*. Published online 2025:3635465241285887. doi:10.1177/03635465241285887
2. Kunze KN, Manzi J, Richardson M, et al. **Combined Anterolateral and Anterior Cruciate Ligament Reconstruction Improves Pivot Shift Compared With Isolated Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Arthrosc: J Arthrosc Relat Surg*. 2021;37(8):2677-2703. doi:10.1016/j.arthro.2021.03.058
3. Onggo JR, Rasaratnam HK, Nambiar M, et al. **Anterior Cruciate Ligament Reconstruction Alone Versus With Lateral Extra-articular Tenodesis With Minimum 2-Year Follow-up: A Meta-analysis and Systematic Review of Randomized Controlled Trials**. *Am J Sports Med*. 2020;50(4):1137-1145. doi:10.1177/03635465211004946
4. Park YB, Lee HJ, Cho HC, Pujol N, Kim SH. **Combined Lateral Extra-Articular Tenodesis or Combined Anterolateral Ligament Reconstruction and Anterior Cruciate Ligament Reconstruction Improves Outcomes Compared to Isolated Reconstruction for Anterior Cruciate Ligament Tear: A Network Meta-analysis of Randomized Controlled Trials**. *Arthrosc: J Arthrosc Relat Surg*. 2023;39(3):758-776.e10. doi:10.1016/j.arthro.2022.11.032
5. Halperin SJ, Prenner S, Dhodapkar MM, Santos E, Medvecky MJ, Grauer JN. **Variables Affecting 90-Day Overall Reimbursement After Anterior Cruciate Ligament Reconstruction: Analysis of Nearly 250,000 Patients in the United States**. *Orthop J Sports Med*. 2024;12(12):23259671241300500. doi:10.1177/23259671241300500
6. Lynch JR, Okoroha KR, Lizzio V, Yu CC, Jildeh TR, Moutzouros V. **Adductor Canal Block Versus Femoral Nerve Block for Pain Control After Anterior Cruciate Ligament Reconstruction: A Prospective Randomized Trial**. *Am J Sports Med*. 2019;47(2):355-363. doi:10.1177/0363546518815874
7. Dhumey T, Bhalerao N, Paul A, Wanjari D. **Adductor Canal Block Versus Femoral Nerve Block for Postoperative Pain Management in Anterior Cruciate Ligament Reconstruction: A Prospective Interventional Study**. *Cureus*. 2024;16(7):e64625. doi:10.7759/cureus.64625
8. Min H, Ouyang Y, Chen G. **Anterior cruciate ligament reconstruction with the use of adductor canal block can achieve similar pain control as femoral nerve block**. *Knee Surg, Sports Traumatol, Arthrosc*. 2020;28(8):2675-2686. doi:10.1007/s00167-020-05933-6
9. Yin X, Li X, Zhao P. **Comparison of adductor canal block and femoral nerve block for pain management in anterior cruciate ligament reconstruction: A meta-analysis of randomized controlled trials**. *Medicine*. 2022;101(25):e29295. doi:10.1097/md.0000000000029295
10. Hoope W ten, Admiraal M, Hermanides J, et al. **The Effectiveness of Adductor Canal Block Compared to Femoral Nerve Block on Readiness for Discharge in Patients Undergoing Outpatient Anterior Cruciate Ligament Reconstruction: A Multi-Center Randomized Clinical Trial**. *J Clin Med*. 2023;12(18):6019. doi:10.3390/jcm12186019
11. Gruskay JA, Pearce SS, Ruttum D, Conrad ES, Hackett TR. **Surgeon-Administered Anterolateral Geniculate Nerve Block as an Adjunct to Regional Anesthetic for Pain Management Following Anterior Cruciate Ligament Reconstruction**. *Arthrosc Tech*. 2022;11(1):e1-e6. doi:10.1016/j.eats.2021.08.034

12. Stebler K, Martin R, Kirkham KR, Lambert J, Sede AD, Albrecht E. **Adductor canal block versus local infiltration analgesia for postoperative pain after anterior cruciate ligament reconstruction: a single centre randomised controlled triple-blinded trial**. *Br J Anaesth*. 2019;123(2):e343-e349. doi:10.1016/j.bja.2019.04.053
13. Sujatha SSN, Gupta K, Guria S, Chhabra PH. **Comparison of genicular nerve block with adductor canal block for postoperative pain management in patients undergoing arthroscopic knee ligament reconstruction: A randomised controlled trial**. *Indian J Anaesth*. 2024;68(5):454-459. doi:10.4103/ija.ija_994_23
14. Schaver AL, Glass NA, Duchman KR, Wolf BR, Westermann RW. **Periarticular Local Infiltrative Anesthesia and Regional Adductor Canal Block Provide Equivalent Pain Relief After Anterior Cruciate Ligament Reconstruction**. *Arthrosc: J Arthrosc Relat Surg*. 2022;38(4):1217-1223. doi:10.1016/j.arthro.2021.10.031
15. Mouarbes D, Menetrey J, Marot V, Courtot L, Berard E, Cavaignac E. **Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis of Outcomes for Quadriceps Tendon Autograft Versus Bone–Patellar Tendon–Bone and Hamstring-Tendon Autografts**. *Am J Sports Med*. 2019;47(14):3531-3540. doi:10.1177/0363546518825340
16. Tan TK, Subramaniam AG, Ebert JR, Radic R. **Quadriceps Tendon Versus Hamstring Tendon Autografts for Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis**. *Am J Sports Med*. 2021;50(14):3974-3986. doi:10.1177/03635465211033995
17. Rangasamy K, Baburaj V, Gopinathan NR, Dhillon MS, Parikh SN. **Quadriceps tendon autograft is promising with lower graft rupture rates and better functional Lysholm scores than hamstring tendon autograft in pediatric ACL reconstruction. A systematic review and meta-analysis**. *J Orthop*. 2024;49:156-166. doi:10.1016/j.jor.2023.12.014
18. Runer A, Csapo R, Hepperger C, Herbort M, Hoser C, Fink C. **Anterior Cruciate Ligament Reconstructions With Quadriceps Tendon Autograft Result in Lower Graft Rupture Rates but Similar Patient-Reported Outcomes as Compared With Hamstring Tendon Autograft: A Comparison of 875 Patients**. *Am J Sports Med*. 2020;48(9):2195-2204. doi:10.1177/0363546520931829
19. Stokes DJ, Elrick BP, Cram TR, Schantz K, Shinsako KK, Frank RM. **Anterior Cruciate Ligament Reconstruction Basics: Quadriceps Tendon (All-Soft Tissue) Autograft Preparation—Part 2**. *Arthrosc Tech*. 2024;13(12):103147. doi:10.1016/j.eats.2024.103147
20. Lubowitz JH, Ahmad CS, Amhad CH, Anderson K. **All-Inside Anterior Cruciate Ligament Graft-Link Technique: Second-Generation, No-Incision Anterior Cruciate Ligament Reconstruction**. *Arthrosc: J Arthrosc Relat Surg*. 2011;27(5):717-727. doi:10.1016/j.arthro.2011.02.008
21. Williams A, Ball S, Stephen J, White N, Jones M, Amis A. **The scientific rationale for lateral tenodesis augmentation of intra-articular ACL reconstruction using a modified 'Lemaire' procedure**. *Knee Surg, Sports Traumatol, Arthrosc*. 2017;25(4):1339-1344. doi:10.1007/s00167-017-4537-3
22. Melick N van, Cingel REH van, Brooijmans F, et al. **Evidence-based clinical practice update: practice guidelines for anterior cruciate ligament rehabilitation based on a systematic review and multidisciplinary consensus**. *Br J Sports Med*. 2016;50(24):1506. doi:10.1136/bjsports-2015-095898
23. Myles PS, Myles DB, Galagher W, et al. **Measuring acute postoperative pain using the visual analog scale: the minimal clinically important difference and patient acceptable symptom state**. *Br J Anaesth*. 2017;118(3):424-429. doi:10.1093/bja/aew466
24. Dixit A, Prakash R, Yadav AS, Dwivedi S, Sr. **AD, Yadav A. Comparative Study of Adductor Canal Block and Femoral Nerve Block for Postoperative Analgesia After Arthroscopic Anterior Cruciate Ligament Tear Repair Surgeries**. *Cureus*. 2022;14(4):e24007. doi:10.7759/cureus.24007

25. Wiggins AJ, Grandhi RK, Schneider DK, Stanfield D, Webster KE, Myer GD. **Risk of Secondary Injury in Younger Athletes After Anterior Cruciate Ligament Reconstruction**. *Am J Sports Med*. 2016;44(7):1861-1876. doi:10.1177/0363546515621554
26. D'Ambrosi R, Corona K, Cerciello S, et al. **Combining an Anterolateral Complex Procedure With Anterior Cruciate Ligament Reconstruction Reduces Graft Reinjury Without Increasing the Rate of Complications: A Systematic Review and Meta-analysis of Randomized Controlled Trials**. *Am J Sports Med*. 2024;53(10):2462-2470. doi:10.1177/03635465241285887
27. Sonnery-Cottet B, Carrozzo A, Saithna A, et al. **Indications for Lateral Extra-articular Procedures in the Anterior Cruciate Ligament–Reconstructed Knee: Part I of an International Consensus Statement**. *Arthrosc: J Arthrosc Relat Surg*. 2025;41(9):3303-3312. doi:10.1016/j.arthro.2025.06.012
28. Chmielewski TL, Jones D, Day T, Tillman SM, Lentz TA, George SZ. **The association of pain and fear of movement/reinjury with function during anterior cruciate ligament reconstruction rehabilitation**. *J Orthop Sports Phys Ther*. 2008;38(12):746-753. doi:10.2519/jospt.2008.2887
29. Kejriwal R, Cooper J, Legg A, Stanley J, Rosenfeldt MP, Walsh SJ. **Efficacy of the Adductor Canal Approach to Saphenous Nerve Block for Anterior Cruciate Ligament Reconstruction With Hamstring Autograft: A Randomized Controlled Trial**. *Orthop J Sports Med*. 2018;6(10):2325967118800948. doi:10.1177/2325967118800948
30. Schnabel A, Reichl SU, Weibel S, et al. **Adductor canal blocks for postoperative pain treatment in adults undergoing knee surgery**. *Cochrane Database Syst Rev*. 2019;2019(10). doi:10.1002/14651858.cd012262.pub2
31. Fonkoué L, Behets C, Kouassi JÉK, et al. **Distribution of sensory nerves supplying the knee joint capsule and implications for genicular blockade and radiofrequency ablation: an anatomical study**. *Surg Radiol Anat*. 2019;41(12):1461-1471. doi:10.1007/s00276-019-02291-y
32. Sutaria RG, Lee SW, Kim SY, Howe R, Downie SA. **Localization of the Lateral Retinacular Nerve for Diagnostic and Therapeutic Nerve Block for Lateral Knee Pain: A Cadaveric Study**. *PMR*. 2017;9(2):149-153. doi:10.1016/j.pmrj.2016.06.017
33. Zabrzyński J, Erdmann J, Zabrzyńska M, Łapaj Ł, Malik SS, Kwapisz A. **Are there any complications after lateral extra-articular tenodesis in anterior cruciate ligament reconstruction? – a systematic review**. *J Orthop Surg Res*. 2025;20(1):451. doi:10.1186/s13018-025-05880-3
34. Imbert P, Lustig S, Steltzlen C, et al. **Midterm results of combined intra- and extra-articular ACL reconstruction compared to historical ACL reconstruction data. Multicenter study of the French Arthroscopy Society**. *Orthop Traumatol: Surg Res*. 2017;103(8):S215-S221. doi:10.1016/j.otsr.2017.09.005
35. Eggeling L, Drenck TC, Frings J, et al. **Additional lateral extra-articular tenodesis in revision ACL reconstruction does not influence the outcome of patients with low-grade anterior knee laxity**. *Arch Orthop Trauma Surg*. 2022;142(2):291-299. doi:10.1007/s00402-021-04145-y
36. Getgood AMJ, Bryant DM, Litchfield R, et al. **Lateral Extra-articular Tenodesis Reduces Failure of Hamstring Tendon Autograft Anterior Cruciate Ligament Reconstruction: 2-Year Outcomes From the STABILITY Study Randomized Clinical Trial**. *Am J Sports Med*. 2019;48(2):285-297. doi:10.1177/0363546519896333

chapter 9

SUMMARY, DISCUSSION, AND FUTURE PROSPECTS

SUMMARY

The **central aim** of this thesis was **to improve understanding of how concomitant injuries, secondary stabilizing structures, and osseous alignment influence anterior cruciate ligament (ACL) biomechanics and knee kinematics. This knowledge was translated into clinical practice to optimize surgical decision-making and perioperative management and ultimately improve patient outcomes.**

1. Secondary Stabilizers of the ACL

The systematic review in **chapter 2** evaluates the influence of concomitant pathology and secondary restraints on ACL graft force and pathological knee kinematics. Data of 43 studies were included. The review shows that several concomitant soft-tissue injuries and alignment abnormalities substantially increase strain or force on the native or ACL-reconstructed knee and influence knee kinematics. High-volume medial or lateral meniscectomy, peripheral meniscal tears, medial meniscus ramp tears, and lateral meniscus posterior root (LMPR) tears all increase native ACL or ACL graft forces. Injuries to the posterolateral corner (PLC), the medial collateral ligament (MCL)/posteromedial structures, as well as increased posterior tibial slope (PTS) and varus and valgus malalignment likewise increase ACL (graft) forces. The majority of studies reported that medial meniscus (ramp) injury and increasing PTS cause a significant increase in anterior tibial translation, whereas a medial meniscus ramp injury and PLC injury cause a significant increase in tibial external rotation; lateral meniscal injuries cause a significant increase in anterior tibial translation with simulated pivot-shift testing, whereas a LMPR injury causes a significant increase in tibial internal rotation. A MCL injury significantly increases valgus rotation, whereas a PLC injury significantly increases varus rotation. The systematic review provides a rationale to systematically identify and treat pathologies in ACL-injured knees, because when undiagnosed or left untreated, these specific concomitant pathologies could lead to ACL graft overload and failure in both primary and revision ACL-reconstructed knees.

The review in **chapter 3** evaluates the role of the iliotibial band (ITB) and the anterolateral ligament (ALL) on anterolateral rotatory instability in ACL-injured knees, and compares the effects of LET and ALL reconstruction in ACL-reconstructed knees. Data of 6 sectioning studies and 9 reconstruction studies were included. Most sectioning studies found that the ITB acts as a secondary stabilizer to the ACL and helps to resist both internal rotation and internal rotation during the pivot shift. Most sectioning studies reported no secondary stabilizing effect of the ALL in resisting internal rotation and internal rotation during the pivot shift. Furthermore, in most studies both a modified Lemaire LET and an ALL reconstruction could significantly reduce the residual anterolateral rotatory instability in isolated ACL-reconstructed knees and were able to improve tibial internal rotation laxity and tibial internal rotation laxity during the pivot shift. It was suggested referring to both of these reconstructions as anterolateral corner (ALC) reconstructions instead of denominating them separately, because they both have relatively the same biomechanical effect.

The combination of LMPR tears and Kaplan fiber injury frequently accompanies ACL injury. The systematic reviews in **chapters 2 and 3** demonstrated that both injuries influence tibial internal rotation and tibial internal rotation during the pivot shift. Their effects on ACL-related knee kinematics may therefore be additive.

2. Combined Pathology and ACL Biomechanics

The biomechanical study in **chapter 4** investigates the individual and combined effects of LMPR and Kaplan fiber tears on ACL-related knee kinematics, as well as the impact of LMPR repair, ALC reconstruction, or both, in the ACL-reconstructed knee. It was found that both the LMPR and Kaplan fibers act as secondary stabilizers to isolated tibial internal rotation, as well as to coupled internal rotation, anterior tibial translation, and valgus rotation during the pivot shift in the ACL-deficient knee. There was an additive biomechanical effect of Kaplan fiber injury to the ACL-deficient and LMPR tear knee state for isolated tibial internal rotation as well as for coupled internal rotation and anterior tibial translation during the pivot shift. An ACL reconstruction (ACLR) alone in the LMPR and Kaplan fiber injured knee state did not fully restore stability. Adding an ALC reconstruction to the ACLR and LMPR deficient knee state restored knee stability for isolated tibial internal rotation, coupled internal rotation during the pivot shift, and coupled anterior tibial translation during the pivot shift, but not for coupled valgus rotation during the pivot shift compared to the intact knee state. Adding a LMPR repair to the ACLR and Kaplan fiber deficient knee state restored coupled valgus rotation and internal rotation during a pivot shift at most flexion angles and coupled internal rotation and anterior tibial translation during a pivot shift at certain flexion angles compared to the intact knee state. Both LMPR repair and an ALC reconstruction were therefore needed to restore knee kinematics comparable to the intact knee state.

The beneficial biomechanical effect of an ALC reconstruction – both modified Lemaire LET and ALL reconstruction – on residual anterolateral rotatory instability in ACL-reconstructed knees warrants translation into clinical practice to optimize surgical decision-making.

3. Patient Outcomes after Isolated ACLR versus ACLR with ALC Reconstruction

The clinical comparative study in **chapter 5** evaluates isolated single-bundle hamstring autograft ACLR with or without modified Lemaire LET ALC reconstruction at 2-year follow-up in patients younger than 25 years, with a preoperative Tegner score ≥ 7 and intent to return to competitive sports. The outcome measurements were the Forgotten Joint Score-12 (FJS-12) and other patient reported outcome measures (PROMs). In addition, complication rates and graft re-ruptures were evaluated. At 12 months the FJS-12 was statistically significant improved in the non-ALC reconstruction group; however, this difference did not meet the minimal clinically important difference (MCID). At 24 months, FJS-12 scores were similar between groups. No significant differences were found in other PROMs at 24 months. Re-ruptures occurred in 14.6% in the non-ALC reconstruction group and in 7.4% in the ALC reconstruction group. No statistically significant differences in complication rates were found between groups. It was concluded that adding a Lemaire LET ALC reconstruction to ACLR was not associated with clinically meaningful difference in FJS-12 scores at 24-month follow-up.

Despite the observed differences in graft re-rupture rates, the interpretation of these findings requires a clear understanding of the underlying anatomical structures contributing to anterolateral rotatory instability.

The editorial commentary in **chapter 6** discusses the study by Hohmann et al, and interprets its biomechanical findings on the contributions of the ALL complex to rotational and anterior knee stability in ACL-intact, ACL-deficient, and ACL-reconstructed knees.[1] It was argued, partly based on the systematic review described in **chapter 3**, that it is an oversimplification to focus solely on the ALL in the setting of ACL injury. In the systematic review by Hohmann et al. it was stated that isolated ALL reconstruction or LET may not be necessary in the management of ACL-deficient knees or may not provide biomechanical benefit when added to ACLR. Based on the systematic review in **chapter 3**, as well as on several clinical studies and systematic reviews demonstrating a substantial reduction in ACLR failure rates in high-risk patients, it was argued that the statements should be interpreted with caution. Furthermore, the view that ALC injury encompasses a broad range of full or partial injuries to different anatomical structures, each contributing variably to anterolateral rotatory instability after ACL injury was stated. Consequently, it was reasoned, that biomechanical analysis of injury to only one component of the ALC (i.e. the ALL) cannot and should not be directly translated to clinical practice.

The biomechanical consequences of injury to the ALC and increased PTS were presented in **chapter 2 and 3**, and the clinical outcomes of ALC reconstruction were evaluated in **chapter 5**. However, the interaction between these factors and their combined effect on graft survival in clinical practice remains insufficiently understood.

4. Anterolateral Corner Reconstruction and Revision Risk after Primary ACL Reconstruction in Patients with Increased Posterior Tibial Slope

The clinical comparative cohort study in **chapter 7** investigates the prevalence of increased PTS (≥12°) in young high-risk primary ACLR patients and evaluates whether ALC reconstruction is associated with lower ACLR revision rates in patients with increased PTS. It was found that increased PTS (≥12°) was present in 28.2% of patients and more common in those requiring revision ACLR. Furthermore, in patients with increased PTS, revision occurred in 21.0% without ALC reconstruction, and 9.2% with ALC reconstruction. In patients with a PTS <12°, revision occurred in 13.2% without ALC reconstruction, and 5.4% with ALC reconstruction. Finally, ALC reconstruction was associated with lower odds of revision ACLR, whereas higher PTS was independently associated with revision ACLR.

While the addition of an ALC reconstruction may improve clinical outcome as presented in **chapter 5**, the additional lateral incision at the distal femur may influence postoperative pain perception and early recovery.

5. Perioperative Pain Management after Combined ACL Reconstruction and Anterolateral Corner Reconstruction

The multicenter, double-blind, randomized controlled trial protocol in **chapter 8** evaluates the efficacy of adductor canal block (ACB) alone versus ACB combined with an anterolateral genicular nerve block for postoperative pain control in patients undergoing combined ACL and ALC reconstruction. For this trial, 80 patients aged 16 years or older undergoing primary quadriceps tendon autograft ACLR combined with modified Lemaire ALC reconstruction will be randomized in a 1:1 ratio to receive either ACB alone or ACB with an anterolateral genicular nerve block using ropivacaine. The primary outcome measure is the Numeric Rating Scale (NRS) pain score during movement at 2 hours postoperatively and will be analyzed using an Analysis of Covariance (ANCOVA) model. It is hypothesized that the addition of the genicular block reduces postoperative pain and opioid use, thereby enhancing patient comfort and facilitating early rehabilitation.

GENERAL DISCUSSION

In **chapter 2** and **chapter 3**, comprehensive reviews were conducted to evaluate the influence of concomitant pathology and secondary restraints on ACL graft force and pathological knee kinematics. The overall methodologic quality of the included studies in both systematic reviews was high. Most studies received methodologic quality ratings of “excellent” or “substantial” according to the Quality Appraisal for Cadaveric Studies (QUACS) scale, while none were rated as “moderate” or “poor”. A meta-analysis of the data could not be performed because of substantial heterogeneity among the included studies. The heterogeneity was related to differences in specimen numbers and characteristics, surgical procedures, kinematic testing systems, and testing protocols. Considerable variation existed in testing protocols across studies, including differences in sample size, cadaver age, specimen preparation, tested flexion angles, loading conditions, testing systems, and measurement methods. Sample sizes ranged from 4 to 24 and from 10 to 20 in the 2 systematic reviews, respectively. The age of cadaveric specimens ranged from 18 to 98 years and from 28 to 93 years, respectively. In most studies, the femoral and tibial diaphyses were cut approximately 20 cm from the joint line, whereas some studies used whole legs including the hip joint. Flexion angles ranged from full extension to deep flexion. Some studies tested only a limited number of discrete angles, whereas others used dense increments across the range of motion. Loading protocols also varied substantially, combining different magnitudes, directions, and multi-planar loads. For example, axial compression loads applied in PTS studies ranged from 200N in most studies[2–5] up to 400 N,[6,7] and up to 1000 N in one study[8] to simulate weight-bearing conditions. In most studies, muscle forces were not simulated, although some studies did include them. A wide range of testing systems was used, including instrumented Lachman testing, mechanized pivot shift testing, force controlled rotational testing, custom fixtures applying torques or forces, and six degrees of freedom robotic testing systems. Different methods were also used to measure ACL (graft) force or strain. These included the superimposition principle, load cells attached to the graft, and transducers positioned within the anteromedial bundle of the ACL.

It is well recognized that biomechanical findings in cadaveric studies represent only time-zero conditions, because the biological process of tissue healing cannot be replicated. Nevertheless, the two systematic reviews provide valuable insights into the surgically relevant biomechanical consequences of additional pathologies in ACL-injured knees. This knowledge can help guide clinical decision-making and optimize treatment strategies.

In addition to the high heterogeneity of biomechanical studies, several practical considerations should be acknowledged. These include the high procurement costs of cadaveric specimens, biohazard and waste concerns,[9,10] challenges related to storage and preservation, and potential ethical considerations.[9] Recent advances in computational modeling have provided new opportunities for investigating knee biomechanics. In particular, developments of finite element analysis and rigid body dynamics modeling of joint and tissue mechanics have expanded the possibilities for biomechanical research.[11]

Since completion of the systematic review presented in **chapter 2**, one additional biomechanical study on combined ACL and PLC injury has been published.[12] This study evaluated the effect of sequential sectioning of the ACL and PLC structures on lateral compartment gapping under varus stress. The authors reported that sectioning of the posterolateral structures resulted in a significant increase in varus rotation in both ACL-intact and ACL-deficient knees, which is consistent with the findings of the systematic review.[13–16] However, when evaluating the effect of ACL sectioning on lateral compartment opening, no significant difference was found between sectioning the ACL first and sectioning the fibular collateral ligament (FCL) first. This finding contrasts with one study included in the systematic review, which did not report a significant increase in knee adduction after isolated ACL sectioning.[14] This discrepancy between these findings is likely related to differences in the biomechanical testing setups.[12]

Since completion of the systematic review in **chapter 3**, one additional sequential sectioning study by Willinger et al. has investigated the contributions of ACL and ALC structures to rotatory knee instability.[17] The authors reported that the Kaplan fibers represent the most important restraint against tibial internal rotation. In contrast to the findings of one study included in the systematic review[18], isolated injury to the anterolateral capsule and ALL or to the Kaplan fibers did not increase anterolateral rotational instability. However, in the study by Willinger et al., the superficial ITB was split to section both the proximal and distal Kaplan fibers (compared with no split of the superficial ITB in the study included in the systematic review), and the ALL was transected together with the anterolateral capsule (compared with releasing the ALL from its tibial attachment). Because this approach involves more extensive sectioning, a greater increase in rotational instability might have been expected. A possible explanation for the discrepant findings may lie in methodologic difference between the studies. The study by Willinger et al. included relatively smaller subgroups and used different testing systems, combining robot testing in five knees with kinematic rig testing in six or seven knees, whereas the comparable study in the systematic review used robotic testing in twenty knees.

The fact that the sectioning study by Willinger et al. was only directly comparable to one of six sectioning studies included in the systematic review highlights the substantial variability in how surgical sectioning procedures are performed in biomechanical studies. Sectioning of the ALL has been performed using several techniques, including release from the tibial attachment,[18] transection together with the mid-third anterolateral capsule,[17,19–21] transection together with the entire anterolateral capsule,[22] or isolated transection through a longitudinal split of the superficial ITB.[23]

Similarly, sectioning of the ITB has been performed in multiple ways, including detachment from the tibia at Gerdy's tubercle,[19,21] release of the superficial ITB from the femur combined with detachment from Gerdy's tubercle,[20] release of the superficial ITB from the tibia combined with detachment from Gerdy's tubercle and sectioning of the proximal and distal Kaplan fibers,[22] isolated sectioning of the proximal and distal Kaplan fibers,[18] sectioning of the Kaplan fibers through a split in the superficial ITB,[17] or with insufficient description of the technique.[23]

Two comparative ALC reconstruction studies have been published since completion of the systematic review. Van de Velde et al. reported that ACLR restored native tibiofemoral kinematics except for internal rotation at flexion greater than 30°. In their study, the increased internal rotation at flexion angles greater than 30° was restored to normal with an LET, but not with an ALL reconstruction.[24] Similarly, Ying et al. reported full restoration of internal rotation stability after ACLR combined with artificial ALL reconstruction or LET, but not at 0° and 15° after ACLR combined with autologous ALL reconstruction.[25] These findings contrast with those of seven of eight comparative studies included in the systematic review, in which both LET and ALL reconstruction restored native knee kinematics.[18,26–31] In the only study within the systematic review in which ALL reconstruction did not restore residual internal rotation laxity, the graft was tensioned at 30°.[32] The same author subsequently reported that residual internal rotation laxity was restored when the ALL was tensioned at 0°.[31] In both studies by van de Velde et al. and Ying et al., the ALL-graft was tensioned at 0°, loading conditions were comparable, and sample sizes were justified by power calculations based on previous studies. It therefore remains unclear how to fully explain the discrepant findings. Nevertheless, based on the current systematic review, most available studies still demonstrate comparable biomechanical effects of both reconstruction techniques.

Three studies have investigated the influence of LMPR tears on ACL graft force and knee kinematics since completion of the systematic review, providing additional data on the ACL-reconstructed knee, the role of the meniscofemoral ligaments, and the magnitude of changes in ACL graft forces.[17,33,34] Willinger et al. reported that LMPR deficiency did not result in significant instability when the ACL was intact.[17] Uffman et al. sectioned the entire LMPR complex, including both meniscofemoral ligaments, in ACL-reconstructed knees. This resulted in increased rotational and translational laxity at 30° of flexion and significantly increased ACL graft strain under combined anterior load and internal torque. LMPR tear repairs without meniscofemoral ligament repair reduced strain during internal rotation but did not normalize it under anterior loading, and the overall strain reduction after repair was not statistically significant.[34] Seiter et al. reported different findings by modeling a segmental LMPR loss in an ACL-reconstructed knee while, largely preserving the meniscofemoral ligaments. In this setting, a LMPR tear did not significantly increase ACL graft force in any test condition, although it did significantly increase anterior tibial translation during a simulated pivot shift by 2.7 mm. In situ LMPR repair (performed at a non-anatomic position) restored native laxity and significantly reduced ACL graft force compared with isolated

ACLR (–26.6 N). Additional meniscofemoral ligament augmentation did not further alter graft force or knee kinematics.[33]

Although these biomechanical studies provide valuable insight into the role of the LMPR and meniscofemoral ligaments, clinical evidence addressing these structures remains limited. Clinical studies demonstrate that LMPR tears associated with ACL injury are common and that concomitant LMPR repair generally results in favorable short-to mid-term outcomes with acceptable healing rates.[35–40] However, the status of the meniscofemoral ligament is rarely documented intra-operatively, and no clinical studies have systematically evaluated repair of the meniscofemoral ligaments or compared LMPR repair alone with LMPR repair combined with meniscofemoral ligament repair.

The biomechanical study presented in **chapter 4** evaluated the combined influence of LMPR deficiency and Kaplan fiber injury on knee kinematics. The meniscofemoral ligaments were left intact, while both the proximal and distal Kaplan fibers were sectioned from the lateral femur. Although the study provides valuable insight into the combined effect of Kaplan fiber and LMPR injuries and their repairs in the ACL-injured and ACL-reconstructed knee, it is important to recognize that the Kaplan fiber injury created represents a worst-case scenario.

MRI-based cohorts have reported (partial) Kaplan fiber injury in 21 – 60% of acute ACL tears, depending on the image protocol.[41–50] Injury or partial injury to the anterolateral capsule or ALL has been reported in 21 to 71% of cases,[42,47,48,50–52] while (partial) injury to the ITB described as superficial or deep injury, has been reported in 51-87% of cases.[42,51,52]

In the editorial commentary presented in **chapter 6,** it was proposed that ALC injury encompasses a broad spectrum of partial or complete injuries to different anatomical structures, each contributing variably to anterolateral rotatory instability following ACL injury. An ALC injury may consist of a partial tear of the anterolateral capsule with or without involvement of the ALL, (partial) disruption of the proximal and/or distal Kaplan fiber, and/or (partial) injury to the capsulo-osseous layer. The cumulative effect of these injuries, together with other concomitant pathologies and individual knee characteristics as described in **chapter 2**, determines the overall degree of anterolateral rotatory instability in the ACL-injured knee.

In the biomechanical study presented in **chapter 4**, we unfortunately observed a high rate of LMPR repair failures during robotic testing. However, during the repair procedures, all constructs appeared solid both during fixation and when probed arthroscopically. Post-testing arthroscopic evaluations were performed after we became aware of reports from colleagues describing clinical failures of the SutureLoc implant, which subsequently led them to discontinue its use.

Several factors might explain the observed failures in the cadaveric model. Cadaveric bone quality is generally weaker than in clinical patients, and repairs at time zero remain relatively fragile. In addition, the robotic testing protocol applies relatively harsh loading conditions. These factors may explain why loosening and failure of the LMPR repairs occurred during biomechanical testing, whereas clinical repairs may benefit from biological healing over time. Therefore, caution is warranted when implementing this repair technique in clinical practice until additional biomechanical studies become available.

In **chapter 5**, the clinical relevance of adding an ALC reconstruction to ACLR in high-risk patients was investigated. The primary outcome was the FJS-12. Psychometric reviews indicate that commonly used PROMs after ACL injury and reconstruction – including the International Knee Documentation Committee (IKDC), Knee Injury and Osteoarthritis Outcome Score (KOOS), Lysholm score, Tegner Activity Scale, visual analogue scale (VAS) for pain, and the ACL–Return to Sport after Injury scale (ACL-RSI) - generally demonstrate acceptable reliability, validity, and responsiveness. However, these instruments assess different constructs. IKDC, KOOS, and Lysholm primarily evaluate symptoms and function, Tegner measures activity level, VAS assesses pain, and ACL-RSI focuses on psychological readiness to return to sport. Because no single instrument captures all relevant domains, combined use of several PROMs is generally recommended.[53–55] At the same time, correlations between PROMs and objective outcomes – such as laxity testing or hop performance - are predominantly negligible to weak. This indicates that PROMs primarily reflect patients' perceptions rather than mechanical stability or physical performance and therefore cannot substitute for objective testing.[56–58]

Studies defining patient acceptable symptom state (PASS) and other clinically meaningful thresholds for IKDC, KOOS, Lysholm, Tegner, VAS and ACL-RSI show that these scores correspond reasonably well with a patient-reported "feeling well" or "acceptable" state. However, PASS thresholds are typically lower than age-matched normative values. As a result, many patients consider their knee satisfactory while still performing below "normal" population benchmarks. In addition, ceiling or plateau effects occur approximately 12–24 months after surgery.[53,55,57,59,60]

For high-functioning patients, this reduced sensitivity at the upper end represents a major limitation of traditional PROMs. This has motivated increasing interest in instruments that assess joint awareness. The FJS-12, originally developed for arthroplasty outcomes, has now been validated in ACLR and ACL repair cohorts.[61–66] Studies have demonstrated high internal consistency, moderate to strong correlations with IKDC, KOOS and other traditional PROMs, and markedly lower ceiling effects than Lysholm, KOOS or some satisfaction scales, especially in younger or well-functioning patients.[62,66–68]

Conceptually, the FJS-12 measures joint awareness – that is, how often patients "forget" their knee in daily life. It therefore captures an aspect of recovery that many patients associate with true normalization and that is only partially reflected in symptom or sport-oriented instruments.[62,66–69] However, FJS-12 is less ACL and sport-specific than instruments like KOOS, Tegner, or ACL-RSI. Current evidence therefore does not support its use as a standalone replacement for measures specifically targeting high-demand sport function or psychological readiness.[54,66,69,70]

In the current study in **chapter 5**, FJS-12, IKDC, Lysholm, Tegner, ACL-RSI and VAS improved over time and ultimately converged between groups at 24 months follow-up. This occurred despite a numerically lower re-rupture rate in the ALC reconstruction cohort. These findings suggest that neither traditional PROMs nor the FJS-12 capture all clinically relevant differences between surgical strategies, and that perceived recovery may not fully reflect ACL graft protection or re-rupture risk. FJS-12 values of approximately 70 at two years indicated moderate joint awareness rather than a truly “forgotten” joint. This observation mirrors findings from the broader literature in which PROM scores often reach “good-but-not-normal” plateaus in many ACL patients.

Overall, current and emerging evidence supports using a multi-domain PROM battery – such as IKDC or KOOS combined with Tegner and ACL-RSI complemented by joint-awareness instruments such as the FJS-12 and by objective performance and stability testing. This approach may be particularly important when evaluating high-risk athletes or procedures such as ALC reconstruction, where subtle differences in joint protection may not be captured by PROM profiles alone.[54,59,62,66,71–74]

In **chapter 7,** based on the findings of the current study, a stepwise approach was proposed in which ALC reconstruction appears to be an appropriate first addition to reduce revision risk in patients with increased PTS. However, because increasing PTS remained independently associated with revision ACLR despite ALC reconstruction, slope reducing osteotomy may be considered in selected primary cases, particularly in patients with PTS substantially above 12°.

Only one comparative study evaluated the clinical benefits of osteotomy procedures in primary ACLR.[75] Patients with a PTS ≥15° and excessive anterior tibial subluxation of the lateral compartment were included. Twenty-five and forty-eight patients underwent ACLR combined with slope reducing osteotomy and isolated ACLR, respectively. Slope-reducing tibial osteotomy combined with primary ACLR significantly decreased anterior tibial subluxation, reduced the incidence of graft roof impingement, and lowered the graft laxity rate in patients with increased PTS (≥15°) and excessive anterior tibial subluxation of the lateral compartment (≥6 mm). Furthermore, in patients with a PTS ≥16°, the combined procedure improved anterior knee stability and reduced the graft failure rate. Based on these findings, it was concluded that a PTS ≥16° combined with anterior tibial subluxation of the lateral compartment ≥6 mm may represent an appropriate indication for combining slope-reducing tibial osteotomy with primary ACLR. No studies have prospectively evaluated the clinical benefits of adding ALC reconstruction in high-risk primary ACLR patients with increased PTS. A threshold of ≥15° appears to be a reasonable cut-off value. This is supported by the odds ratio of 1.09 per degree increase above 12° as independent risk factor for revision ACLR in the current study. Considering the prevalence of approximately 30% of patients with a PTS ≥12°, it should be feasible to include enough patients in such studies.

In **chapter 8**, it was argued that evolving surgical strategies in ACLR may require adapted perioperative pain management protocols. The results of the ongoing multicenter, double-blind, randomized controlled trial - including patients aged 16 years or older undergoing primary quadriceps tendon autograft ACLR combined with ALC reconstruction – will provide insight into whether perioperative pain control can be improved by adding an anterolateral genicular nerve block to a standard adductor canal block using ropivacaine.

Similarly, the addition of slope-reducing osteotomy as part of the surgical strategy in primary or revision ACLR may also require adapted pain management protocols.

FUTURE DIRECTIONS

Several directions for future research can be identified.

1. **Standardization of biomechanical study protocols** is needed to improve comparability between cadaveric knee studies, including consensus on flexion angles, loading conditions, and measurement techniques.
2. **Development and validation of computational knee models** may provide a reusable and cost-effective approach to studying knee biomechanics and complement cadaveric research.
3. **Standardization and detailed reporting of sectioning techniques** are required to improve comparability across biomechanical studies and to ensure consistent interpretation of anatomic structures.
4. **Further clinical research on meniscofemoral ligament injury** is needed to determine its biomechanical and clinical relevance and to evaluate whether combined repair strategies improve patient outcomes.
5. **Investigation of partial and combined anterolateral complex injury patterns** is necessary to better reflect clinical reality, rather than focusing on isolated or worst-case injury models.
6. **Integration of joint awareness outcome measures**, such as the Forgotten Joint Score-12, into multi-domain PROM batteries may improve the evaluation of patient outcomes after ACL reconstruction.
7. **Prospective comparative studies**, preferably randomized controlled trials, should evaluate the relative clinical benefits of ACL reconstruction with ALC reconstruction, slope-reducing osteotomy, and their combination in patients with increased posterior tibial slope.
8. **Optimization of perioperative pain management strategies** should be investigated in patients undergoing more complex ACL procedures, including combined ALC reconstruction and slope-reducing osteotomy.

REFERENCES

1. Hohmann E, Keough N, Molepo M, Arciero R, Imhoff A. **The anterolateral ligament complex has limited impact on anterior tibial translation or internal rotational stability in ACL-deficient and ACL-reconstructed knees. A systematic review of biomechanical cadaver studies**. *Arthrosc: J Arthrosc Relat Surg*. 2025;41(11):4882-4899.e15. doi:10.1016/j.arthro.2025.04.043
2. Bernhardson AS, Aman ZS, Dornan GJ, et al. **Tibial Slope and Its Effect on Force in Anterior Cruciate Ligament Grafts: Anterior Cruciate Ligament Force Increases Linearly as Posterior Tibial Slope Increases**. *Am J Sports Medicine*. 2019;47(2):296-302. doi:10.1177/0363546518820302
3. Giffin JR, Vogrin TM, Zantop T, Woo SLY, Harner CD. **Effects of Increasing Tibial Slope on the Biomechanics of the Knee**. *Am J Sports Medicine*. 2004;32(2):376-382. doi:10.1177/0363546503258880
4. Nelitz M, Seitz AM, Bauer J, Reichel H, Ignatius A, Dürselen L. **Increasing posterior tibial slope does not raise anterior cruciate ligament strain but decreases tibial rotation ability**. *Clin Biomech*. 2013;28(3):285-290. doi:10.1016/j.clinbiomech.2013.01.011
5. Yamaguchi KT, Cheung EC, Markolf KL, et al. **Effects of Anterior Closing Wedge Tibial Osteotomy on Anterior Cruciate Ligament Force and Knee Kinematics**. *Am J Sports Medicine*. 2018;46(2):370-377. doi:10.1177/0363546517736767
6. Imhoff FB, Comer B, Obopilwe E, Beitzel K, Arciero RA, Mehl JT. **Effect of Slope and Varus Correction High Tibial Osteotomy in the ACL-Deficient and ACL-Reconstructed Knee on Kinematics and ACL Graft Force: A Biomechanical Analysis**. *Am J Sports Medicine*. 2020;49(2):410-416. doi:10.1177/0363546520976147
7. Imhoff FB, Mehl J, Comer BJ, et al. **Slope-reducing tibial osteotomy decreases ACL-graft forces and anterior tibial translation under axial load**. *Knee Surg Sports Traumatology Arthrosc*. 2019;27(10):3381-3389. doi:10.1007/s00167-019-05360-2
8. Samuelsen BT, Aman ZS, Kennedy MI, et al. **Posterior Medial Meniscus Root Tears Potentiate the Effect of Increased Tibial Slope on Anterior Cruciate Ligament Graft Forces**. *Am J Sports Medicine*. 2019;48(2):334-340. doi:10.1177/0363546519889628
9. Augat P, Hast MW, Schemitsch G, et al. **Biomechanical models: key considerations in study design**. *OTA Int*. 2021;4(2 Suppl):e099(1-6). doi:10.1097/oi9.0000000000000099
10. Elfar JJ, Menorca RMG, Reed JD, Stanbury S. **Composite Bone Models in Orthopaedic Surgery Research and Education**. *J Am Acad Orthop Surg*. 2014;22(2):111-120. doi:10.5435/jaaos-22-02-111
11. Erdemir A, Besier TF, Halloran JP, et al. **Deciphering the “Art” in Modeling and Simulation of the Knee Joint: Overall Strategy**. *J Biomech Eng*. 2019;141(7). doi:10.1115/1.4043346
12. Gursoy S, Perry AK, Dandu N, et al. **Effect of Sectioning of the Anterior Cruciate Ligament and Posterolateral Structures on Lateral Compartment Gapping: A Randomized Biomechanical Study**. *Orthop J Sports Med*. 2022;10(6):23259671221100216. doi:10.1177/23259671221100216
13. Markolf KL, Wascher DC, Finerman GA. **Direct in vitro measurement of forces in the cruciate ligaments. Part II: The effect of section of the posterolateral structures**. *J Bone Jt Surg*. 1993;75(3):387-394. doi:10.2106/00004623-199303000-00010
14. Wroble RR, Grood ES, Cummings JS, Henderson JM, Noyes FR. **The role of the lateral extraarticular restraints in the anterior cruciate ligament-deficient knee**. *Am J Sports Medicine*. 1993;21(2):257-263. doi:10.1177/036354659302100216

15. LaPrade RF, Resig S, Wentorf F, Lewis JL. **The Effects of Grade III Posterolateral Knee Complex Injuries on Anterior Cruciate Ligament Graft Force**. *Am J Sports Medicine*. 1999;27(4):469-475. doi:10.1177/03635465990270041101
16. Veltri DM, Deng XH, Torzilli PA, Warren RF, Maynard MJ. **The Role of the Cruciate and Posterolateral Ligaments in Stability of the Knee**. *Am J Sports Medicine*. 1995;23(4):436-443. doi:10.1177/036354659502300411
17. Willinger L, Athwal KK, Holthof S, Imhoff AB, Williams A, Amis AA. **Role of the Anterior Cruciate Ligament, Anterolateral Complex, and Lateral Meniscus Posterior Root in Anterolateral Rotatory Knee Instability: A Biomechanical Study**. *Am J Sports Med*. 2023;51(5):1136-1145. doi:10.1177/03635465231161071
18. Geeslin AG, Moatshe G, Chahla J, et al. **Anterolateral Knee Extra-articular Stabilizers: A Robotic Study Comparing Anterolateral Ligament Reconstruction and Modified Lemaire Lateral Extra-articular Tenodesis**. *Am J Sports Medicine*. 2018;46(3):607-616. doi:10.1177/0363546517745268
19. Huser LE, Noyes FR, Jurgensmeier D, Levy MS. **Anterolateral Ligament and Iliotibial Band Control of Rotational Stability in the Anterior Cruciate Ligament–Intact Knee: Defined by Tibiofemoral Compartment Translations and Rotations**. *Arthrosc J Arthrosc Relat Surg*. 2017;33(3):595-604. doi:10.1016/j.arthro.2016.08.034
20. Lording T, Stinton SK, Neyret P, Branch TP. **Diagnostic findings caused by cutting of the iliotibial tract and anterolateral ligament in an ACL intact knee using a standardized and automated clinical knee examination**. *Knee Surg Sports Traumatology Arthrosc*. 2017;25(4):1161-1169. doi:10.1007/s00167-017-4499-5
21. Noyes FR, Huser LE, Levy MS. **Rotational Knee Instability in ACL-Deficient Knees**. *J Bone Jt Surg*. 2017;99(4):305-314. doi:10.2106/jbjs.16.00199
22. Kittl C, El-Daou H, Athwal KK, et al. **The Role of the Anterolateral Structures and the ACL in Controlling Laxity of the Intact and ACL-Deficient Knee**. *Am J Sports Medicine*. 2016;44(2):345-354. doi:10.1177/0363546515614312
23. Sonnery-Cottet B, Lutz C, Daggett M, et al. **The Involvement of the Anterolateral Ligament in Rotational Control of the Knee**. *Am J Sports Medicine*. 2016;44(5):1209-1214. doi:10.1177/0363546515625282
24. Velde SKV de, Telfer S, Arkel ERA van, Schmale GA. **A lateral extra-articular tenodesis without additional hardware: Surgical technique and biomechanical comparison with an anatomic anterolateral ligament reconstruction in the augmentation of anterior cruciate ligament reconstruction**. *Knee*. 2024;47:112-120. doi:10.1016/j.knee.2024.02.003
25. Ying H, Li X, Yao G, et al. **Artificial anterolateral ligament reconstruction provides similar knee kinematics as compared to an autologous reconstruction and a lateral extra-articular tenodesis**. *Knee Surg, Sports Traumatol, Arthrosc*. Published online 2025. doi:10.1002/ksa.12811
26. Smith PA, Thomas DM, Pomajzl RJ, Bley JA, Pfeiffer FM, Cook JL. **A Biomechanical Study of the Role of the Anterolateral Ligament and the Deep Iliotibial Band for Control of a Simulated Pivot Shift With Comparison of Minimally Invasive Extra-articular Anterolateral Tendon Graft Reconstruction Versus Modified Lemaire Reconstruction After Anterior Cruciate Ligament Reconstruction**. *Arthrosc J Arthrosc Relat Surg*. 2019;35(5):1473-1483. doi:10.1016/j.arthro.2018.11.011
27. Delaloye JR, Hartog C, Blatter S, et al. **Anterolateral Ligament Reconstruction and Modified Lemaire Lateral Extra-Articular Tenodesis Similarly Improve Knee Stability After Anterior Cruciate Ligament Reconstruction: A Biomechanical Study**. *Arthrosc J Arthrosc Relat Surg*. 2020;36(7):1942-1950. doi:10.1016/j.arthro.2020.03.027

28. Jette C, Gutierrez D, Sastre S, Llusa M, Combalia A. **Biomechanical comparison of anterolateral ligament anatomical reconstruction with a semi-anatomical lateral extra-articular tenodesis. A cadaveric study**. *Knee*. 2019;26(5):1003-1009. doi:10.1016/j.knee.2019.07.005
29. Neri T, Dabirrahmani D, Beach A, et al. **Different anterolateral procedures have variable impact on knee kinematics and stability when performed in combination with anterior cruciate ligament reconstruction**. *J Isakos Jt Disord Orthop Sports Medicine*. 2021;6(2):74-81. doi:10.1136/jisakos-2019-000360
30. Xu J, Han K, Lee TQ, et al. **Anterolateral Structure Reconstruction Similarly Improves the Stability and Causes Less Overconstraint in Anterior Cruciate Ligament-Reconstructed Knees Compared With Modified Lemaire Lateral Extra-articular Tenodesis: A Biomechanical Study**. *Arthrosc J Arthrosc Relat Surg*. 2022;38(3):911-924. doi:10.1016/j.arthro.2021.06.023
31. Inderhaug E, Stephen JM, Williams A, Amis AA. **Anterolateral Tenodesis or Anterolateral Ligament Complex Reconstruction: Effect of Flexion Angle at Graft Fixation When Combined With ACL Reconstruction**. *Am J Sports Medicine*. 2017;45(13):3089-3097. doi:10.1177/0363546517724422
32. Inderhaug E, Stephen JM, Williams A, Amis AA. **Biomechanical Comparison of Anterolateral Procedures Combined With Anterior Cruciate Ligament Reconstruction**. *Am J Sports Medicine*. 2017;45(2):347-354. doi:10.1177/0363546516681555
33. Seiter M, Douglass BW, Brady AW, Dornan GJ, Brown JR, Hackett TR. **In situ repair of segmental loss posterior lateral meniscal root tears outperforms meniscofemoral ligament imbrication in the ACL reconstructed knee**. *J Exp Orthop*. 2023;10(1):8. doi:10.1186/s40634-023-00572-5
34. Uffmann W, ElAttrache N, Nelson T, et al. **Posterior Lateral Meniscal Root Tears Increase Strain on the Reconstructed Anterior Cruciate Ligament: A Cadaveric Study**. *Arthrosc, Sports Med, Rehabilitation*. 2021;3(2):e505-e513. doi:10.1016/j.asmr.2020.11.005
35. Forkel P, Noack J, Hinz M, Imhoff AB, Wörtler K, Feucht MJ. **Coronal extrusion of the lateral meniscus does not increase after pullout repair of the posterior root of the lateral meniscus at short-term follow-up**. *Arch Orthop Trauma Surg*. 2023;143(8):5199-5206. doi:10.1007/s00402-023-04815-z
36. Krych AJ, Song BM, Nauert RF, et al. **Prospective Consecutive Clinical Outcomes After Transtibial Root Repair for Posterior Meniscal Root Tears: A Multicenter Study**. *Orthop J Sports Med*. 2022;10(2):23259671221079794. doi:10.1177/23259671221079794
37. Aga C, Aasen IB, Brocker C, Kise NJ, Heir S. **Lateral meniscal posterior root tears experience acceptable healing status after transtibial repair technique**. *J Exp Orthop*. 2021;8(1):114. doi:10.1186/s40634-021-00433-z
38. Jeon YS, Alsomali K, Yang SW, Lee OJ, Kang B, Wang JH. **Posterior Horn Lateral Meniscal Oblique Radial Tear in Acute Anterior Cruciate Ligament Reconstruction Incidence and Outcomes After All-Inside Repair: Clinical and Second-Look Arthroscopic Evaluation**. *Am J Sports Med*. 2022;50(14):3796-3804. doi:10.1177/03635465221126506
39. Thomas B, Florent B de V, Alexandre F, et al. **Patients with meniscus posterolateral root tears repair during ACL reconstruction achieve comparable post-operative outcome than patients with isolated ACL reconstruction**. *Knee Surg, Sports Traumatol, Arthrosc*. 2023;31(8):3405-3411. doi:10.1007/s00167-023-07415-x
40. Zhuo H, Chen Q, Zhu F, Li J. **Arthroscopic side-to-side repair for complete radial posterior lateral meniscus root tears**. *BMC Musculoskelet Disord*. 2020;21(1):130. doi:10.1186/s12891-020-3156-1

41. Batty LM, Murgier J, Feller JA, O'Sullivan R, Webster KE, Devitt BM. **Radiological Identification of Injury to the Kaplan Fibers of the Iliotibial Band in Association With Anterior Cruciate Ligament Injury**. *Am J Sports Med*. 2020;48(9):2213-2220. doi:10.1177/0363546520931854
42. Dyck PV, Smet ED, Roelant E, Parizel PM, Heusdens CHW. **Assessment of Anterolateral Complex Injuries by Magnetic Resonance Imaging in Patients With Acute Rupture of the Anterior Cruciate Ligament**. *Arthrosc: J Arthrosc Relat Surg*. 2019;35(2):521-527. doi:10.1016/j.arthro.2018.08.032
43. Iordache EA, Hirschmann MT, Amsler F, Yang SR, Hess S, Hirschmann A. **Injuries of Kaplan fibers in ACL deficient and reconstructed knees – redefining the structure and risk assessment on MRI using injury patterns**. *Orthop J Sports Med*. 2021;9(6 suppl2):2325967121S00182. doi:10.1177/2325967121s00182
44. Marom N, Greditzer HG, Roux M, et al. **The Incidence of Kaplan Fiber Injury Associated With Acute Anterior Cruciate Ligament Tear Based on Magnetic Resonance Imaging**. *Am J Sports Med*. 2020;48(13):3194-3199. doi:10.1177/0363546520956302
45. Berthold DP, Willinger L, LeVasseur MR, et al. **High Rate of Initially Overlooked Kaplan Fiber Complex Injuries in Patients With Isolated Anterior Cruciate Ligament Injury**. *Am J Sports Med*. 2021;49(8):2117-2124. doi:10.1177/03635465211015682
46. Chandra AA, Chandra A, Murray T, Azam MdQ. **Radiological anatomy and injuries of the condylar strap and Kaplan fibers associated with ACL pathology**. *Indian J Musculoskelet Radiol*. 2023;5(1):25-30. doi:10.25259/ijmsr_17_2023
47. Firoozabadi MA, Mortazavi SMJ, Shakiba M, et al. **Investigating Injuries to the Anterolateral Corner of the Knee: Imaging Insights Into Kaplan Fibers and the Anterolateral Ligament in Anterior Cruciate Ligament Tears**. *Orthop J Sports Med*. 2025;13(3):23259671251319504. doi:10.1177/23259671251319504
48. Leao RV, Helito PVP, Saithna A, Correa MF de P, Helito CP. **Anterolateral Ligament and Kaplan Fiber Injury Both Occur Frequently in Acute Anterior Cruciate Ligament-Injured Knees**. *J Clin Med*. 2024;13(4):946. doi:10.3390/jcm13040946
49. Watanabe S, Nagai K, Hoshino Y, et al. **Influence of Injury to the Kaplan Fibers of the Iliotibial Band on Anterolateral Rotatory Knee Laxity in Anterior Cruciate Ligament Injury: A Retrospective Cohort Study**. *Am J Sports Med*. 2022;50(12):3265-3272. doi:10.1177/03635465221116097
50. Runer A, Dammerer D, Kranewitter C, et al. **Injuries to the anterolateral ligament are observed more frequently compared to lesions to the deep iliotibial tract (Kaplan fibers) in anterior cruciate ligament deficient knees using magnetic resonance imaging**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(1):309-318. doi:10.1007/s00167-021-06535-6
51. Balendra G, Willinger L, Pai V, et al. **Anterolateral complex injuries occur in the majority of 'isolated' anterior cruciate ligament ruptures**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(1):176-183. doi:10.1007/s00167-021-06543-6
52. Polat A, Gurpinar T, Aydin D, et al. **Prevalence of anterolateral complex injury and associated injuries in knees with acute complete and partial anterior cruciate ligament injury**. *Ann Méd Res*. 2020;27(5):1412. doi:10.5455/annalsmedres.2020.01.084
53. Arp K, Varnum C, Dalgas U, et al. **Translation and psychometric evaluation of the Danish version of the knee outcome survey - activities of daily living scale in patients with anterior cruciate ligament injuries**. *BMC Musculoskelet Disord*. 2025;26(1):42. doi:10.1186/s12891-024-08000-0
54. Prodromidis AD, Thivaios GC, Mourikis A, et al. **Patient-Reported Outcome Measures Used on Patients With Anterior Cruciate Ligament Injury**. *Cureus*. 2024;16(7):e64546. doi:10.7759/cureus.64546

55. Scott EJ, Westermann R, Glass NA, Hettrich C, Wolf BR, Bollier MJ. **Performance of the PROMIS in Patients After Anterior Cruciate Ligament Reconstruction**. *Orthop J Sports Med*. 2018;6(5):2325967118774509. doi:10.1177/2325967118774509
56. Al-Gburi MHH, Kristiansen JB, Christensen KB, Krogsgaard M. **7 Functional performance tests, clinical measurements, and patient reported outcome measures are separate outcomes after primary anterior cruciate ligament reconstruction**. *ACL Adolesc Knee Pain*. Published online 2024:A3.1-A3. doi:10.1136/bmjsem-2024-sportskongres2024.7
57. Al-Gburi M, Kristiansen JB, Christensen KB, Krogsgaard MR. **Functional performance tests, clinical measurements, and patient-reported outcome measures do not correlate as outcomes 1 year after anterior cruciate ligament reconstruction**. *Knee Surg, Sports Traumatol, Arthrosc*. 2023;31(12):5905-5912. doi:10.1007/s00167-023-07648-w
58. Sonesson S, Österberg A, Gauffin H, Ardern CL, Kvist J, Hägglund M. **Low correlation between functional performance and patient reported outcome measures in individuals with non-surgically treated ACL injury**. *Phys Ther Sport*. 2021;47:185-192. doi:10.1016/j.ptsp.2020.12.006
59. Abed V, Kapp S, Nichols M, et al. **Lysholm and KOOS QoL Demonstrate High Responsiveness in Patients Undergoing Anterior Cruciate Ligament Reconstruction: A Systematic Review and Meta-analysis of Randomized Clinical Trials**. *Am J Sports Med*. 2023;52(12):3161-3166. doi:10.1177/03635465231219966
60. Hansen CF, Jensen J, Odgaard A, et al. **Four of five frequently used orthopedic PROMs possess inadequate content validity: a COSMIN evaluation of the mHHS, HAGOS, IKDC-SKF, KOOS and KNEES-ACL**. *Knee Surg, Sports Traumatol, Arthrosc*. 2022;30(11):3602-3615. doi:10.1007/s00167-021-06761-y
61. Behrend H, Giesinger K, Giesinger JM, Kuster MS. **The “Forgotten Joint” as the Ultimate Goal in Joint Arthroplasty Validation of a New Patient-Reported Outcome Measure**. *J Arthroplast*. 2012;27(3):430-436.e1. doi:10.1016/j.arth.2011.06.035
62. Behrend H, Giesinger K, Zdravkovic V, Giesinger JM. **Validating the forgotten joint score-12 in patients after ACL reconstruction**. *Knee*. 2017;24(4):768-774. doi:10.1016/j.knee.2017.05.007
63. Ferreira A, Saithna A, Carrozzo A, et al. **The Minimal Clinically Important Difference, Patient Acceptable Symptom State, and Clinical Outcomes of Anterior Cruciate Ligament Repair Versus Reconstruction: A Matched-Pair Analysis From the SANTI Study Group**. *Am J Sports Med*. 2022;50(13):3522-3532. doi:10.1177/03635465221126171
64. Ferretti A, Carrozzo A, Saithna A, et al. **Comparison of Primary Repair of the Anterior Cruciate Ligament and Anterolateral Structures to Reconstruction and Lateral Extra-articular Tenodesis at 2-Year Follow-up**. *Am J Sports Med*. 2023;51(9):2300-2312. doi:10.1177/03635465231178301
65. Lee JY, Low YM, Jiang L, et al. **The Forgotten Joint Score-12 in Anterior Cruciate Ligament injuries**. *J Orthop*. 2020;21:117-121. doi:10.1016/j.jor.2020.03.029
66. Vermeijden HD, Yang XA, List JP van der, DiFelice GS. **Reliable Internal Consistency and Adequate Validity of the Forgotten Joint Score-12 after Primary Anterior Cruciate Ligament Repair**. *Arthrosc, Sports Med, Rehabilitation*. 2021;3(3):e893-e900. doi:10.1016/j.asmr.2021.03.003
67. Das L, Johri AS, Abdusamad V, Schuh A, Goyal T. **Joint awareness and return to pre-injury level of activities after ACL reconstruction in athletes vs non-athletes**. *Eur J Orthop Surg Traumatol*. 2023;33(4):819-827. doi:10.1007/s00590-022-03208-z
68. Sakamoto T, Watanabe S, Horii M, et al. **Longitudinal Evaluation Using the Forgotten Joint Score-12 for Double-Bundle Primary Anterior Cruciate Ligament Reconstruction: A Retrospective Observational Study**. *Cureus*. 2024;16(9):e70547. doi:10.7759/cureus.70547

69. Mirghaderi P, Poursalehian M, Eshraghi N, Firoozabadi MA, Mortazavi SMJ. **Patients' joint perception after anterior cruciate ligament reconstruction as a reliable patient-reported outcome measure**. *Knee Surg, Sports Traumatol, Arthrosc*. 2025;33(3):828-836. doi:10.1002/ksa.12416
70. Petushek EJ, Diekfuss JA, Lamplot JD, et al. **Usefulness of Current Patient-Reported Outcome Scales for ACL Injury: A Mixed-Methods Evaluation of Stakeholder-Perceived Utility of Specific Constructs and Items Across the Rehabilitation Timeline**. *Orthop J Sports Med*. 2024;12(3):23259671231218964. doi:10.1177/23259671231218964
71. Gagnier JJ, Shen Y, Huang H. **Psychometric Properties of Patient-Reported Outcome Measures for Use in Patients with Anterior Cruciate Ligament Injuries: A Systematic Review**. *JBJS Rev*. 2018;6(4):e5-e5. doi:10.2106/jbjs.rvw.17.00114
72. List JP van der, Blom IF, Hofstee DJ, Jonkers FJ, Benner JL. **Short-Term Outcomes and Rehabilitation Following Anterior Cruciate Ligament Reconstruction with and without Lateral Extra-articular Tenodesis in Younger Patients: A Prospective Comparison**. *J Knee Surg*. 2025;39(04):218-227. doi:10.1055/a-2712-4279
73. Kekki C, Wörner T, Stålman A, Essen C von. **Item-reduced Forgotten Joint Score provides adequate psychometric properties in ACLR patients**. *J Exp Orthop*. 2024;11(3):e12058. doi:10.1002/jeo2.12058
74. Lee H, Ambrose M, Thompson XD, et al. **Comparison of patient-reported and objective functional measures during the early rehabilitative phase in patients with primary versus revision ACL reconstruction**. *Phys Ther Sport*. 2025;74:88-95. doi:10.1016/j.ptsp.2025.05.010
75. Wang D, Di M, Zheng T, et al. **Effect of Slope-Reducing Tibial Osteotomy With Primary Anterior Cruciate Ligament Reconstruction on Clinical and Radiological Results in Patients With a Steep Posterior Tibial Slope and Excessive Anterior Tibial Subluxation: Propensity Score Matching With a Minimum 2-Year Follow-up**. *Am J Sports Med*. 2025;53(6):1381-1391. doi:10.1177/03635465251330976

NEDERLANDSE SAMENVATTING

Achtergrond

De knie is een complex gewichtdragend gewricht, waarmee flexie, extensie, en beperkte rotatie bewegingen kunnen worden uitgevoerd, terwijl het grote krachten opvangt tijdens dagelijkse- en sportactiviteiten. De stabiliteit van de knie wordt bepaald door het samenspel van botten, kraakbeen, menisci, banden, het gewrichtskapsel en de spieren rondom de knie. Centraal in de knie ligt de voorste kruisband: een sterke band van bindweefsel die schuin verloopt van het bovenbeen (femur) naar het onderbeen (tibia). De voorste kruisband is de belangrijkste stabilisator tegen het naar voren schuiven van het onderbeen ten opzichte van het bovenbeen, en speelt daarnaast een ondersteunende rol bij rotatiebewegingen. Daarmee is de voorste kruisband onmisbaar voor activiteiten waarbij snel gedraaid, afgeremd of gesprongen moet worden.

Een ruptuur (scheur) van de voorste kruisband is een van de meest voorkomende ernstige knieblessures, vooral bij jonge sporters. De blessure ontstaat meestal zonder direct contact, bijvoorbeeld bij een plotselinge afremming, een verkeerde landing, of een snelle draaibeweging waarbij de knie naar binnen knikt en het onderbeen naar binnen draait ten opzichte van het bovenbeen. Wereldwijd worden jaarlijks honderdduizenden voorste kruisbandrupturen gerapporteerd, en in Nederland alleen al worden naar schatting zo'n 12.000 voorste kruisbandreconstructies per jaar uitgevoerd. Het aantal letsels stijgt, met name bij vrouwelijke sporters: door anatomische, hormonale en neuromusculaire factoren hebben zij een aanzienlijk hogere kans op een voorste kruisbandletsel dan mannen.

Bij symptomatische instabiliteitsklachten van de knie wordt vaak gekozen voor een operatieve behandeling: de voorste kruisbandreconstructie. Hierbij wordt de gescheurde band vervangen door een transplantaat (de "graft"), meestal afkomstig uit een eigen pees, zoals de hamstrings, de patellapees of de quadricepspees. Door bot tunneltjes te boren in het bovenbeen en het onderbeen en het transplantaat hierin te bevestigen, wordt gestreefd de oorspronkelijke functie van de voorste kruisband te herstellen. Hoewel deze operatie wereldwijd de standaard is en de operatieve technieken en revalidatieprotocollen de afgelopen decennia sterk zijn verbeterd, blijven de resultaten niet altijd optimaal. Een aanzienlijk deel van de patiënten ervaart restinstabiliteitsklachten, keert niet terug op het oude sportniveau, of loopt opnieuw een ruptuur op – nu van het transplantaat. Bij jonge, actieve patiënten onder de 25 jaar kunnen de re-ruptuurpercentages oplopen tot ongeveer tien procent. Ongeveer een vijfde van de patiënten hervat hun sport niet, een derde behaalt niet het oorspronkelijke sportniveau en slechts de helft keert terug op competitief sportniveau.

De stabiliteit van de knie wordt niet alleen bepaald door de voorste kruisband zelf. De knie functioneert als een geïntegreerd systeem, waarin de voorste kruisband samenwerkt met andere structuren die als secundaire (ondersteunende) stabilisatoren fungeren. Hieronder vallen onder meer de menisci (de twee schokdempende elastische weefselschijfjes in de knie), de binnen- en buitenband en gerelateerde structuren, en de structuren aan de voor-buitenzijde van de knie, de zogenaamde anterolaterale hoek structuren. De anterolaterale hoek bestaat uit verschillende lagen, waaronder de iliotibiale band met zijn diepe Kaplan-vezels, en het anterolaterale ligament en kapsel. Wanneer een of meer van deze structuren beschadigd raken, kan dit leiden tot abnormale bewegingsuitslagen in de knie en een verhoogde belastingkracht op het transplantaat na voorste kruisbandreconstructie.

Daarnaast speelt ook de vorm en stand van het onderbeenbot een belangrijke rol. Een toegenomen helling naar achteren van het plateau van het onderbeenbot ten opzichte van de schacht van dit bot – de zogenoemde posterieure tibiale helling – zorgt ervoor dat het scheenbeen onder belasting verder naar voren schuift, en levert daardoor extra spanning op de voorste kruisband of op het transplantaat. Ook een afwijkende stand van het gehele been in het frontale vlak, zoals een varus- of valgus afwijking (O- of X-benen), beïnvloedt de krachten op de voorste kruisband.

Bijkomende letsels en varianten van de vorm van het bot zijn eerder regel dan uitzondering: bij ongeveer 60 tot 80 procent van de patiënten met een voorste kruisbandruptuur wordt aanvullend letsel gevonden. Veel voorkomend zijn meniscusscheuren – waaronder een wortelscheur van de laterale meniscus en een ramplaesie van de mediale meniscus –, kraakbeenschade, en letsels van de mediale collaterale band en in de anterolaterale hoek. Wanneer deze bijkomende letsels niet worden herkend of niet adequaat worden behandeld, kan dit leiden tot blijvende abnormale bewegingen in de knie en tot overbelasting van het voorste kruisbandtransplantaat. De afgelopen jaren is er steeds meer aandacht gekomen voor het gericht mee behandelen van deze structuren, bijvoorbeeld door het verrichten van een aanvullende reconstructie van de anterolaterale hoek of het terug hechten van een afgescheurde meniscuswortel. Toch ontbreekt nog veel kennis over hoe deze structuren precies samenwerken, in welke combinaties ze het beste behandeld kunnen worden, en hoe dit zich vertaalt naar de uitkomsten voor de patiënt.

Bovendien gaat het toevoegen van een aanvullende ingreep – zoals een reconstructie van de anterolaterale hoek – gepaard met een extra incisie aan de buitenzijde van de knie. Dit kan leiden tot meer pijnklachten na de operatie, wat de revalidatie en het vroege herstel kan beïnvloeden. Een effectieve pijnbehandeling rondom de operatie is daarom essentieel. De gebruikelijke pijnstillingsprotocollen, gericht op de standaard voorste kruisbandreconstructie, dekken niet altijd het buitenste deel van de knie waar deze aanvullende ingreep plaatsvindt.

Op basis van deze achtergrond kan gesteld worden dat hoewel de voorste kruisbandreconstructie een effectieve behandeling is, restinstabiliteitsklachten en het opnieuw scheuren van het transplantaat belangrijke klinische problemen blijven. Om deze uitkomsten te verbeteren is een beter begrip nodig van de bijdrage van bijkomende letsels, secundaire stabiliserende structuren en de stand en vorm van het been aan de biomechanica van de knie en aan de belasting van de voorste kruisband. Deze biomechanische kennis moet vervolgens worden vertaald naar de klinische praktijk, zodat de chirurg op basis van het individuele letselpatroon en de individuele anatomie van de patiënt de juiste keuzes kan maken – zowel tijdens de operatie als in de zorg eromheen.

Centrale doelstelling

Het centrale doel van dit proefschrift is om beter te begrijpen hoe bijkomende letsels, secundaire stabiliserende structuren en de stand van het been de biomechanica en de bewegingen van de knie beïnvloeden. Deze biomechanische kennis wordt vervolgens vertaald naar de klinische praktijk, met als doel de chirurgische besluitvorming en de perioperatieve zorg te optimaliseren, en zo de uitkomsten voor patiënten verder te verbeteren.

Specifieke doelen

Om deze centrale doelstelling te bereiken zijn onderstaande zeven specifieke doelen geformuleerd:

1. Het systematisch in kaart brengen van de invloed van bijkomende letsels in en buiten het kniegewricht, en van de stand van het been in het frontale en sagittale vlak, op de krachten in de voorste kruisband en het voorste kruisbandtransplantaat en op de bewegingen van de knie.
2. Het beoordelen van de biomechanische rol van de iliotibiale band en het anterolaterale ligament bij anterolaterale rotatie-instabiliteit in knieën met een gescheurde voorste kruisband, en het vergelijken van twee aanvullende ingrepen aan de buitenzijde van de knie – de laterale extra-articulaire tenodese (LET) en de reconstructie van het anterolaterale ligament – in knieën die een voorste kruisbandreconstructie ondergaan.
3. Het bepalen van de afzonderlijke en gecombineerde biomechanische effecten van een wortelscheur van de laterale meniscus en van letsel aan de Kaplan-vezels in de anterolaterale hoek in een knie zonder functionerende voorste kruisband, en het beoordelen van het effect van het terug hechten van de meniscuswortel, een gemodificeerde Lemaire plastiek (een vorm van LET), of beide ingrepen samen, op de bewegingen van de knie na voorste kruisbandreconstructie.
4. Het onderzoeken of het toevoegen van een anterolaterale hoek reconstructie aan een voorste kruisbandreconstructie leidt tot betere patiëntgerapporteerde uitkomsten – in het bijzonder een verbeterde “joint awareness”, dat wil zeggen de mate waarin een patiënt zijn of haar knie nog opmerkt tijdens dagelijkse activiteiten – en tot lagere percentages van re-ruptuur van het transplantaat bij jonge sporters met een hoog risico hierop.
5. Het interpreteren van biomechanische bevindingen over het anterolaterale ligament binnen het bredere geheel van de anterolaterale hoek structuren, en het verduidelijken

van wat deze bevindingen betekenen voor de chirurgische besluitvorming bij voorste kruisbandreconstructies.

6. Het vaststellen van de prevalentie van een toegenomen posterieure tibiale helling in een populatie van jonge, hoog-risicopatiënten die een primaire voorste kruisbandreconstructie ondergaan, en het beoordelen of een aanvullende reconstructie van de anterolaterale hoek bij deze subgroep gepaard gaat met minder voorste kruisbandrevisieoperaties.
7. Het onderzoeken of het toevoegen van een anterolaterale geniculaire zenuwblokkade aan de standaard adductorkanaalblokkade de postoperatieve pijn vermindert en het gebruik van pijnstillers verlaagt na een gecombineerde voorste kruisbandreconstructie en reconstructie van de anterolaterale hoek.

Resultaten

In **hoofdstuk 2** wordt door middel van een systematische review van 43 biomechanische laboratorium studies de invloed van bijkomende letsels en secundaire stabilisatoren op de krachten in de voorste kruisband (graft) en op de bewegingen van de knie geëvalueerd. Verschillende bijkomende letsels en afwijkingen in de stand van het been verhogen de spanning of kracht op de oorspronkelijke voorste kruisband en op het voorste kruisbandtransplantaat. Een ruime verwijdering van de mediale of laterale meniscus, perifere meniscusscheuren, ramplaesies van de mediale meniscus, wortelscheuren van de laterale meniscus, letsels van de mediale collaterale band, de posteromediale en de posterolaterale hoek, een toegenomen posterieure tibiale helling, alsook een varus- of valgusafwijking, leiden allemaal tot een toename van deze krachten. Daarnaast geeft elk letsel een specifieke afwijking in de bewegingen van de knie: een (ramp)laesie van de mediale meniscus en een toegenomen posterieure tibiale helling vergroten het naar voren schuiven van het onderbeen; een ramplaesie van de mediale meniscus en een letsel van de posterolaterale hoek vergroten de externe rotatie van het onderbeen; een wortelscheur van de laterale meniscus vergroot de interne rotatie; een letsel van de mediale collaterale band leidt tot meer valgusrotatie; en een letsel van de posterolaterale hoek tot meer varusrotatie. De review onderbouwt daarmee waarom bijkomende letsels in een knie met een voorste kruisbandletsel systematisch opgespoord en behandeld moeten worden, omdat onbehandelde letsels kunnen leiden tot overbelasting en falen van de voorste kruisbandgraft.

In **hoofdstuk 3** wordt door middel van een systematische review van zes biomechanische knie cadaver dissectie studies en negen knie cadaver reconstructie studies de rol van de iliotibiale band en het anterolaterale ligament bij anterolaterale rotatie-instabiliteit beoordeeld, en het effect vergeleken van een laterale extra-articulaire tenodese en een reconstructie van het anterolaterale ligament. De iliotibiale band fungeerde in de meeste studies als secundaire stabilisator van de voorste kruisband; het anterolaterale ligament niet of nauwelijks. Zowel een gemodificeerde Lemaire plastiek (een vorm van LET) als een reconstructie van het anterolaterale ligament konden de resterende anterolaterale rotatie-instabiliteit in een knie met een geïsoleerde voorste kruisbandreconstructie significant verminderen. Geadviseerd werd om beide aan te duiden als reconstructies van de anterolaterale hoek, omdat het biomechanische effect hetzelfde is.

De combinatie van een wortelscheur van de laterale meniscus en letsel van de Kaplan-vezels komt veel voor bij een voorste kruisbandletsel, en hun afzonderlijke effecten op de bewegingen van de knie zouden additief kunnen zijn. In **hoofdstuk 4** wordt dit in een biomechanische knie cadaver studie onderzocht, samen met het effect van het terug hechten van de meniscuswortel, een reconstructie van de anterolaterale hoek, of beide ingrepen samen, in knieën met een voorste kruisbandreconstructie. Zowel de wortel van de laterale meniscus als de Kaplan-vezels bleken te fungeren als secundaire stabilisator. Een letsel van de Kaplan-vezels had een additief biomechanisch effect bovenop een knie met een voorste kruisbandletsel én een wortelscheur van de laterale meniscus. Een geïsoleerde voorste kruisbandreconstructie alleen herstelde de stabiliteit niet volledig in deze gecombineerde letselsituatie; zowel het terug hechten van de meniscuswortel als een reconstructie van de anterolaterale hoek bleken nodig om de stabiliteit van de knie volledig te herstellen tot het niveau van de intacte knie.

In **hoofdstuk 5** wordt een klinische vergelijkende cohortstudie gepresenteerd waarin een geïsoleerde voorste kruisbandreconstructie met een hamstringtransplantaat wordt vergeleken met dezelfde reconstructie gecombineerd met een gemodificeerde Lemaire plastiek, twee jaar na de operatie, bij patiënten jonger dan 25 jaar met een preoperatieve Tegner score van 7 of hoger en de intentie om terug te keren naar competitieve sport. De primaire uitkomstmaat was de Forgotten Joint Score-12 (FJS-12). Op 12 maanden was de FJS-12 statistisch significant beter in de groep zonder reconstructie van de anterolaterale hoek, maar dit verschil was niet klinisch relevant; op 24 maanden waren de scores tussen de groepen vergelijkbaar. Ook op de andere patiëntgerapporteerde uitkomstmaten werden geen significante verschillen gevonden. Re-rupturen traden op bij 14,6% in de groep zonder en bij 7,4% in de groep met reconstructie van de anterolaterale hoek. Het toevoegen van een Lemaire plastiek hing dus niet samen met een klinisch relevant verschil in FJS-12 na 24 maanden.

In **hoofdstuk 6** wordt in een redactioneel commentaar de studie van Hohmann et al. besproken. In deze systematische review van biomechanische cadaver studies werd gesteld dat het anterolaterale ligament geen significante biomechanische meerwaarde zou hebben ten opzichte van de (gereconstrueerde) voorste kruisband. Op basis van de systematische review uit **hoofdstuk 3** en op basis van klinische studies en reviews die een aanzienlijke vermindering van het falen van het voorste kruisbandtransplantaat bij hoog-risicopatiënten laten zien, werd geadviseerd deze stelling met voorzichtigheid te interpreteren. Een letsel van de anterolaterale hoek omvat een breed spectrum van volledige of gedeeltelijke letsels van verschillende anatomische structuren, die elk in wisselende mate bijdragen aan de anterolaterale rotatie-instabiliteit. Een biomechanische analyse van uitsluitend het anterolaterale ligament kan en mag daarom niet zonder meer worden vertaald naar de klinische praktijk.

In **hoofdstuk 7** wordt een klinische vergelijkende cohortstudie in meerdere centra gepresenteerd, waarin de prevalentie van een toegenomen posterieure tibiale helling (≥12°) bij jonge hoog-risicopatiënten met een primaire voorste kruisbandreconstructie werd onderzocht, en werd geëvalueerd of een aanvullende reconstructie van de anterolaterale hoek samenhangt met minder voorste kruisbandtransplantaat in de groep met een verhoogde posterieure tibiale helling. Een toegenomen posterieure tibiale helling was aanwezig bij 28,2% van de patiënten en kwam vaker voor in de groep die een revisie operatie nodig had. Bij patiënten met een toegenomen posterieure tibiale helling traden revisie operaties op bij 21,0% van de patiënten zonder, en bij 9,2% van de patiënten met een reconstructie van de anterolaterale hoek; bij patiënten met een posterieure tibiale helling van minder dan 12° waren deze percentages 13,2% en 5,4%. Een reconstructie van de anterolaterale hoek was geassocieerd met een lagere kans op een revisie operatie van de voorste kruisbandreconstructie, terwijl een hogere posterieure tibiale helling daarvoor onafhankelijk een risicofactor was.

In **hoofdstuk 8** wordt het protocol gepresenteerd van een gerandomiseerd, dubbelblind, multicenter klinisch onderzoek, waarin een geïsoleerde adductorkanaalblokkade wordt vergeleken met een adductorkanaalblokkade gecombineerd met een anterolaterale geniculaire zenuwblokkade, voor de pijnbehandeling na een gecombineerde voorste kruisbandreconstructie en reconstructie van de anterolaterale hoek. Voor deze studie zullen 80 patiënten van 16 jaar of ouder die een primaire voorste kruisbandreconstructie met een quadricepspeestransplantaat in combinatie met een gemodificeerde Lemaire reconstructie ondergaan, in een 1:1 verhouding worden gerandomiseerd voor één van beide pijnbehandelingen. De primaire uitkomstmaat is de pijnscore tijdens beweging twee uur na de operatie. De hypothese is dat het toevoegen van de geniculaire zenuwblokkade leidt tot minder pijn na de operatie en minder gebruik van opioïden, en daarmee tot meer comfort voor de patiënt en een snellere revalidatie.

Discussie

De methodologische kwaliteit van de geïncludeerde studies in beide systematische reviews (**hoofdstukken 2 en 3**) was overwegend hoog. Een meta-analyse was echter niet mogelijk vanwege aanzienlijke heterogeniteit tussen de studies, samenhangend met verschillen in aantallen en kenmerken van de cadaver knieën, in de chirurgische procedures, en in gebruikte testopstellingen, belastingprotocollen en meetmethoden. Bevindingen uit knie cadaver studies beschrijven bovendien alleen de toestand op tijdstip nul, omdat het biologische genezingsproces niet kan worden nagebootst. Ondanks deze beperkingen geven de twee reviews waardevolle inzichten in de chirurgisch relevante biomechanische gevolgen van bijkomende letsels in een knie met een voorste kruisbandletsel. Naast de heterogeniteit zijn er praktische bezwaren aan cadaver onderzoek, zoals de hoge kosten, biologisch gevaar- en afvalproblematiek, opslag- en conserveringsvraagstukken en mogelijke ethische overwegingen. Recente ontwikkelingen op het gebied van computermodellen, zoals eindige-elementenanalyse en rigid-body modellering van gewrichten en weefsels, bieden nieuwe mogelijkheden voor biomechanisch onderzoek aan de knie.

Sinds afronding van de reviews zijn enkele aanvullende biomechanische studies gepubliceerd. Een studie naar gecombineerd voorste kruisband- en posterolaterale hoek letsel bevestigde grotendeels de bevindingen uit de review. Een aanvullende dissectie studie concludeerde dat de Kaplan-vezels de belangrijkste structuur vormen die de interne rotatie tegenhoudt, maar vond geen toename van anterolaterale rotatie-instabiliteit bij geïsoleerde letsels van afzonderlijke structuren van de anterolaterale hoek; deze afwijkende bevinding hangt waarschijnlijk samen met methodologische verschillen in de manier waarop structuren worden doorgenomen. De variatie tussen biomechanische studies in dergelijke dissectie technieken is aanzienlijk, met verschillen in hoe en waar het anterolaterale ligament, de iliotibiale band, het gewrichtskapsel en de Kaplan-vezels worden doorgenomen. Twee aanvullende vergelijkende reconstructiestudies vonden, in tegenstelling tot zeven van de acht studies uit de review, geen volledig vergelijkbaar biomechanisch effect van een LET en een reconstructie van het anterolaterale ligament; de oorzaak van deze afwijking blijft onverklaard, maar op basis van de huidige review tonen de meeste beschikbare studies nog steeds vergelijkbare effecten van beide technieken.

Drie aanvullende biomechanische studies hebben de invloed van een wortelscheur van de laterale meniscus op de krachten in de voorste kruisbandgraft en op de bewegingen van de knie onderzocht. De bevindingen liepen uiteen en hingen mede af van de status van de meniscofemorale ligamenten en van de gehanteerde meet- en reparatietechnieken. Klinisch leidt het terug hechten van een wortelscheur van de laterale meniscus, een letsel dat veel voorkomt bij een voorste kruisbandletsel, over het algemeen tot gunstige uitkomsten op korte tot middellange termijn. De status van het meniscofemorale ligament wordt echter zelden tijdens de operatie gedocumenteerd, en er zijn geen klinische studies beschikbaar die het terug hechten van het meniscofemorale ligament systematisch hebben geëvalueerd.

In de biomechanische studie in **hoofdstuk 4** vertegenwoordigde het gecreëerde letsel van de Kaplan-vezels een “worst case” scenario; in MRI-cohorten worden (gedeeltelijke) letsels van de Kaplan-vezels in 19 tot 60% bij acute voorste kruisbandscheuren beschreven, en (gedeeltelijke) letsels van het anterolaterale gewrichtskapsel of het anterolaterale ligament in 21 tot 71% van de gevallen. In het redactioneel commentaar in **hoofdstuk 6** werd dan ook voorgesteld dat een letsel van de anterolaterale hoek een breed spectrum van gedeeltelijke of volledige letsels omvat, die samen met andere bijkomende letsels en individuele kniekenmerken de uiteindelijke mate van anterolaterale rotatie-instabiliteit bepalen. Daarnaast werd in de studie in **hoofdstuk 4** een hoog percentage falen van het terug hechten van de meniscuswortel tijdens robottesten waargenomen, terwijl alle hechtingen tijdens de operatie stevig leken. Mogelijke verklaringen zijn de zwakkere botkwaliteit van cadaver knieën, de fragiliteit van hechtingen op tijdstip nul, en de relatief zware belastingomstandigheden van het robotische testprotocol; een biologisch genezingsproces, dat in de klinische situatie wel optreedt, ontbreekt in de cadaverstudie. Voorzichtigheid is daarom geboden bij het toepassen van deze hechttechniek in de praktijk, totdat aanvullende biomechanische studies beschikbaar komen.

In **hoofdstuk 5** werd de FJS-12 als primaire uitkomstmaat gebruikt. Veelgebruikte patiënt gerapporteerde uitkomstmaten na een voorste kruisbandletsel en -reconstructie - zoals de IKDC, KOOS, Lysholm score, Tegner Activity Scale, Visual Analogue Scale (VAS) voor pijn, en de ACL-Return to Sport after Injury scale (ACL-RSI) - zijn over het algemeen betrouwbaar, valide en gevoelig, maar meten elk verschillende aspecten en bereiken ongeveer 12 tot 24 maanden na de operatie een plafondeffect. Voor hoog-functionerende patiënten is dit een belangrijke beperking. De FJS-12, oorspronkelijk ontwikkeld voor uitkomsten na een gewrichtsvervangende operatie en inmiddels gevalideerd bij een voorste kruisbandreconstructie, meet hoe vaak patiënten hun knie “vergeten” in het dagelijks leven (joint awareness), en heeft duidelijk minder uitgesproken plafondeffecten. In de studie in **hoofdstuk 5** verbeterden alle uitkomstmaten in de loop van de tijd, en convergeerden de scores tussen de groepen in 24 maanden, ondanks een numeriek lager percentage re-rupturen in de groep met reconstructie van de anterolaterale hoek. Noch de traditionele uitkomstmaten, noch de FJS-12 lijken dus alle klinisch relevante verschillen tussen chirurgische strategieën te kunnen aantonen, en FJS-12 waarden van ongeveer 70 op twee jaar wijzen eerder op een matige joint awareness dan op een werkelijk “vergeten” knie. Het gebruik van een multidomein-benadering van patiëntgerapporteerde uitkomstmaten - aangevuld met joint awareness instrumenten en met objectieve prestatie- en stabiliteitstesten - lijkt dan ook aan te bevelen, vooral bij hoog-risicopatiënten en bij procedures zoals een reconstructie van de anterolaterale hoek.

Op basis van de bevindingen in **hoofdstuk 7** werd voorgesteld om een stapsgewijze aanpak te hanteren waarin een reconstructie van de anterolaterale hoek een geschikte eerste toevoeging lijkt te zijn om het risico op een revisie operatie te verminderen bij patiënten met een toegenomen posterieure tibiale helling. Omdat een toenemende posterieure tibiale helling onafhankelijk geassocieerd bleef met de revisie van een voorste kruisbandreconstructie - met een odds ratio van 1,09 per graad toename boven de 12° - kan een osteotomie ter vermindering van de helling worden overwogen in geselecteerde primaire gevallen, met name bij patiënten met een posterieure tibiale helling die aanzienlijk hoger ligt dan 12°. De enige beschikbare vergelijkende klinische studie over deze osteotomie suggereert dat een posterieure tibiale helling van ≥16° gecombineerd met een excessieve voorwaartse subluxatie van het laterale compartiment van ≥6 mm een passende indicatie kan vormen voor het combineren van een osteotomie met een primaire voorste kruisbandreconstructie. Er zijn echter nog geen prospectieve studies die het klinische voordeel van een aanvullende reconstructie van de anterolaterale hoek bij patiënten met een toegenomen posterieure tibiale helling hebben geëvalueerd; gezien de prevalentie van ongeveer 30% van patiënten met een posterieure tibiale helling van ≥12° zou dergelijk onderzoek haalbaar moeten zijn.

In **hoofdstuk 8** werd betoogd dat de evolutie van chirurgische strategieën bij voorste kruisbandreconstructie kan vragen om aanpassing van de perioperatieve pijnbehandelingsprotocollen. Het lopende multicenter onderzoek moet inzicht geven in de vraag of dit voor de gecombineerde voorste kruisbandreconstructie en reconstructie van de anterolaterale hoek kan worden gerealiseerd door het toevoegen van een anterolaterale geniculaire zenuwblokkade aan een standaard adductorkanaalblokkade. Vergelijkbaar zou ook het toevoegen van een osteotomie ter vermindering van de helling, als onderdeel van een primaire of revisie voorste kruisbandreconstructie, vragen om aangepaste pijnbehandelingsprotocollen.

Toekomstperspectieven

Op basis van het werk in dit proefschrift kunnen verschillende richtingen voor toekomstig onderzoek worden geformuleerd:

1. **Standaardisatie van protocollen voor biomechanische knie cadaver studies** is nodig om de vergelijkbaarheid tussen studies te verbeteren, met onder andere consensus over flexiehoeken, belastingomstandigheden en meettechnieken.
2. **Ontwikkeling en validatie van computermodellen van de knie** kunnen een herbruikbare en kostenefficiënte aanpak bieden voor het bestuderen van de biomechanica van de knie, en kunnen dienen als aanvulling op cadaveronderzoek.
3. **Standaardisatie en gedetailleerde rapportage van dissectie technieken** zijn nodig om de vergelijkbaarheid tussen biomechanische studies te verbeteren en om de interpretatie van anatomische structuren consistent te maken.
4. **Aanvullend klinisch onderzoek naar letsels van het meniscofemorale ligament** is nodig om de biomechanische en klinische relevantie hiervan vast te stellen, en om te beoordelen of een gecombineerd herstel de patiëntuitkomsten verbetert.
5. **Onderzoek naar gedeeltelijke en gecombineerde letselpatronen van de anterolaterale hoek** is nodig om de klinische werkelijkheid beter weer te geven, in plaats van zich te richten op geïsoleerde of “worst case” letselscenario’s.
6. **Het integreren van uitkomstmaten voor joint awareness**, zoals de Forgotten Joint Score-12, in een multidomein-benadering van patiëntgerapporteerde uitkomstmaten kan de evaluatie van patiëntuitkomsten na een voorste kruisbandreconstructie verbeteren.
7. **Prospectieve vergelijkende studies**, bij voorkeur gerandomiseerde gecontroleerde onderzoeken, moeten de relatieve klinische voordelen evalueren van een voorste kruisbandreconstructie met aanvullende reconstructie van de anterolaterale hoek, met een osteotomie ter vermindering van de helling, en met de combinatie van beide ingrepen, bij patiënten met een toegenomen posterieure tibiale helling.

8. **De optimalisatie van perioperatieve pijnbehandelingsstrategieën** moet verder worden onderzocht bij patiënten die een meer complexe voorste kruisbandreconstructie ondergaan, waaronder een gecombineerde reconstructie van de anterolaterale hoek en een osteotomie ter vermindering van de helling.

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CURRICULUM VITAE

Wybren Ayold van der Wal was born on 11 May 1977 in Gouda, the Netherlands, and grew up in Ouderkerk aan den IJssel and Arnhem. He completed secondary school at the KGL in Arnhem while training as a member of the Dutch national gymnastics team at the national sports centre Papendal. Awaiting admission to medical school under the fixed quota system, he started studying Pharmacy at Utrecht University in 1997. Two years later Wybren transferred to Medicine at the same university, from which he graduated in 2005. During his medical studies he undertook a clinical internship in South Africa.

After graduation, Wybren worked as an emergency physician at the University Medical Centre Utrecht. He subsequently held positions at the Department of Orthopaedic Surgery of Radboud University Medical Centre Nijmegen and at the Department of General Surgery of the Lucas Andreas Hospital in Amsterdam, before starting his pre-training in general surgery at Rijnstate Hospital in Arnhem. In 2010 Wybren began his orthopaedic surgery residency, training at the Sint Maartenskliniek Nijmegen, Radboud University Medical Centre Nijmegen, and Rijnstate Hospital Arnhem. During this period, he also completed an adult trauma fellowship at the Royal Infirmary of Edinburgh, Scotland.

Following his residency, Wybren undertook an overland expedition from the Netherlands to Cape Town, driving through Europe, Asia and Africa over a period of five months. His first appointment as an orthopaedic surgeon was at the Spaarne Gasthuis in Hoofddorp, after which he further specialized in knee surgery during a fellowship at the University Medical Centre Utrecht.

In 2016 Wybren was appointed consultant orthopaedic knee and sports surgeon at Gelderse Vallei Hospital in Ede, where he helped establish Sports Valley, the High Performance Medical Centre for athletes. Today, Wybren treats elite athletes who train at the very Papendal where he himself once trained. Over the years he completed visiting fellowships in Cape Town, London, and Vail, Colorado. In 2023 Wybren was selected for the ISAKOS Global Traveling Fellowship, visiting international experts across Canada and the United States.

From 2019 until 2025 Wybren served on the board of the Dutch Arthroscopy Society (NVA), first as Secretary and subsequently as Chair of the Congress Committee, and he is an editorial board member of the Arthroscopy Journal. In 2025 he was recognized as High Performance Partner of TeamNL by the Dutch Olympic Committee (NOC*NSF) and joined the medical team at the World Athletics Championships in Tokyo, Japan. Wybren is co-founder and co-owner of the Knee Arthroscopy Belt, designed to optimize efficiency and ergonomics during knee arthroscopy. He has lectured at numerous conferences and served as faculty for advanced knee surgery courses, and in 2026 was guest speaker at the ACL Study Group meeting in Brazil. From September 2026 Wybren is set to become President of the NVA.

LIST OF PUBLICATIONS

1. **Increased Posterior Tibial Slope and Lateral Extra-articular Tenodesis Are Independently Associated With Revision ACLR in a Young High-risk Population.**
   van der Wal WA, de Groot TM, Tamana L, Tsoulgkounidis N, Veraart JT, Hoogeslag RAG, van der Hoeven H, Engelsma Y, Custers RJH, Saris DBF.
   Am J Sports Med, 2026 Aug 19. doi: 10.1177/03635465261473931. Online ahead of print. (Chapter 7 of this thesis)

2. **Modified Lemaire Anterolateral Corner Reconstruction Does Not Impact Forgotten Joint Score-12 at 2 Years in Hamstring Graft Anterior Cruciate Ligament Reconstructions in High-Risk Patients**
   Hendriks JRH, de Groot TM, Oosting E, **van der Wal WA**
   Arthroscopy. 2026 Jul 2. doi: 10.1002/arj.70339. Online ahead of print (Chapter 5 of this thesis)

3. **Nutrition and rehabilitation after anterior cruciate ligament reconstruction: A systematic review**
   Raghoebar S, Roozenboom-van Vliet C, **van der Wal WA**, Welling W, Boersma D, Oosting E, Zwerver J, Mensink M
   Knee Surg Sports Traumatol Arthrosc. 2026 May 22. doi: 10.1002/ksa.70441. Online ahead of print

4. **Lateral Meniscus Posterior Root Repair with Lateral Extra-articular Tenodesis Significantly Decreased Internal Rotation and Pivot Shift Loading in a Cadaveric Study of Anterior Cruciate Ligament Reconstructed Knees**
   van der Wal WA, Tollefson LV, Hoogeslag RAG, Slette EL, Carlson MR, Shoemaker EP, LaPrade RF
   Arthroscopy. 2026 Jul;42(7):1197-1213. (Chapter 4 of this thesis)

5. **Quadriceps tendon autograft is not inferior to bone-patellar tendon-bone or hamstring autograft in anterior cruciate ligament reconstruction in terms of subjective patient-reported outcomes: Two-year results of a multicenter randomised controlled study**
   Boer BC, Brouwer RW, Olde Heuvel J, de Vries AJ, **van der Wal WA**, Christiaan Rompen J, van Houten AH, Hoogeslag RAG
   Knee Surg Sports Traumatol Arthrosc. 2026 Feb 27. doi: 10.1002/ksa.70354. Online ahead of print

6. **A Wearable Leg Support for Surgical Ergonomics in Knee Arthroscopy**
   Luttjeboer JS, Meuffels DE, **van der Wal WA**
   Arthrosc Tech. 2025 Sep 25;14(11):103879.

7. **International Delphi Consensus on Medial Meniscal Root Tears Shows High Agreement on Diagnosis, Treatment, and Rehabilitation but Lack of Agreement on Treatment of Asymptomatic Tears**
   Chahla J, Garcia JR, Tollefson L, Dzidzishvili L, Allende F, Gerhold C, Krych AJ, LaPrade RF; Meniscus Root International Expert Group (incl. **van der Wal WA**)
   Arthroscopy. 2025 Nov;41(11):4683-4698. (as member of the Meniscus Root International Expert Group)

8. **Editorial Commentary: The Anterolateral Ligament Is Only Part of the Puzzle of Anterolateral Corner Injury in Anterior Cruciate Ligament Disruption and Reconstruction**
   van der Wal WA, van der List JP

Arthroscopy. 2025 Nov;41(11):4900-4902. (Chapter 6 of this thesis)

9. **A Contemporary International Expert Consensus Statement on the Evaluation, Diagnosis, Treatment, and Rehabilitation of Injuries to the Posterolateral Corner of the Knee**
LaPrade RF, Gerhold C, Kunze KN, Geeslin AG, Tollefson LV, Dave U, Garcia JR, Barenius B, Brown C, de Oliveira Campos TV, Cohen M, Engebretsen L, Ferrer G, Franciozi CE, Fritsch BA, Frosch KH, Gelber PE, Getgood A, Hantes M, Held M, Helito CP, Inderhaug E, Johansen S, Lagae KC, Levy BA, Lind M, Lording T, Maestu R, Margheritini F, Menetrey J, Moatshe G, Monllau JC, Murray IR, Negrín R, Parker DA, Pujol N, Robinson J, Samuelsson K, Stevenson C, Tuca MJ, Uchida S, **van der Wal WA**, Villascusa S, Von Bormann RPB, Chahla J
Arthroscopy. 2025 Nov;41(11):4630-4640.

10. **The Iliotibial Band is the Main Secondary Stabilizer for Anterolateral Rotatory Instability and both a Lemaire Tenodesis and Anterolateral Ligament Reconstruction Can Restore Native Knee Kinematics in the Anterior Cruciate Ligament Reconstructed Knee: A Systematic Review of Biomechanical Cadaveric Studies**
van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF
Arthroscopy. 2024 Feb;40(2):632-647. (Chapter 3 of this thesis)

11. **Translation, Validity, and Reliability of the Dutch Anterior Cruciate Ligament-Quality of Life Questionnaire**
de Vries AJ, Brouwer RW, Veld RHIT, **van der Wal WA**, Reininga IHF, Hoogeslag RAG
Orthop J Sports Med. 2022 Sep 15;10(9

12. **Meniscal Tears, Posterolateral and Posteromedial Corner Injuries, Increased Coronal Plane and Increased Sagittal Plane Tibial Slope All Influence Anterior Cruciate Ligament-Related Knee Kinematics and Increase Forces on the Native and Reconstructed Anterior Cruciate Ligament: A Systematic Review of Cadaveric Studies**
van der Wal WA, Meijer DT, Hoogeslag RAG, LaPrade RF
Arthroscopy. 2022 May;38(5):1664-1688. (Chapter 2 of this thesis)

13. **Repair versus reconstruction for proximal anterior cruciate ligament tears: a study protocol for a prospective multicenter randomized controlled trial**
van der List JP, Vermeijden HD, Sierevelt IN, Rademakers MV, Falke MLM, Helmerhorst GTT, Hoogeslag RAG, **van der Wal WA**, van Noort A, Kerkhoffs GMMJ
BMC Musculoskelet Disord. 2021 Apr 30;22(1):399.

14. **Anatomical superficial medial collateral ligament reconstruction with posteromedial capsule reefing successfully restores valgus knee laxity**
van der Wal WA, Van Gennip S, Heesterbeek PJ, Busch VJ, Wymenga AB
Acta Orthop Belg. 2020 Mar;86(1):69-76

15. **Posterolateral corner reconstruction in combined injuries of the knee: Improved stability with Larson's fibular sling reconstruction and comparison with LaPrade anatomical reconstruction**
van Gennip S, **van der Wal WA**, Heesterbeek PJC, Wymenga AB, Busch VJJF
Knee. 2020 Jan;27(1):124-131.

16. **Groin pain in athletes (in Dutch)**
Sanders RJ, Kokshoorn AP, Kolkman KA, **van der Wal WA**, van Loon CJ
Ned Tijdschr Geneeskd. 2014;158:A7787

17. **Anatomical reconstruction of posterolateral corner and combined injuries of the knee**
van der Wal WA, Heesterbeek PJ, van Tienen TG, Busch VJ, van Ochten JH, Wymenga AB
Knee Surg Sports Traumatol Arthrosc. 2016 Jan;24(1):221-8.

18. **The natural course of chronic exertional compartment syndrome of the lower leg**
van der Wal WA, Heesterbeek PJ, Van den Brand JG, Verleisdonk EJ
Knee Surg Sports Traumatol Arthrosc. 2015 Jul;23(7):2136-41.

19. **Fibrous dysplasia of bone associated with soft-tissue myxomas as well as an intra-osseous myxoma in a woman with Mazabraud's syndrome: a case report**
van der Wal WA, Unal H, de Rooy JW, Flucke U, Veth RP
J Med Case Rep. 2011 Jun 27;5:239.

20. **Virtual reality training for endoscopic surgery: voluntary or obligatory?**
van Dongen KW, **van der Wal WA**, Rinkes IH, Schijven MP, Broeders IA
Surg Endosc. 2008 Mar;22(3):664-7.

21. **Spondylodiscitis as cause of unexplained fever (in Dutch)**
van der Wal WA, Oner FC
Ned Tijdschr Geneeskd. 2007 Nov 10;151(45):2485-90