Systematic Review

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

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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 methodological 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 and 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.

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

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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 (Fig 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 methodological 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, 2).

Results

Search Results

The initial search yielded 851 records, of which 177 were duplicates that were removed. The titles and

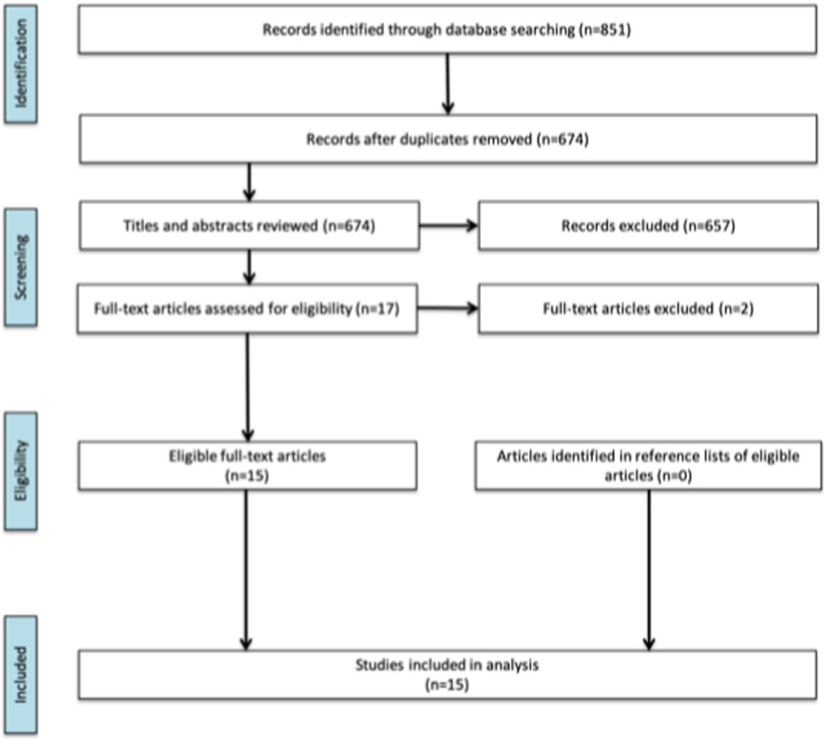

Fig 1. Systematic search flowchart for the systematic review.

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 (Fig 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.

According to the QUACS scale, 11 articles received methodological 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°. 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°.

Table 1. Characteristic and Results of ALC Sequential Sectioning Studies

Authors	n	QS	Dissection Protocol	Tests Performed	ATT Measurements	IR Measurements	PS Measurements	Conclusion
Kittl et al.[23] (2016)	16	85	n = 8: Intact → sITB* → dcITB† → ALL→Cap	AP (90N) at 0°, 30°, 60°, 90°	NS restraint of all structures except ACL (ACL intact group)	sITB restraint at 90°: 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 30° to 45° in a simulated PS
			n = 8: Intact → ACL → sITB → dcITB →ALL →Cap	IR and ER (5nM) at 0°, 30°, 60°, 90°	sITB S restraint at 60° and 90°,dcITB S restraint at 0° and 90°	dcITB restraint at 30°: 26% ± 9% (ACL intact group)/33% ± 12% (ACLd group)	ALL no significant PS restraint	
				simulated PS (4nM IR, 8nM VALG) at 15°, 30°, 45°		ALL no significant IR restraint		
Sonnery-Cottet et al.[24] (2016)	12	92	n = 6: Intact → ACL → ALL transection after ITB longitudinal split → ITB (midporting transection)	IR (2nM) at 20°, 90°		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 30°		ALL S↑ IR 19% (20°)/22% (90°), additional ITB S↑ 42% (20°)/38% (90°)	ALL S↑ 43%, additional ITB S↑ 94%	
						Compared to ACLd knee:	Compared to ACLd knee:	
						ALL S↑ IR 13% (90°), additional ITB S↑ 30% (20°)/28% (90°)	ALL S↑ 43%, additional ITB S↑ 78%	
			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% (20°)/63% (90°), additional ACL S↑ 54% (20°)/75% (90°)	ALL S↑ 60%, additional ACL S↑ 147%	
						Compared to ITB deficient knee:	Compared to ITB deficient knee:	
						ALL S↑ IR 15% (90°), additional ITB S↑ 23% (90°)	Additional ITB S↑ 76%	

(continued)

Table 1. Continued

Authors	n	QS	Dissection Protocol	Tests Performed	ATT Measurements	IR Measurements	PS Measurements	Conclusion
Noyes et al.[25] (2017)	14	85	n = 7: Intact → ACL → ALL (limited incision) → ITB (at Gerdy)	ANT (100N) at 25°, 60°, 90°	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
			n = 7: Intact → ACL → ITB (at Gerdy) → ALL (limited incision)	IR (5 nM) at 25°, 60°, 90°	ITB after ACL: S↑ at 25° and 60° (highest 2.0 mm at 60°)	ITB after ACL: S↑ at all flexion angles (highest 2.5° at 60°)	ITB after ACL: S↑ (1.8 mm/2.0°)	
				Simulated PS (1 nm IR, 7 nM 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↑ (4.4 mm/5.2°)	
				Simulated PS (5 nm IR, 7nM VALG, 100N ANT) at 25°	(Highest 5.4 mm medial and 2.0 mm lateral at 60°)			
Huser et al.[26] (2017)	19	77	n = 10: Intact → ALL (limited incision) → ITB lateral tibial tubercle transection	ANT (100 N) 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 that would likely not be clinically detectable.
			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° simulated PS (5nm 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°)	Both ALL and ITB after intact: S↑ IR 2.0°	

(continued)

Table 1. Continued

Authors	n	QS	Dissection Protocol	Tests Performed	ATT Measurements	IR Measurements	PS Measurements	Conclusion
Lording et al.[27] (2017)	12	77	n = 12: Intact → sITB (release at Gerdy) → dcITB (at tibia distally) → n = 6: ALL	ANT (200N) at 30° IR and ER (5 nM) at 30° VAR and VALG (14nM) 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°		Although the sequential release of the sITB, dcITB, and ALL caused similar pattern changes in the 3 investigated tests, the extent of change because of release of the ALL was markedly less than after release of the dcITB, which was markedly less than after release of the sITB
Geeslin et al.[28,29] (2018)	18	92	n = 9: Intact → ACL → ALL (limited incision) → dcITB[‡]	ANT (88N, 10N AX) at 30°, 90°	ALL after ACL: S↑ (0.3 mm 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. Additionally, the ALL and Kaplan fibers contribute to restraint of the PS and ATT in the ACLd knee.
			n = 9: Intact → ACL → dcITB[‡] → ALL (limited incision)	IR (5 nM, 10N AX) 0° to 90° at 15° increments Simulated PS (5nM IR, 10nM VALG, 10N AX) at 15°, 30°	dcITB after ACL: S↑ (0.2 mm at 30°, 0.9 mm 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°/0.3 mm) and 30° (0.5°/0.6 mm)	

ACL, anterior cruciate ligament; ACLd, ACL deficient; ALL, anterolateral ligament; ANT, anterior translation; ATT, anterior tibial translation; AX, axial compression force; Cap, whole anterolateral capsule; dcITB, deep and capsulo-osseous layer of the ITB; ER, external rotation (directed force); IR, internal rotation (directed force); ITB, iliotibial tract; ITB (at Gerdy), transection of all ITB fibers that insert onto Gerdy tubercle; n, amount of specimens; N, Newton; nM, Newton Meter; NS, non-significant; PS, pivot shift; QS, QUACS scale; S, statistically significant; S↑, significant increase; sITB, superficial ITB; VALG, valgus directed force; VAR, varus directed force.

*Longitudinal cut sITB, resection biceps femoris complex, resection from sITB off dcITB.

[†] Including Kaplan fibers and distal tibial attachment.

[‡] Proximal and distal Kaplan fibers.

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 sITB25 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]

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.[32] 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.[36] In 3 studies, overconstraint of IR torque,[33] IR during pivot shift,[29,37] or

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.[30] (2015)	12	85	Intact↓	Fibertape Swivelock anchors (70°)	Modified Lemaire, staple (70°)		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.[28,29] (2018)	20	92	Intact↓	Semitendinosis (30° or 70°)	Modified Lemaire (30° or 70°) Custom fixation clamp	ATT: 30° and 90°	ATT: 88				
			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	
			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)		

(continued)

Table 2. Continued

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.[31] (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: 70 mm 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°
			ALLR ↓ (randomized) 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°	

(continued)

Table 2. Continued

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.[32] (2017)	12	85	Intact↓	2-strand gracilis autograft inverted V (0° or 30° or 60°)	Modified Lemaire (0° or 30° or 60°)	0° to 90°	ATT: 90				
			ACLd ↓	F: 8 mm prox and 5 mm post to lateral epicondyle (interference screw)	F: 8 mm prox and 5 mm 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 0° fixation angle, Si (↑) at 20° and 50°-70° with 30° fixation angle, at 60°-90° with 60° fixation angle	NSi at al fixation angles
			LET (randomized)					NSi at all fixation angles		Sp (↓), NSi with al fixation angles	NSi at al fixation angles
Jette et al.[33] (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)	
			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)	

(continued)

Table 2. Continued

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
Smith et al.[34] (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°	
			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 et al.[35] (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 1 cm below joint line	interference screw			Sp (↑), Si (↑) (whole range of motion comparison)		Sp (↑), Si (↑) (whole range of motion comparison)	
			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)	

(continued)

Table 2. Continued

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
Neri et al.[36] (2020)	10	77	Intact↓	Free gracilis graft (30°)	All reconstructions (30°)	ATT: 30° and 90°	ATT: 90				
			ACLd↓	F: 5 mm prox and 5 mm 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 1 cm below joint line (interference screw)	Modified Lemaire 5 mm prox and 5 mm post to lateral epicondyle (interference screw)			Sp (↑), Si (↑)		Sp (↑), Si (↑)	
			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	

(continued)

Table 2. Continued

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 et al.[37] (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: 5 mm post to lateral epicondyle	F: 5 mm 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°	
								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 comparted to intact knee state; Sp, statistically significant compared to previous knee state; T, tibial; VALG, valgus directed force.

ATT during pivot shift[29] was found for both an ALLR and modified Lemaire tenodesis.

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 al27 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 the 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.[30] 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 1 overconstraint of IR, torque was found for modified Lemaire, superficial Lemaire, and modified MacIntosh tenodeses.[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 referring to both of these reconstructions as anterolateral corner reconstructions instead of denominating them separately, because 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.

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Appendix

Pubmed search

Filters: 1 January 2010 – 1 October 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

#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

′cadaver′/exp OR cadaver.ti,ab,kw. OR cadaveric.ti,ab,kw.

54,438

#6

′cadaver′/exp OR cadaver.ti,ab,kw. OR cadaveric.ti,ab,kw.

54,438

#5

′cadaver′

67,702

#4

′anterior cruciate ligament′/exp OR acl.ti,ab,kw. OR ′anterior cruciate ligament′

28,834

#3

′anterior cruciate ligament′

28,834

#2

′knee′/exp OR knee.ti,ab,kw

71,082

#1

′knee′/exp OR ′knee′ICMJE author disclosure forms