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Risk analysis of tunnel collision in combined anterior cruciate ligament and anterolateral ligament reconstructions

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ABSTRACT

Background: To assess the risk of tunnel collision in combined anterior cruciate ligament (ACL) and anterolateral ligament (ALL) reconstructions.
Methods: Three-dimensional (3D) CT reconstructions of 32 knees after transtibial (TT) (N = 16) or anteromedial portal (AMP) (N = 16) ACL reconstruction were used to simulate potential tunnel collision of the femoral ACL tunnel if combined with a virtual ALL reconstruction. The minimal distance between tunnels, the ALL tunnel length, and the lateral femoral condyle (LFC) width were measured. Moreover, the relationship between the ALL tunnel and the intercondylar notch, trochlear groove and posterior femoral cortex was determined.
Results: The highest rate of tunnel collision (81%) was observed when the ALL tunnel was aimed at 20° in the coronal plane and 0° in the axial plane. However, by aiming the ALL tunnel at 0° coronal and 40° axial angulation, collision was avoided in all patients and no violation of the trochlea was observed. Tunnel collision rate was significantly higher (P = 0.002) when the ACL tunnel was drilled by the AMP technique.
Conclusions: Risk of tunnel collision was significantly increased when the tunnel was drilled at 0° in the axial plane. Tunnel collision was avoided by aiming the ALL tunnel 40° anteriorly and perpendicular to the anatomical axis of the femur. A more horizontal orientation of the ACL with the AMP technique is a risk factor for tunnel conflicts.
Clinical relevance: ALL tunnel orientation needs to be adjusted to avoid tunnel conflicts in combined ACL–ALL reconstructions.

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1. Introduction

Since a detailed anatomical description of the anterolateral ligament (ALL) was published in 2013 [1], ALL reconstruction (ALLR) has become more popular. Numerous studies have recently confirmed the existence or 'rediscovery' of this structure and its importance in contributing to anterolateral rotatory knee stability [2–8]. In addition, biomechanical and histological studies have demonstrated that this structure displays the characteristics of a true ligament [2,5,9] and plays an important role as a secondary stabilizer to the anterior cruciate ligament (ACL) in resisting anterior and internal tibial rotation and preventing the knee pivot shift phenomenon [10–14]. Based on radiological abnormalities on magnetic resonance imaging (MRI), the prevalence of ALL injuries in patients with an acute ACL rupture is estimated between 33% and 79% [15–17].

Where isolated ACL reconstruction did not restore anterior and internal tibial rotation during a simulated pivot shift in anterolateral and ACL deficient cadaveric knees, several studies have now shown that combined ACL and ALL reconstructions result in significantly reduced tibiofemoral rotational laxity [18–20]. As a consequence, several authors advocate ALLR in revision cases, patients with a high-grade pivot shift, hyperlaxity patients, and those participating in pivoting sports or high-level athletic motor tasks [21–29]. Clinical outcome studies of combined ACL and ALLR show promising results and a reduced failure rate [30,31].

Several surgical techniques for anatomic ALLR have been described in literature, but unfortunately there is still a lack of comparative biomechanical and clinical studies on the different surgical options. Commonly used graft types are gracilis [22,23,25,28], semitendinosus [26], iliotibial band [24] and polyester tape [27]. Biomechanical work has demonstrated that hamstring grafts have a five to eight times higher elastic modulus than the ALL and could therefore theoretically overconstrain the lateral compartment [32,33]. Another point for discussion is the femoral fixation site, although the ALL Expert Group has recently reached a consensus that the attachment should be located proximal and posterior to the lateral epicondyle on the femur [21].

During the last decade, ACL reconstruction (ACLR) has evolved toward an anatomically orientated reconstruction with the femoral socket localized in the center of the footprint [34–36]. With this technique, the femoral tunnel is drilled through an anteromedial portal (AMP) which creates a biomechanical advantage on rotational stability [37–40]. Because of the more horizontal orientation of the femoral ACL tunnel [41], the tunnel comes in closer proximity with the ALL femoral origin, with a potential risk of tunnel collision and potential graft damage [42]. Although the AMP technique for ACLR is gaining popularity, clinical studies have not always demonstrated a superior outcome in comparison with the classic transtibial (TT) femoral drilling technique, and maybe the TT tunnel could therefore regain interest in combined ACL–ALLR [43,44].

The primary purpose of this study was to assess the risk of tunnel collision in combined ACLR and ALLR and define the optimal drilling angle for ALL femoral tunnel placement. We hypothesize that a more anterior direction of the ALL tunnel could reduce the risk of tunnel collision. The secondary purpose was to compare the risk of tunnel conflict in the AMP and TT technique and to provide guidelines to avoid collision with the ALL tunnel for each technique. The hypothesis was that surgeons who drill the femoral ACL tunnel through the AMP have more risk for tunnel collision than those who use the TT technique.

2. Material and methods

2.1. Study population

Thirty-two patients who underwent an ACLR were included in the study. In 16 of them the femoral tunnel was drilled using a TT technique (nine men, seven women, mean 34.3 ± 9.9 years), in the other 16 the AMP technique was used (nine men, seven women, mean 34.4 ± 10.0 years). All patients were randomly selected and ACLR was performed by three orthopedic surgeons. The selection of the technique was based on the surgeon's preference. The study was approved by the Institutional Review Board.

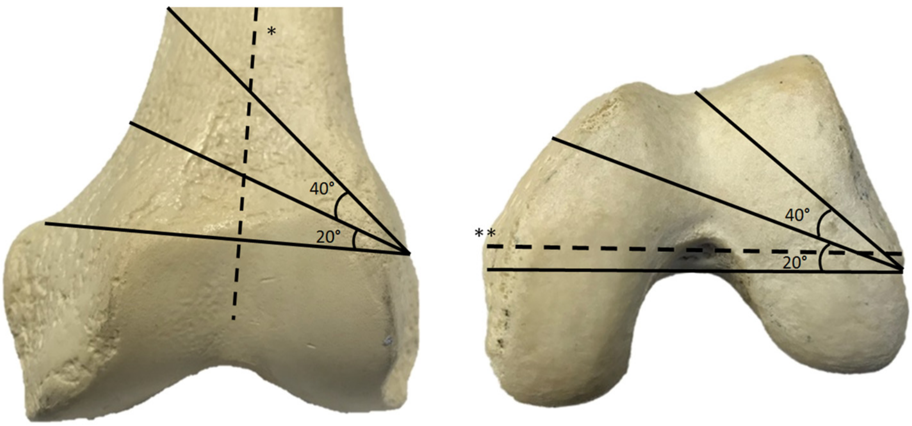

Figure 1. Nine different ALL tunnels were created by aiming the tunnel at 0°, 20° and 40° of coronal and axial angulation.

2.2. 3D computed tomography imaging

The patients received a post-operative Computed Tomography (CT) scan on a Siemens Sensation 64 (slice thickness 0.750 mm; slice increment 0.400 mm; 120 kV; 153 mA). Each CT-scan was processed by a medical image processing program (Mimics 17.0, Materialise, Leuven, Belgium) and three dimensional (3D) reconstructions were made from the femur and ACL-tunnels.

The image processing program 3-Matic (Materialise, Leuven, Belgium) was then used to create the virtual ALL tunnel. The starting point for drilling the ALL tunnel was made proximal and posterior to the lateral epicondyle, as defined by the ALL Expert Group [21]. The neutral tunnel orientation (0°–0°) was made perpendicular to the anatomical axis of the femur in the coronal plane and parallel to the epicondylar axis in the axial plane. In both planes, permutations from the neutral tunnel using 20° intervals were created to obtain nine different ALL tunnel directions with a diameter of 4.5 mm (Figures 1 and 2).

With the image processing software, the ACL and ALL tunnels were examined for tunnel collisions. If no collision occurred, the minimal distance between both tunnels was noticed. When both tunnels interfered, the length of the ALL tunnel was recorded. To evaluate the length of the ALL tunnel as a possible cause of tunnel collision, both 25 mm and 30 mm tunnels were reconstructed on each orientation and investigated for collision (Figure 3). Distances were also measured between the posterior femoral cortex and the ALL tunnel (30 mm tunnels drilled in 0° orientation in the axial plane), between the intercondylar notch and the ALL tunnel (30 mm tunnels drilled in 0°coronal and 0°axial orientation), and the trochlea and the ALL tunnel (30 mm tunnels drilled in 0°coronal/40°axial orientation).

2.3. Statistical analysis

For each femur, different ALL tunnel settings (orientation, length ALL tunnel, and drilling technique) were created and for each setting the outcomes were examined. The outcomes observed for the different settings of the same femur could not be treated as independent observations. Generalized estimating equation (GEE) models with an unstructured working correlation were used to take into account the dependency of observations. For the primary outcome (tunnel collision yes or no) a logit link with a binomial distribution was specified and for the continuous outcomes (length of the ALL tunnel, shortest length between ACL and ALL tunnels) an identity link with a normal distribution was used. Univariate analysis was performed to investigate the effect of tunnel orientation, tunnel length and ACL drilling technique on tunnel collision and tunnel lengths. The effect of orientation and of ALL tunnel length was also investigated conditional on the drilling technique used, so separately for the ACL tunnels drilled through AMP or TT. A five percent level of significance is used and statistical analysis is performed in Statistical Analysis System (SAS) for Windows version 9.4.

3. Results

3.1. Tunnel orientation

The highest rate of tunnel collision (81%) was observed when the ALL tunnel was aimed at 20° from the ALL femoral insertion point to a proximal direction in the coronal plane and 0° in the axial plane. By aiming the ALL tunnel at 0° coronal and 40° axial angulation, collision was avoided in 100% of the patients (Table 1, Figure 4). Tunnel conflict was observed in 10% when aiming the ALL tunnel 40° anteriorly in the axial plane, independent of the coronal orientation, and was significantly lower relative to a 20° anterior angulation (38% conflicts, ($P < 0.001$)) or a 0° anterior angulation (62% conflicts, ($P < 0.001$)).

Figure 2. Medial and frontal view of a patient with an anteromedial portal (AMP) drilled ACL reconstruction and subsequent nine different superimposed ALL tunnel orientations, each with 30 mm tunnel length. Tunnel collision was observed in five of nine combinations.

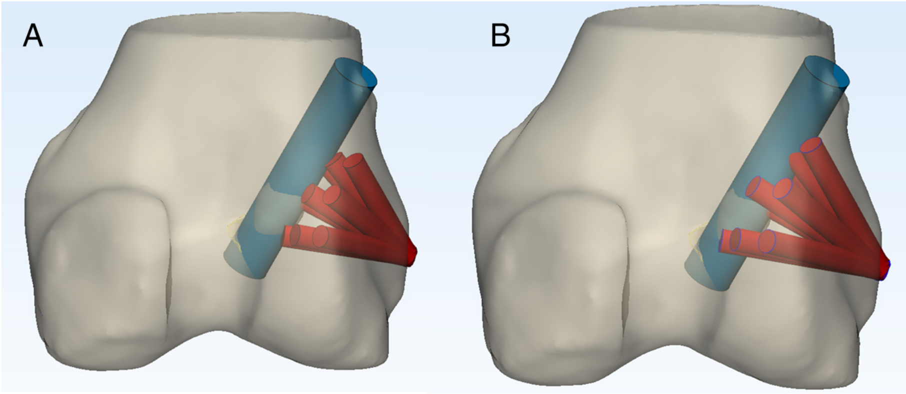

Figure 3. Frontal view of a patient with a transtibial drilled ACL and nine different ALL tunnel orientations with 25 mm (A) and (B) 30 mm tunnel length.

3.2. Tunnel length and ACL drilling technique

Tunnel collision was significantly higher ($P = 0.02$) when the ACL tunnel was drilled by the AMP technique (48% conflicts) in comparison to the TT technique (25% conflicts). When the length of the ALL tunnel was 30 mm, there was a significant higher collision rate relative to a 25 mm length (42% vs 31%, respectively; $P = 0.001$) (Figure 3).

No significant difference in tunnel collision was seen between a 25 mm and 30 mm ALL tunnel length when the ACL tunnel was drilled through the AMP. This was in contrast to the TT technique where a significant difference in collision occurrence was noticed between a 25 mm and 30 mm ALL tunnel (16% vs 35%, respectively; $P < 0.001$).

When collision of both tunnels was observed, the mean length of the ALL tunnel was 18.4 mm in the AMP drilled group. With a TT tunnel however, the mean length of the ALL tunnel was significantly higher with 25.5 mm ($P < 0.0001$).

When no collision between both tunnels was noticed, the mean shortest length between the ACL and ALL tunnel was six millimeters, but significant differences were calculated between the different ALL tunnel orientations ($P < 0.0001$) (Table 2).

3.3. Relation to the trochlea, the intercondylar notch and the posterior femoral cortex

No violation of the trochlea was observed when drilling the ALL tunnel at 0° coronal and 40° axial orientation. Moreover, the mean distance from the end of this 30 mm ALL tunnel (0°–40°) to the trochlear groove was 19.9 mm (range 14.5–27.6 mm).

No intercondylar notch violation was seen with a neutral tunnel orientation (0° coronal and 0° axial angulation) and the mean distance to the intercondylar notch was seven millimeters (range 2.2 mm–13.3 mm).

There was a risk of violating the posterior femoral cortex when ALL tunnels were drilled at 0° in the axial plane (Figure 2). Violation of the cortex was observed in 68.75%, 18.75% and 25% of the patients for the 0°coronal/0°axial, 20°coronal/0°axial and 40° coronal/0°axial ALL tunnel orientation, respectively.

4. Discussion

The primary purpose of this study was to assess the risk of tunnel collision in combined ACLR and ALLR and define the optimal drilling angle for ALL femoral tunnel placement. Our data supports the hypothesis that a more anterior direction of the ALL tunnel reduces the risk of tunnel collision. Independently of the orientation in the coronal plane, aiming the tunnel 40° anteriorly avoids

Table 1
Tunnel collision occurrence between the ALL and ACL tunnel.

	Tunnel conflict (%)				
	Anteromedial portal		Transtibial		Total
	25 mm	30 mm	25 mm	30 mm	
0° coronal/0° axial	63	69	31	75	59
0° coronal/20° axial	6	13	6	6	8
0° coronal/40° axial	0	0	0	0	0
20° coronal/0° axial	94	100	50	81	81
20° coronal/20° axial	63	69	6	44	45
20° coronal/40° axial	13	13	0	0	6
40° coronal/0° axial	56	56	19	50	45
40° coronal/20° axial	81	88	19	50	59
40° coronal/40° axial	38	38	13	6	23
P value	<0.0001	<0.0001	0.0009	<0.0001	<0.0001

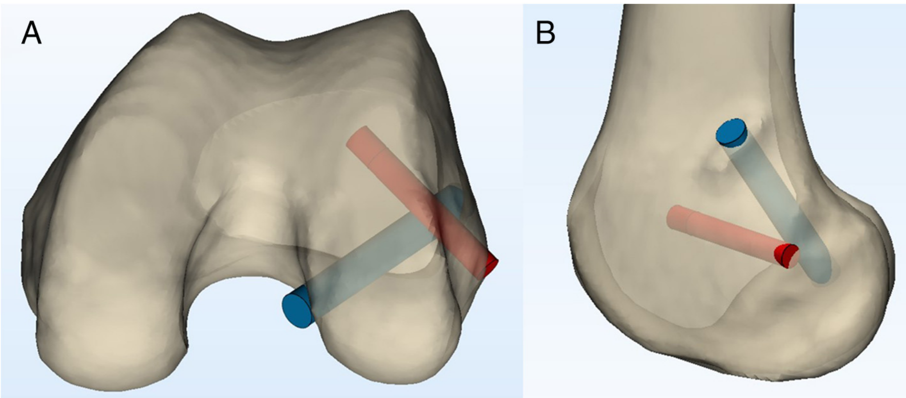

Figure 4. Anteromedial portal drilled ACL and a 30 mm ALL tunnel at 0° coronal and 40° axial orientation. No collision was observed and no violation of the trochlea was noticed.

tunnel conflict in 90% of the patients. Moreover, by aiming the ALL tunnel 40° anteriorly and perpendicular to the anatomical axis of the femur, tunnel collision was avoided in 100% of cases, and therefore this position could be recommended as the safest angle. Drilling the tunnel at 0° in the axial plane, however, significantly increased the risk for convergence and showed potential conflicts with the posterior femoral cortex. Furthermore, the highest risk for tunnel collision (81%) was seen when aiming the ALL tunnel at 20° coronal and 0° axial orientation. Therefore, we do not recommend drilling the ALL tunnel at 0° in the axial plane, regardless of the proximal-distal orientation. Furthermore, aiming the ALL tunnel 40° anteriorly did not result in violating the trochlea. A safe distance of at least 14.5 mm was noticed. Tunnel angulations higher than 40° in the axial plane were avoided because this can result in elliptical tunnels and thinned cortices [45].

The secondary purpose was to compare the risk of creating a tunnel conflict in the AMP and TT technique and to provide guidelines to avoid collision for each technique. The TT technique is widely used but is associated with non-anatomical placement of the femoral tunnel, resulting in vertical graft placement and recurrent rotational instability [34]. Drilling the femoral ACL tunnel through an AMP, however, was found to allow easier and more anatomical placement of the ACL tunnel [46]. It has been shown that this technique creates a more horizontal graft orientation [41] and therefore it comes in closer proximity with the ALL origin. Our second hypothesis was therefore confirmed, meaning that surgeons who drill the femoral ACL tunnel through the AMP have an almost twice as high risk for tunnel collision than those who use the TT technique. Although concerns are made about recurrent instability and graft failure, surgeons who use the transtibial method for femoral ACL tunnel drilling are advantageous to avoid tunnel conflicts in combined ACL and ALL reconstructions.

Another important risk factor for tunnel collision is the ALL tunnel length. Our study however shows that this is largely dependent of the ACL femoral tunnel drilling technique that is used. When a more horizontal ACL graft was created by an AMP technique, the risk for tunnel collision remained almost 50%, both for the 25 mm and 30 mm ALL tunnels. This is in contrast with the TT technique where the risk for collision between the ACL and ALL tunnels was halved using a 25 mm ALL tunnel length.

Femoral socket depth for the ALL tunnel varies among authors between 20 mm and 30 mm [21,22,26,47]. Our data show that – when there was a conflict with the ACL tunnel – the mean length of the ALL tunnel was 18.4 mm (95% Confidence Interval (CI): 16.6–20.1) and 25.5 mm (95% CI: 24.3–26.7), for the AMP and TT techniques respectively. No significant differences were noted between the different drilling orientations. For this reason, reaming a 20 mm long ALL tunnel when femoral ACL tunnel was drilled transtibial can be enough to avoid tunnel collision. In the AMP technique, however, even a 20 mm ALL tunnel is not sufficient to reduce the risk for tunnel collision.

Table 2
ALL tunnel length and minimal distance between ALL and ACL tunnels.

	ALL tunnel length (tunnel collision)		Minimal distance ACL–ALL (no tunnel collision)	
	Anteromedial portal	Transtibial	Anteromedial portal	Transtibial
0° coronal/0° axial	19.6 (17.7–21.5)	25.3 (24–26.6)	0.8 (0.5–1.2)	1.5 (1–2.4)
0° coronal/20° axial	18.9 (16.4–21.4)	26.4 (25.2–27.71)	3.0 (2.0–4.5)	4.1 (2.9–5.8)
0° coronal/40° axial	/		7.8 (4.9–10.8)	12.2 (8.6–17.3)
20° coronal/0° axial	18.1 (16.3–19.8)	24.7 (23.3–26.1)	0.9 (0.3–2.6)	1.9 (1.2–3.2)
20° coronal/20° axial	18.3 (16.2–20.3)	25.8 (24.1–27.4)	1.5 (1–2.4)	2.4 (1.7–3.6)
20° coronal/40° axial	18.5 (16.9–20.2)		3.7 (2.5–5.6)	7.5 (5.3–10.7)
40° coronal/0° axial	17.9 (16.1–19.7)	25.9 (24.4–27.4)	2.3 (1.5–3.6)	3.2 (2.1–4.7)
40° coronal/20° axial	18.2 (16.5–20)	26.3 (24.9–27.8)	0.7 (0.4–1.2)	2.3 (1.6–3.5)
40° coronal/40° axial	18.4 (16.6–20.2)	28 (26.7–29.2)	2.1 (1.4–3.1)	5.3 (3.7–7.6)
P value	0.1265	0.1553	<0.0001	<0.0001

Notes. All data are expressed in millimeters as mean (95% CI).

To our knowledge, no previous data on the risk for tunnel collision in combined ACL and ALL reconstructions exist. Because of the close relation with the origin of the fibular collateral ligament (FCL) comparisons can be made with previous studies investigating the risk of tunnel collisions in combined ACL and FCL reconstructions. Moatshe et al. [48] and Gelber et al. [42] demonstrated that 0° coronal and 30° axial angulation of the FCL tunnel was the most safe combination to avoid conflicts. Shuler et al. [45] recommend a 0° coronal and 40° axial orientation of the FCL tunnel.

Our study has a number of limitations. All ACL reconstructions were performed by three experienced orthopedic surgeons who used the same surgical technique, but variability between them is likely. Femoral socket diameter for the ALL tunnel was 4.5 mm in our study and therefore the number of tunnel conflicts is expected to be higher in ALL reconstruction techniques using a greater tunnel diameter [23,26]. Also our study did not consider any effects of tunnel orientation on fixation strength. Less perpendicular tunnel orientations could in theory be associated with less solid interference screw fixation.

5. Conclusion

ALL tunnel orientation needs careful intra-operative attention in order to avoid tunnel conflicts in combined ACL–ALL reconstructions. Our study shows that risk of tunnel collision is a reality and becomes significantly increased when the ALL tunnel is drilled at 0° in the axial plane. Tunnel collision can be avoided by aiming the ALL tunnel 40° anteriorly and perpendicular to the anatomical axis of the femur. A more horizontal orientation of the ACL as in the AMP technique is an additional risk factor for tunnel conflicts.

Declaration of Competing Interest

Each author certifies that there are no conflicts of interest in connection with the submitted paper.

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Ethical statement

No funding was received.

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;223:321–8.
[2] Smeets K, Slane J, Scheys L, Forsyth R, Claes S, Bellemans J. The anterolateral ligament has similar biomechanical and histologic properties to the inferior glenohumeral ligament. Arthroscopy 2017;33:1028–35 [e1].
[3] Daggett M, Ockuly AC, Cullen M, Busch K, Lutz C, Imbert P, et al. Femoral origin of the anterolateral ligament: an anatomic analysis. Arthroscopy 2016;32:835–41.
[4] Helito CP, do Prado Torres JA, Bonadio MB, Aragao JA, de Oliveira LN, Natalino RJ, et al. Anterolateral ligament of the fetal knee: an anatomic and histological study. Am J Sports Med 2017;45:91–6.
[5] Helito CP, Demange MK, Bonadio MB, Tirico LE, Gobbi RG, Pecora JR, et al. Anatomy and histology of the knee anterolateral ligament. Orthop J Sports Med 2013; 1:2325967113513546.
[6] Stijak L, Bumbasirevic M, Radonjic V, Kadija M, Puskas L, Milovanovic D, et al. Anatomic description of the anterolateral ligament of the knee. Knee Surg Sports Traumatol Arthrosc 2016;24:2083–8.
[7] Sonnery-Cottet B, Saithna A, Helito C, Daggett M, Thaunat M. Regarding “anterolateral ligament of the knee, fact or fiction?”. Arthroscopy 2016;32:1740–1.
[8] Watanabe J, Suzuki D, Mizoguchi S, Yoshida S, Fujimiya M. The anterolateral ligament in a Japanese population: study on prevalence and morphology. J Orthop Sci 2016;21:647–51.
[9] Vincent JP, Magnussen RA, Gezmez F, Uguen A, Jacobi M, Weppe F, et al. The anterolateral ligament of the human knee: an anatomic and histologic study. Knee Surg Sports Traumatol Arthrosc 2012;20:147–52.
[10] Kittl C, El-Daou H, Athwal KK, Gupte CM, Weiler A, Williams A, 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;44:345–54.
[11] Kraeutler MJ, Welton KL, Chahla J, LaPrade RF, McCarty EC. Current concepts of the anterolateral ligament of the knee: anatomy, biomechanics, and reconstruction. Am J Sports Med 2018;46:1235–42: 363546517701920.
[12] Sonnery-Cottet B, Lutz C, Daggett M, Dalmay F, Freychet B, Niglis L, et al. The involvement of the anterolateral ligament in rotational control of the knee. Am J Sports Med 2016;44:1209–14.
[13] Spencer L, Burkhart TA, Tran MN, Rezansoff AJ, Deo S, Caterine S, et al. Biomechanical analysis of simulated clinical testing and reconstruction of the anterolateral ligament of the knee. Am J Sports Med 2015;43:2189–97.
[14] 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 Joint Surg Am 2016;98:937–43.
[15] Helito CP, Helito PVP, Costa HP, Demange MK, Bordalo-Rodrigues M. Assessment of the anterolateral ligament of the knee by magnetic resonance imaging in acute injuries of the anterior cruciate ligament. Arthroscopy 2017;33:140–6.
[16] Claes S, Bartholomeeusen S, Bellemans J. High prevalence of anterolateral ligament abnormalities in magnetic resonance images of anterior cruciate ligament-injured knees. Acta Orthop Belg 2014;80:45–9.
[17] Van Dyck P, Clockaerts S, Vanhoenacker FM, Lambrecht V, Wouters K, De Smet E, et al. Anterolateral ligament abnormalities in patients with acute anterior cruciate ligament rupture are associated with lateral meniscal and osseous injuries. Eur Radiol 2016;26:3383–91.
[18] Nitri M, Rasmussen MT, Williams BT, Moulton SG, Cruz RS, Dornan GJ, et al. An in vitro robotic assessment of the anterolateral ligament, part 2: anterolateral ligament reconstruction combined with anterior cruciate ligament reconstruction. Am J Sports Med 2016;44:593–601.
[19] Schon JM, Moatshe G, Brady AW, Serra Cruz R, Chahla J, Dornan GJ, et al. Anatomic anterolateral ligament reconstruction of the knee leads to overconstraint at any fixation angle. Am J Sports Med 2016;44:2546–56.

[20] Geeslin AG, Moatshe G, Chahla J, Kruckeberg BM, Muckenhirn KJ, Dornan GJ, 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;46:607–16: 363546517745268.
[21] Sonnery-Cottet B, Daggett M, Fayard JM, Ferretti A, Helito CP, Lind M, et al. Anterolateral Ligament Expert Group consensus paper on the management of internal rotation and instability of the anterior cruciate ligament-deficient knee. J Orthop Traumatol 2017;18:91–106.
[22] Smith JO, Yasen SK, Lord B, Wilson AJ. Combined anterolateral ligament and anatomic anterior cruciate ligament reconstruction of the knee. Knee Surg Sports Traumatol Arthrosc 2015;23:3151–6.
[23] Sonnery-Cottet B, Barbosa NC, Tuteja S, Daggett M, Kajetanek C, Thaunat M. Minimally invasive anterolateral ligament reconstruction in the setting of anterior cruciate ligament injury. Arthrosc Tech 2016;5:e211–5.
[24] Kernkamp WA, van de Velde SK, Bakker EW, van Arkel ER. Anterolateral extra-articular soft tissue reconstruction in anterolateral rotatory instability of the knee. Arthrosc Tech 2015;4:e863–7.
[25] Helito CP, Bonadio MB, Gobbi RG, da Mota EARF, Pecora JR, Camanho GL, et al. Combined intra- and extra-articular reconstruction of the anterior cruciate ligament: the reconstruction of the knee anterolateral ligament. Arthrosc Tech 2015;4:e239–44.
[26] Chahla J, Menge TJ, Mitchell JJ, Dean CS, LaPrade RF. Anterolateral ligament reconstruction technique: an anatomic-based approach. Arthrosc Tech 2016;5:e453–7.
[27] Wagih AM, Elguindy AM. Percutaneous reconstruction of the anterolateral ligament of the knee with a polyester tape. Arthrosc Tech 2016;5:e691–7.
[28] Ferreira Mde C, Zidan FF, Miduati FB, Fortuna CC, Mizutani BM, Abdalla RJ. Reconstruction of anterior cruciate ligament and anterolateral ligament using interlinked hamstrings — technical note. Rev Bras Ortop 2016;51:466–70.
[29] Vundelinckx B, Herman B, Getgood A, Litchfield R. Surgical indications and technique for anterior cruciate ligament reconstruction combined with lateral extra-articular tenodesis or anterolateral ligament reconstruction. Clin Sports Med 2017;36:135–53.
[30] Sonnery-Cottet B, Barbosa NC, Vieira TD, Saithna A. Clinical outcomes of extra-articular tenodesis/anterolateral reconstruction in the ACL injured knee. Knee Surg Sports Traumatol Arthrosc 2018;26:596–604.
[31] Sonnery-Cottet B, Saithna A, Cavalier M, Kajetanek C, Temponi EF, Daggett 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;45:1547–57.
[32] Smeets K, Slane J, Scheys L, Claes S, Bellemans J. Mechanical analysis of extra-articular knee ligaments. Part one: native knee ligaments. Knee 2017;24:957–64.
[33] Smeets K, Bellemans J, Scheys L, Eijnde BO, Slane J, Claes S. Mechanical analysis of extra-articular knee ligaments. Part two: tendon grafts used for knee ligament reconstruction. Knee 2017:949–56.
[34] Pearle AD, McAllister D, Howell SM. Rationale for strategic graft placement in anterior cruciate ligament reconstruction: I.D.E.A.L. femoral tunnel position. Am J Orthop (Belle Mead NJ) 2015;44:253–8.
[35] Siebold R. The concept of complete footprint restoration with guidelines for single- and double-bundle ACL reconstruction. Knee Surg Sports Traumatol Arthrosc 2011;19:699–706.
[36] Tibor L, Chan PH, Funahashi TT, Wyatt R, Maletis GB, Inacio MC. Surgical technique trends in primary ACL reconstruction from 2007 to 2014. J Bone Joint Surg Am 2016;98:1079–89.
[37] Loh JC, Fukuda Y, Tsuda E, Steadman RJ, Fu FH, Woo SL. Knee stability and graft function following anterior cruciate ligament reconstruction: comparison between 11 o'clock and 10 o'clock femoral tunnel placement. 2002 Richard O'Connor Award paper. Arthroscopy 2003;19:297–304.
[38] Musahl V, Plakseychuk A, VanScyoc A, Sasaki T, Debski RE, McMahon PJ, et al. Varying femoral tunnels between the anatomical footprint and isometric positions: effect on kinematics of the anterior cruciate ligament-reconstructed knee. Am J Sports Med 2005;33:712–8.
[39] Scopp JM, Jasper LE, Belkoff SM, Moorman 3rd CT. The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. Arthroscopy 2004;20:294–9.
[40] Bedi A, Musahl V, Steuber V, Kendoff D, Choi D, Allen AA, et al. Transtibial versus anteromedial portal reaming in anterior cruciate ligament reconstruction: an anatomic and biomechanical evaluation of surgical technique. Arthroscopy 2011;27:380–90.
[41] Clockaerts S, Van Haver A, Verhaegen J, Vuylsteke K, Leenders T, Lagae KC, et al. Transportal femoral drilling creates more horizontal ACL graft orientation compared to transtibial drilling: a 3D CT imaging study. Knee 2016;23:412–9.
[42] Gelber PE, Erquicia JI, Sosa G, Ferrer G, Abat F, Rodriguez-Baeza A, et al. Femoral tunnel drilling angles for the posterolateral corner in multiligamentary knee reconstructions: computed tomography evaluation in a cadaveric model. Arthroscopy 2013;29:257–65.
[43] Riboh JC, Hasselblad V, Godin JA, Mather 3rd RC. Transtibial versus independent drilling techniques for anterior cruciate ligament reconstruction: a systematic review, meta-analysis, and meta-regression. Am J Sports Med 2013;41:2693–702.
[44] MacDonald P, Kim C, McRae S, Leiter J, Khan R, Whelan D. No clinical differences between anteromedial portal and transtibial technique for femoral tunnel positioning in anterior cruciate ligament reconstruction: a prospective randomized, controlled trial. Knee Surg Sports Traumatol Arthrosc 2018;26:1335–42.
[45] Shuler MS, Jasper LE, Rauh PB, Mulligan ME, Moorman 3rd CT. Tunnel convergence in combined anterior cruciate ligament and posterolateral corner reconstruction. Arthroscopy 2006;22:193–8.
[46] Gelber PE, Erquicia J, Abat F, Torres R, Pelfort X, Rodriguez-Baeza A, et al. Effectiveness of a footprint guide to establish an anatomic femoral tunnel in anterior cruciate ligament reconstruction: computed tomography evaluation in a cadaveric model. Arthroscopy 2011;27:817–24.
[47] Stuyts B, Van den Eeden E, Victor J. A new reconstructive technique of the anterolateral ligament with iliotibial band-strip. Open Orthop J 2017;11:321–6.
[48] Moatshe G, Brady AW, Slette EL, Chahla J, Turnbull TL, Engebretsen L, et al. Multiple ligament reconstruction femoral tunnels: intertunnel relationships and guidelines to avoid convergence. Am J Sports Med 2017;45:563–9.