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PART I

GENERAL INTRODUCTION

GENERAL INTRODUCTION

1. PREFACE

The ‘rediscovery’ of the anterolateral ligament (ALL) provided a potential explanation for the rotational instability patterns witnessed in many anterior cruciate ligament (ACL) deficient knees. Indeed, it was illogical that a centrally located structure like the ACL could sufficiently control tibial rotation relative to the femur.[1] Although, anterolateral structures had been vaguely described with terms like ‘a pearly, resistant, fibrous band’ and ‘mid-third lateral capsular ligament’ , it was not until 2013 that a detailed anatomic description of the ALL was given in a series of cadaveric knees.[2]

Defining the anterolateral structures of the knee has been an objective of anatomist and orthopaedic surgeons for many decades.[3] Paul Segond is frequently referred to as the first to describe the structure which is now deemed to be the ALL. [2,4,5] In 1879, he described a tibial plateau fracture fragment of the anterolateral proximal tibia which is now known as a Segond fracture. Segond described the presence of a ‘pearly, resistant, fibrous band which invariably showed extreme amounts of tension during forced internal rotation of the knee’. [6] In fact before Segond, in 1752, Weitbrecht had referred to ‘fibrous bunches that reinforce the capsule and bands that supplement the fixation of the semicircular cartilages (meniscus). [3] But that is where the trail went cold, for a time.

Next, French anatomists Vallois and Jost explored this area in the early 1900s. [3] In 1914, Vallois described the lateral epicondylomeniscal ligament as a ‘fibrous band that inserts on top of the femoral epicondyle […] taking an oblique course downward and forward, ends on the superior edge of the lateral meniscus’. In 1921, Jost described this ligament as ‘arising from the lateral femoral epicondyle […] Through an oblique anteroinferior course, and after getting slightly wider, it attaches behind the tibial attachment of the anterior horn of the lateral meniscus.'

The anterolateral structures of the knee have been described as being organised into two layers [7], three layers [8] or five layers [9], including the lateral joint capsule and other ligaments. The term 'mid-third lateral capsular ligament' was attributed to the work of Jack Hughston in 1976. [10] He described this ligament as 'technically strong and a major lateral static support around 30° of flexion. [11] Norwood stated in 1980 that an injury to this mid-third lateral capsular ligament is predictive of anterolateral instability. He also described the lateral capsular sign as an avulsion of the lateral capsular ligament. [12] An anatomical description of this ligament was provided by Terry et al. in 1996 with the authors detailing how the lateral tibial attachment of the lateral meniscus is provided by the meniscotibial portion of the mid-third lateral capsular ligament. [13] Subsequently, Haims demonstrated the presence of the mid-third lateral capsular ligament on MRI imaging and described it as a thickening of the lateral joint capsule with attachments to the femoral condyle and lateral tibia. [14] Several other authors assigned different names to this anterolateral structure such as anterior oblique band of the lateral collateral ligament [15], anterior oblique band [16] and the capsulo-osseus layer of the iliotibial band (ITB). [9] The term 'anterolateral ligament' was coined by Vieira et al. (2007), in describing the capsulo-osseus layer of the ITB [17] and was reiterated by Vincent et al. (2012) when the authors noted 'a relatively consistent structure in the lateral knee'.[18]

The complex anatomy of the lateral aspect of the knee has made it difficult to differentiate between various structures such as the iliotibial band, Kaplan's fibres, capsulo-osseus layer and the anterolateral capsule. [3] This has led to confusion and different names for the anterolateral ligament. Stemming from a detailed anatomic description of the ALL, by Claes et al. in 2013 [2], many authors have investigated the function and biomechanics of the ALL, examined the effect of ALL rupture on knee kinematics and explored the effect of ALL reconstruction. However, by contrast several other authors deny the existence of the ALL as a true ligament, with some suggesting that it is merely a capsular thickening, revealed by 'aggressive' dissection. [19]

The first objective of this introduction chapter is to provide information about the treatment of ACL injuries. Both conservative and operative treatment and the existence of rotational instability in ACL-deficient knees will be discussed. The second goal is to provide an overview of the current knowledge about the ALL and to discuss the controversary in the orthopaedic community that this ligament has generated. Finally, the objectives of this thesis will be explained.

2. ACL-DEFICIENT KNEES

1. Conservative vs. Operative Treatment

Isolated rupture of the anterior cruciate ligament (ACL) is a common injury, with an annual incidence as high as 68.6 per 100,000 person-years. [20] It is characterized by joint instability that leads to decreased activity, unsatisfactory knee function and poor knee-related quality of life, in the short-term. [21,22] Furthermore, it is associated with meniscal damage, chondral joint lesions, and eventually knee osteoarthritis (OA). [23] Untreated ACL injury has been shown to increase the risk of subsequent meniscal injury and early OA. [24,25] It is still debated whether a conservative or operative treatment should be advocated as the best treatment choice in the long term for ACL ruptures. [26]

A widely accepted strategy is that ACL reconstructions (ACLR) should be performed in young and active patients with a greater reliance on a functional ACL and conservative treatment should be preserved for less active patients. However, a recent retrospective study after 20-year follow-up in high-level athletes showed no difference in knee osteoarthritis and clinical outcome scores between operative and conservative treatment.[23] Moreover, a Cochrane review of the literature showed no difference between both therapies in patient-reported outcomes of knee function at two and five years after injury.[26] This review included randomized controlled trials (RCT) that compared the use of surgical and conservative treatments in patients with an ACL rupture but could only found one report. This RCT of 121 young active adults with acute ACL tears not only demonstrated that operative treatment (rehabilitation and early ACL reconstruction) was not superior to conservative treatment (rehabilitation and optional delayed ACL reconstruction), but also showed that the conservative treatment option reduced the frequency of surgical reconstructions in more than 50% of cases.[27] Yet, long-term observational studies of early versus delayed ACL reconstruction have shown that delayed surgery is associated with a significantly increased rate of secondary damage to the meniscus and articular cartilage. [28,29]

The ultimate goal of both treatment strategies is to restore knee function, to provide a stable knee and to minimise the development of OA. It has been reported that patients with an ACL tear will develop OA irrespective of therapy. [24] A recent retrospective pair-matched study with 20 years follow-up showed no difference in the development of OA between operative versus conservative treatment. [23] However, a systematic review and meta-analysis demonstrated that non-operatively treated ACL injuries had a significantly higher relative risk of developing any grade of osteoarthritis compared with those treated with reconstructive surgery. [30]

Meniscal tears or meniscectomy are associated with an increased risk of developing OA. [23,24] Some studies have reported a protective function of the ACL reconstructed knee on further meniscal lesions, [31,32] whilst others do not support that finding. [23] A meta-analysis of studies with a minimum follow-up of 10 years showed that 50% of patients with a meniscectomy after ACL reconstructions had OA, compared with 16% of patients without meniscectomy. [25]

Many articles on the treatment strategy of ACL injuries are published with somehow conflicting outcomes. The highest level of evidence in literature could be found in the previously mentioned RCT[27] where both treatment strategies showed no significant differences in outcomes scores. Both rehabilitation and surgery are important treatment options in ACL-deficient knees, and probably cannot be separated from each other. Some patients only need a structured rehabilitation program, whilst others will benefit from an operative treatment. It has to be the goal of future research projects to define which treatment strategy is best for a specific patient.

2. *Rotational Instability*

Single-bundle ACL reconstructions can adequately restore anteroposterior stability. [1,23] However, residual rotational instability has been reported to persist in 11% to 60% of patients. [33-35] This rotational instability is one of the reasons that normal knee kinematics after ACL reconstruction (ACLR) are not restored and is associated with recurrent ACL injuries.[36] The cause is often multifactorial:

meniscal damage, ITB lesions, anterolateral capsule and posterolateral injuries and increased tibial slope are described as potential contributing factors. [37-39] The pivot shift test attempts to reproduce the functional combined rotatory and translational instability in ACL deficient knees [40] and is therefore often used to observe rotational instability patterns.[39,41] Although the kinematics of the pivot shift phenomenon are difficult to measure, it is assumed that the predominant pathologic motion of the pivot shift phenomenon is coupled anterior tibial translation and internal rotation. [40]

Musahl et al. described anterior translation of the lateral compartment during the pivot shift by 6mm after a complete lateral meniscectomy. [42] The authors concluded that the lateral meniscus is a secondary stabilizer for rotational stability in the ACL-deficient knee. Shybut et al. concluded that a tear of the lateral meniscal posterior root further reduces the stability of the ACL-deficient knee during rotational loading.[43] Several cadaveric studies also suggest that damage to the ITB plays a role in the development of rotational instability. Sectioning the ITB produced a high-grade pivot shift in an ACL-deficient knee. [44-47] Though, it was not always clear if the anterolateral capsule had been cut when conducting those studies. Moreover, distal ITB injuries are rarely seen in ACL injuries. However, injuries to the anterolateral capsule have been described as a secondary injury in the setting of ACL-deficiency.[14,48,49] Monaco et al. found that sectioning the 'lateral capsular ligament' increased rotational laxity and pivot shift, and suggested that anterolateral capsular injuries may be a secondary injury to ACL-deficient knees causing an increase in the pivot-shift phenomenon. [50]

Collating current knowledge, it is likely that anterolateral capsular injuries involve damage to the ALL, and that this compromise of the ALL may be a significant factor in the development of rotatory knee instability patterns, as witnessed in many ACL-deficient knees. Recent studies have shown that the ALL functions as a secondary stabilizer to the ACL in resisting anterior tibial translation and internal rotation. [4,51-54] And yet, there is no consensus as to whether the ALL truly exists or not and what function it serves with some authors disputing its presence and significance. [19,51,55,56] However, it would be logical to assume that a structure located on the outside of the knee would have a greater lever arm to control excessive tibial rotation. Indeed, the pivot-shift phenomenon is a coupled anterior translation and internal rotation moment and a structure located on the anterolateral side of the knee should theoretically be ideally situated to withstand this force. [1] A recent biomechanical sectioning study reported the potential role of the Kaplan fibers in controlling rotational knee laxity. [57] Both ALL and distal iliotibial band Kaplan fibers restrained anterior tibial translation, internal rotation and pivot-shift in the ACL-deficient knee.

The native ACL is composed of two bundles: the anteromedial bundle that limits antero-posterior tibial translation and the posterolateral bundle that controls tibial rotation. [58-61] Traditional single-bundle ACL reconstructions often resulted in more vertical graft placement and more closely resembled the anteromedial bundle. [62,63] In an attempt to improve rotational instability after ACL reconstruction, double-bundle techniques were developed. [64,65] Despite biomechanical studies demonstrating greater rotational control [63], the clinical benefit of this technically challenging technique has not been demonstrated. [66]

Several authors, however, advocate the use of a lateral extra-articular tenodesis (LET) as an augment to intra-articular ACLR, to address the rotatory instability. [67-69] Historically, ACL deficiency was treated with such LET procedures, as described by McIntosh and others. [70] They were effective in limiting rotational instability, but anterior laxity was only moderately controlled. [71] Indeed, failure of the extra-articular reconstruction and recurrent instability have been reported. [72] Degenerative changes in the lateral tibiofemoral compartment were attributed to overtightening of the graft or to post-operative cast immobilization.[73] Therefore, isolated extra-articular tenodesis procedures were no longer recommended and were displaced by the intra-articular reconstruction techniques which is now the gold standard.

Systematic reviews have demonstrated that combining ACLR with LET procedures decreases the prevalence of residual pivot shift – and so antero-lateral rotatory instability – as compared with isolated ACLR. [36,74,75] Intra-articular ACLRs are now frequently combined with modified LET procedures and show good to excellent results in 80% to 90% of patients [67,70,76-79]. It has been demonstrated that these procedures are safe and efficient in controlling anteroposterior and rotatory instability. [67,68,70,74,75] However, clinical superiority has not been definitively demonstrated. In their meta-analysis, Rezende et al. showed no difference in patient-reported functional outcomes scores. [36] However, the surgical indications for the additional LET procedure varied amongst studies. A systematic review by Song et al. showed a significant reduction in the prevalence of residual pivot shift compared to isolated ACLR at short-term follow-up, but no differences were noticed in objective IKDC scores and anterior knee stability. [74] Longer-term comparative studies are necessary to determine the potential benefits and surgical indication for a LET procedure. Nevertheless, a protective effect of lateral augmentation to ACLR has been noted. Engebretsen et al. showed that a lateral extra-articular augmentation reduces the force on the ACL graft by up to 43%.[80] It has been demonstrated that adding a LET to ACLR significantly improved restraint of internal tibial rotation. [81,82] Combined ACLR and LET procedures were able to reduce anterior tibial translation and internal tibial rotation in response to different physical examinations but the authors warned that a LET should only be added if there was a combined injury of the ACL and anterolateral complex, otherwise there was a risk of over-constraining the knee joint. [83]

Concerns have existed about overtightening the lateral compartment with an extra-articular reconstruction and the potential risk of late osteoarthritis. [38] Biomechanical studies showed that adding a LET alters knee kinematics and could therefore potentially overconstrain the lateral tibiofemoral joint. [84,85] Studies with longer follow-up, with combined ACLR and LET procedures, have demonstrated good outcome, but with degenerative changes as a downside. [69,86,87] Those results might be explained by a combination of non-anatomic ACL reconstruction, an empirical extra-articular lateral tenodesis, and a post-operative protocol involving immobilization of the knee and a slow rehabilitation program. [78]

3. ANTEROLATERAL LIGAMENT

1. *Anatomy*

Debate exists about the presence and prevalence of the ALL. It remains difficult to anatomically define the anterolateral structures of the knee and, as mentioned in the preface of this introduction, several authors described similar structures with different names. A first clear anatomical description of the ALL was given in 2013.[2] This landmark cadaveric study found the ALL in 97% of cases. The origin was located at the prominence of the lateral femoral condyle and the insertion on the tibia was situated midway between Gerdy's tubercle and the tip of the fibular head. Subsequently, additional anatomic studies confirmed the existence of the ALL with an incidence of between 50% and 100%. [88-92] Helito et al. not only dissected fresh-frozen human cadaveric knees but also studied the incidence in human fetuses and found the ALL in 100% of cases. [88,93] Some anatomic studies described the ALL as having an anterior and distal origin to the lateral epicondyle, [88] whereas others describe a more proximal and posterior origin. [89,94,95] A possible explanation for the anatomic variations outlined in various studies is the difficulty of dissection with cadavers preserved using formalin. [96,97] Another explanation may be the different dissection techniques that are employed. The dissection protocol used by Daggett has been put forward as worthy of emulation and involves dissection in a distal to proximal direction to avoid damage to the ALL fibers located over the lateral collateral ligament (LCL), thereby allowing visualization of the superficial structures. [95,96]

The differences in the anatomical descriptions amongst the studies has led to confusion and difficulty in achieving an anatomic reconstruction of these structures. [78] Therefore, an ALL Expert Group was created and according to their consensus paper, the ALL is considered a distinct ligament at the anterolateral side of the human knee. The femoral attachment is posterior and proximal to the lateral epicondyle and the tibial attachment lies between Gerdy's tubercle and the fibular head. [98] The ligament is not isometric and has a mean length, at full extension, of 33 mm to 37.9 mm, a mean width of 7.4 mm, a mean thickness of 2.7 mm and a mean cross-sectional area of 1.54 mm². [4,88,99-102] The length of the ligament increases with knee flexion and internal tibial rotation. [100,102,103] It has been demonstrated that the ALL has firm attachments to the lateral meniscus between his anterior horn and meniscal body, with a mean attachment length of 5.6mm. [4,98]

Anatomical studies have been conducted by others who question the ALLs existence. [19] They argue that an ALL was not found while performing anatomic dissections on 24 different animal species. [55] Additionally, they were unable to dissect a distinct ligamentous structure (ALL) in the anterolateral complex of several human fetuses, while all other anatomic structures were present. [104] The same group found in only 30% of adult human cadaveric specimens a discrete capsular thickening on the anterolateral side, which they postulated was a fold in the capsule as opposed to a distinct ligamentous structure. [19]

2. *Histology*

Histologically, longitudinal sections of the ALL have shown parallel, wavy, collagenous fibers, suggestive of ligamentous or tendinous tissue. [18] Another histological analysis of 10 specimens revealed well-organized, dense connective tissue, uniformally oriented fibers and little cellular material. [88] It was concluded that this structure represented the microstructure of a ligament. Caterine et al. found the morphology of the ALL to be characteristic of ligamentous tissue and described peripheral nerve innervation of the tissue. Moreover, multiple mechanoreceptors were identified which they speculated could be indicative of a proprioceptive role. [90] Mechanoreceptors are neural elements that receive sensory input and mediate a response that regulates muscle tone and coordination. [105]

3. *Imaging*

Several imaging studies have confirmed the presence of the ALL, in both injured and uninjured knees. [11] The prevalence of the ALL on MRI studies varies between 40% and 100%. [90,92,106-110] With knee dissection following MR imaging, Helito et al. found an excellent correlation between the anatomic and radiographic parameters of the ALL. [111] Connections between the ALL and lateral meniscus were also demonstrated via radiological imaging, and have been reported with complete, central, bipolar, or inferior-only connection patterns. [92] In contrast, Flores et al. analyzed 146 MRI scans of patients with a Segond fracture but were unable to localize the ALL as an attachment to this fracture fragment. However, they described structures that were defined as the 'meniscotibial component of the mid-third capsular ligament' and 'posterior fibers of the ITB'. [112] Another study demonstrated that ruptures of the ALL are not specifically associated with bony avulsions of the lateral tibial plateau (Segond fractures) and four different lesion types were identified. [113] Finally, the ALL has also been identified with ultrasonography imaging.[114,115] Cavaignac et al. showed a good correlation with the anatomic findings obtained during subsequent anatomic dissection. [114]

4. *Biomechanics*

Studies investigating the structural properties of the ALL have demonstrated an ultimate load to failure between 50N and 205N and a mean ultimate strain of 36%. [94,101,116] Recent biomechanical studies have shown that the ALL functions as a secondary stabilizer to the ACL in resisting anterior tibial translation and internal rotation and in preventing the pivot-shift phenomenon. [4,51-54,117] Sectioning the ALL in ACL-deficient knees resulted in a significant increase in anteroposterior translation and internal rotation. [52,117-120] It has also been demonstrated that with increasing flexion angles and internal tibial rotation, the length of the ALL increased, implicating that this structure may contribute to anterior and rotational stability. [89]

This function of the ALL is questioned by other biomechanical studies. Some authors suggest that the ITB is the primary restraint during the pivot-shift and that the ALL makes only a small contribution. [51] Another biomechanical study, using a robotic testing system, demoted the contribution of the 'anterolateral capsule' during a simulated pivot shift test, suggesting that it does not function as a traditional ligament but as a sheet of tissue.[121] In contrast, Noyes et al. showed that both ALL and ITB function together as anterolateral secondary restraints. [122]

Although most studies argued the ALL as a restraint to internal rotation, there is no uniformity between the authors. The biomechanical experiments are laboratory cadaveric studies and are strongly dependent of the dissection technique and the testing method that is used. However, they do agree on the importance of the anterolateral structures in preventing the pivot shift phenomenon, whether they call it the ALL, Kaplan fibers, ITB or anterolateral complex.

5. *Reconstruction*

The indications for combining an ACLR with a LET procedure have been widely investigated.[5,37,70,74] It has been shown that there was an unintentional bias toward choosing a combined procedure for patients with more severe instability.[123] However, the description of the anterolateral ligament and its role in controlling rotatory instability has led to the development of new ALL reconstruction techniques with the ALLR indications varying amongst authors.[4,37] Most authors agree that an ALLR should be considered in revision cases and in those patients with a high-grade pivot-shift.[124-130] The subjective grading of the pivot shift as well as the differences in examination techniques may complicate the assessment of this maneuver. [39,40] More accurate and objective descriptions of the pivot shift are necessary to better quantify this method and to determine his predictive role in the functional outcome of the patient. The advice of the ALL Expert Group as to when a combined ACL and ALL reconstruction should be considered focuses on patients who present with at least one major or two minor criteria.[98] Major criteria include ACL revision, a high-grade pivot-shift (2 or 3), a Segond fracture, hyperlaxity, pivoting sports and high level athletes. Minor criteria are contralateral ACL rupture, a difference greater than 7 mm in AP laxity compared to the contralateral knee, a deep lateral femoral notch sign and age less than 25 years.

Few studies with biomechanical evaluation of combined ACL and ALLR were identified and those that were had conflicting results .[53,84,120,131,132] Noyes et al. detected an increase in internal rotation after sectioning the ALL/ITB after an ACLR. [132] When an ALLR was performed, he noticed a significant reduction in internal rotation. Similar findings were observed by Nitri et al. and Schon et al., with a reduction in internal rotation noticed after a combined ACLR and ALLR.[84,131] Whereas an ALLR was able to eliminate the residual rotational laxity, concerns exists regarding overconstraint the lateral compartment. Those concerns arose from the degenerative changes seen in isolated LET and were largely attributed to overtightening of the graft.[73] However, this has not yet been proven for ALLR in both clinical practice and literature. Conversely, Tavlo et al reported no difference having sectioned the ALL after an ALLR and reported no significant difference between the ALLR and the ALL-deficient knee. [120] Spencer et al. performed an ALLR in an ALL-deficient knee and did not observe a significant difference in pivot-shift.[53] A potential explanation for the variability observed in those biomechanical studies might be attributable to differences in ACLR and ALLR techniques. [37]

A renewed interest in the ALL has led to the development of several new surgical techniques in an attempt to mimic the function of the ALL, as a constraint against internal tibial rotation and to protect the ACL reconstruction. However, technical inconsistencies have been noted and no consensus exist yet as regards graft choice and fixation method.[77] Most studies used a femoral graft fixation position posterior and proximal to the femoral attachment of the LCL,[124,125,129] whereas others used an attachment point anterior and distal to the lateral epicondyle. [130] Grafts that are too taut may result in overconstraint of the knee and elastic grafts can result in residual joint laxity. Therefore, graft choice is important and commonly used grafts are gracilis [125,126,128,129], semitendinosus [124], iliotibial band [127] and polyester tape [130].

Clinical results are important to address the biomechanical controversy that exists about the ALL. Given that ALLR techniques are relatively new, no long-term clinical studies exist. However, two outcome studies do show a significantly reduced ACL failure rate and good clinical results at 2-year follow-up with combined ACL and ALL reconstructions.[78,133] One study by Sonnery-Cottet et al.

was a retrospective study of 92 patients after combined ACLR and ALLR with a minimum follow-up of 2 years.[78] Subjective and objective IKDC score and Lysholm score were significantly improved compared with preoperative assessment and they concluded that this procedure was effective and without specific complications. The second study was a prospective comparative study of 502 patients undergoing ACLR with bone-patellar tendon-bone (BPTB) graft, quadruple hamstring (4HT) tendon graft, or hamstring tendon graft combined with an ALLR.[133] The graft failure rate following the combined procedure was 2.5 times less than the BPTB grafts and 3.1 times less than the 4HT grafts. However, no significant differences were found between the groups with regard to subjective clinical outcome scores.

4. OBJECTIVES

The objectives of this thesis were to:

1. Confirm the existence of the anterolateral ligament (ALL)

Despite the fact that several authors have described the ALL as an anatomical, radiographical and/or functionally distinct ligamentous structure,[2,4,11,18] there is still disagreement within the orthopaedic community, with some suggesting that the ALL is merely a thickening of the knee capsule. [19,121,134]

The hypothesis is that the ALL is a real, well-defined structure that can be clearly distinguished from the knee capsule. By investigating the biomechanical and histological properties of the ALL and the knee capsule, we are looking for differences between those structures.

2. Explore how the ALL is related to other ligaments

Biomechanical sectioning studies on cadaveric knees have shown that the ALL functions as a secondary stabilizer to the ACL in resisting anterior tibial translation and internal tibial rotation and in preventing the knee pivot-shift phenomenon.[4] In contrast, some authors stated that the ALL behaves like a sheet of fibrous tissue.[121] Research is needed to compare the mechanical properties of the ALL with other knee ligaments as knowledge of their mechanical properties is key to elucidating upon their in vivo behavior and function.[135]

The hypothesis is that the ALL possesses comparable mechanical properties to other extra-articular knee ligaments.

3. Investigate how the anterolateral ligament is best reconstructed

The ideal graft has material properties that mimic those of the original ligament. However, despite many graft options being described, the gold standard for use in ALL reconstruction has yet to be established.[4] Excessively taut grafts can result in overconstraining the lateral compartment in ALL reconstruction and are already a concern mentioned in previous biomechanical studies.[84,131] Therefore, the goal is to provide information about the material properties of grafts commonly used for knee ligament reconstructions and to compare those results with the material properties of the native ALL ligament.

The hypothesis is that those grafts present different mechanical characteristics and are different from the anterolateral ligament.

4. Investigate potential complications of ALL reconstruction

The current trend in ACL reconstruction is to position the femoral tunnel anatomically and so cover the native ACL footprint sufficiently. This implies that the femoral ACL tunnel runs more obliquely and is in closer proximity to the ALL origin. As a consequence, there is theoretically a greater risk of chance of interfering with the ALLR.

The hypothesis is that there is a high risk of tunnel convergence between the femoral ACL tunnel and the ALL tunnel. The risk of tunnel collision will be assessed by cadaveric and 3D computer simulated studies. If the hypothesis is confirmed, the authors shall aim to define techniques to avoid this complication.

PART II

THE EXISTENCE AND BIOMECHANICS OF THE ANTEROLATERAL LIGAMENT

CHAPTER 1

The anterolateral ligament has similar biomechanical and histological properties as the inferior glenohumeral ligament

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Arthroscopy

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ABSTRACT

Purpose

To characterize the tensile and histological properties of the anterolateral ligament (ALL), inferior glenohumeral ligament (IGHL), and knee capsule.

Methods

Standardized samples of the ALL (N = 19), the anterolateral knee capsule (N = 15), and IGHL (N =13) were isolated from fresh-frozen human cadavers for uniaxial tensile testing to failure. An additional 6 samples of the ALL, capsule and IGHL were procured for histological analysis and elastin content.

Results

All investigated mechanical properties were significantly greater for both the ALL and IGHL when compared to capsular tissue. In contrast, no significant differences were found for any property between the ALL and IGHL. The elastic modulus of ALL and IGHL samples was 174±92 MPa and 139±60 MPa, respectively, compared to 62±30 MPa for capsule ($P = 0.001$). Ultimate stress was significantly lower ($P < 0.001$) for capsule at 13.4±7.7 MPa relative to the ALL and IGHL at 46.4±20.1 MPa and 38.7±16.3 MPa. The ultimate strain at failure for the ALL was 37.8±7.9 % and 39.5±9.4 % for the IGHL, which was significantly greater ($P = 0.041$ and $P = 0.02$, respectively) for both relative to the capsule at 32.6±8.4%. The strain energy density of the ALL was 7.8±3.1 MPa, 2.1±1.3 MPa for the capsule, and 7.1±3.1 MPa for the IGHL ($P < 0.001$). The ALL and IGHL consisted of parallely aligned collagen bundles, containing elastin bundles, which was in contrast to the random collagen architecture noted in capsule samples.

Conclusion

The anterolateral ligament has similar tensile and histological properties as the inferior glenohumeral ligament. The tensile properties of the ALL are significantly greater than those observed in knee capsule.

Clinical Relevance

The anterolateral ligament is not just a thickening of capsular tissue and should be considered as a distinct ligamentous structure comparable to the IGHL in the shoulder. The tensile behavior of the ALL is similar to the IGHL and treatment strategies should take this into account.

INTRODUCTION

Subluxation of the anterior cruciate ligament (ACL) deficient knee was described as early as 1845 by Bonnet, but it was not until 1919 when Hey Groves first specified anterolateral instability; a phenomenon later to become known as the pivot shift.[136] Despite the use of state-of-the-art intra-articular ACL reconstruction techniques, a remaining pivot shift has been reported to persist in 11-60% of patients.[33-35] Therefore, several authors have favoured an ACL reconstruction combined with an extra-articular augmentation in an attempt to limit persistent rotational laxity after ACL treatment.[68,137-139]

Recent studies showed that the anterolateral ligament (ALL) is a distinct ligament in the human knee[2,90], playing an important role as stabilizer for internal rotation[53,117,120,140] and whereby ALL reconstruction can therefore help control anterolateral instability.[131] The inferior glenohumeral ligament (IGHL) is an anatomically, histologically, and biomechanically well described ligamentous structure, and unlike the ALL, it is not perceived as just a thickening of the shoulder capsule but is widely accepted as an important static restraint.[141,142] Given their microscopic appearance and presumed function in restraining motion of the knee and shoulder, it can be hypothesized that the ALL and IGHL are comparable structures with similar roles as internal stabilizers.

Ligaments are essential structures for stabilizing joints. Knowledge of ligament mechanical properties is therefore key to elucidating their *in vivo* behavior and function and for selecting appropriate grafting materials used in reconstruction techniques. Recently, several review articles have discussed the lack of knowledge on the biomechanical properties of the knee's anterolateral components[143] while highlighting the need for further research.[92] One study performed tensile testing of the isolated ALL[101] while other studies have characterized the pull-to-failure strength and stiffness of the bone-ALL-bone complex, however these tests only characterize the structural properties of the bone-ligament-bone complex, not the intrinsic mechanical properties.[94,144] Notwithstanding the lack of information regarding the mechanical properties, the renewed interest in the ALL has led to the development of anatomic reconstruction techniques.[53,78,126,128] Generally, these techniques utilize the gracilis tendon or a portion of iliotibial band as a graft material with a fixed femoral and tibial screw or anchor fixation.

Despite the fact that several authors have described the ALL as an anatomical, radiographical, histological and/or functionally distinct ligamentous structure,[2,18,94,106,145] there is still disagreement within the orthopaedics community, with some suggesting that the ALL is merely a thickening of the knee capsule.[19,146] Therefore, the purpose of this study is tocharacterize the tensile and histological properties of the ALL, IGHL, and knee capsule. It was hypothesized that the mechanical properties of the ALL would be significantly different from the capsule, while being comparable to the IGHL.

METHODS

Twelve fresh-frozen full body cadavers were obtained (74±7 years, 10 male and 2 female) under ethical approval from our Institutional Review Board. All donors had no history of knee/shoulder injury, instability, or prior surgical intervention. Additionally, 3 knees were excluded because of grade III and IV arthrosis or ACL deficiency. Eight shoulder specimens were reserved for other cadaveric studies and therefore could not be utilized in this work. A total of 21 ALL, 21 capsule, and 16 IGHL samples were dissected from the specimens by a final year orthopaedic resident (KS) using previously described techniques.[2,147] Furthermore, the capsule specimens were dissected from the area immediately adjacent and anterior to the ALL (Fig. 1). Isolated specimens were wrapped in saline-soaked gauze and stored at -80°C until needed.

Mechanical Testing

One day prior to testing, specimens were removed from the freezer and thawed at room temperature. Using a surgical scalpel, specimens were cut into standardized shaped samples (dog-bone). Specimens were secured to custom tensile grips with cyanoacrylate adhesive and aligned axially (fibers parallel to loading direction) within a materials testing frame (model 4467, Instron, Norwood MA, USA) equipped with a 1 kN load cell (Fig. 2). A 1 N pre-load was applied and measurements of the cross-sectional area (assuming rectangular geometry) were taken with a calibrated micrometer five times and the average calculated. The distance between the grip faces was measured and taken as the original gage length. Specimens were pre-conditioned using a series of 10 cycles from 1 to 10 N at a strain rate of 0.1%s^{-1}, immediately followed by a test-to-failure using a strain rate of 2%s^{-1}. Tests were performed at room temperature (~22 °C) and samples times to prevent dehydration.

Histological Analysis

An additional 6 ALL, capsule, and IGHL specimens were procured from four cadavers to be used for qualitative histological analysis. Dissected specimens were fixed in 10% buffered formol and embedded in paraffin wax in a longitudinal orientation. An automated system (Symphony, Ventana, Tucson AZ, USA) was used to perform section staining with hematoxylin & eosin (H&E). Additionally, extra slides were prepared for histochemical analysis: trichrome (structural collagen and fibrin) and Von Gieson (elastin). All processed slides were digitally scanned (iScan HT, Ventana) and analysed with specialized software (Virtuoso, Ventana).

Statistical Analysis

Only those specimens that showed mid-substance failure were used for analysis. In total, data from 19 ALL, 15 capsule and 13 IGHL samples could be analyzed. The obtained force and displacement data were converted to stress (force / cross sectional area) and strain (change in length / original length) to allow the calculation of the tissue mechanical properties[135] (Fig. 3): elastic modulus (slope of the linear portion of the stress-strain curve), ultimate stress, ultimate strain, and strain energy density (area under the stress-strain curve, e.g. energy absorbed to failure). The collected mechanical data were found to exhibit non-normal distributions (with the Shapiro-Wilk test) and therefore Kruskal-Wallis tests with pairwise Mann-Whitney U post hoc tests were used. For all statistical analysis, commercial software was used (SPSS 23, IBM, Armonk, NY, USA) and significance level was set to $\alpha = 0.05$. All data are presented as mean ± standard deviation.

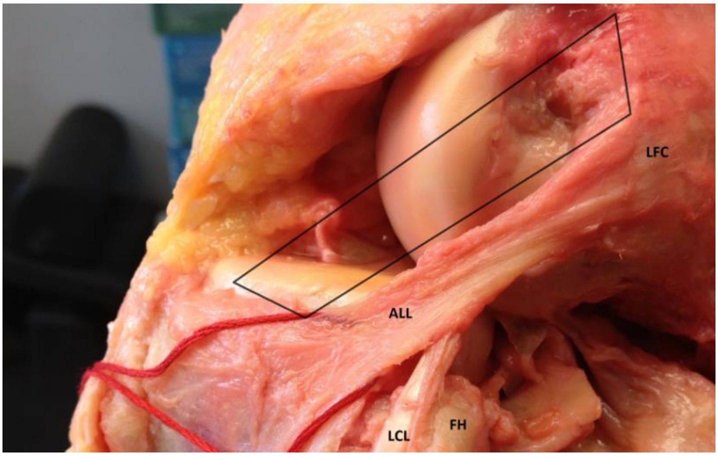

Figure 1: Knee capsule specimens were dissected from the area immediately adjacent and anterior to the ALL, as shown by the bounding box. LFC – lateral femoral condyle, LCL – lateral collateral ligament, FH – fibular head, ALL – anterolateral ligament.

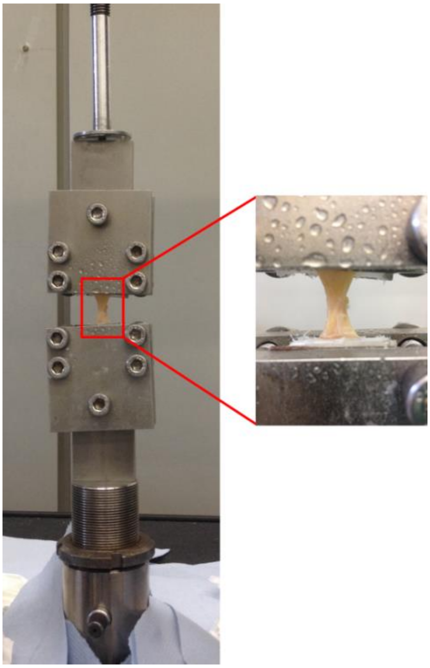

Figure 2: The clamping system used to perform tensile testing of the tissue specimens. Samples were kept hydrated at all times during testing with saline.

RESULTS

Mechanical Testing

The average stress-strain curve obtained for the ALL, capsule, and IGHL specimens is shown in Figure 4. For all curves, specimens were characterized by an initial non-linear toe region followed by a linear stress-strain region and eventual specimen rupture.

All calculated mechanical properties were significantly higher for both the ALL and IGHL compared to the capsule (Fig. 5; see appendix for all tabulated values). In contrast, no significant differences were found for any property between the ALL and IGHL. The elastic modulus of ALL and IGHL samples was 174±92 MPa and 139±60 MPa, respectively, compared to 62±30 MPa for the capsule ($P < 0.001$). Ultimate stress was significantly lower ($P < 0.001$) for the capsule at 13.4±7.7 MPa relative to the ALL and IGHL at 46.4±20.1 MPa and 38.7±16.3 MPa. The ultimate strain at failure for the ALL was 37.8±7.9 % and 39.5±9.4 % for the IGHL, which was significantly greater ($P = 0.041$ and $P = 0.02$, respectively) for both relative to the capsule at 32.6±8.4%. The strain energy density of the ALL was 7.8±3.1 MPa 2.1±1.3 MPa for the capsule, and 7.1±3.1 MPa for the IGHL ($P < 0.001$).

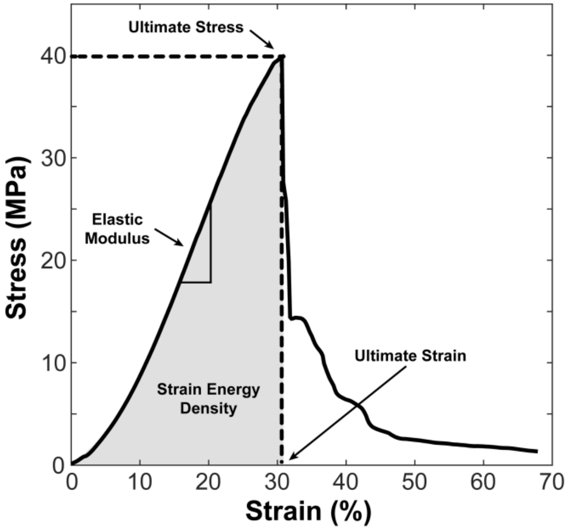

Figure 3: Representative stress-strain curve obtained from tensile testing of the anterolateral ligament showing the derivation of the calculated mechanical properties.

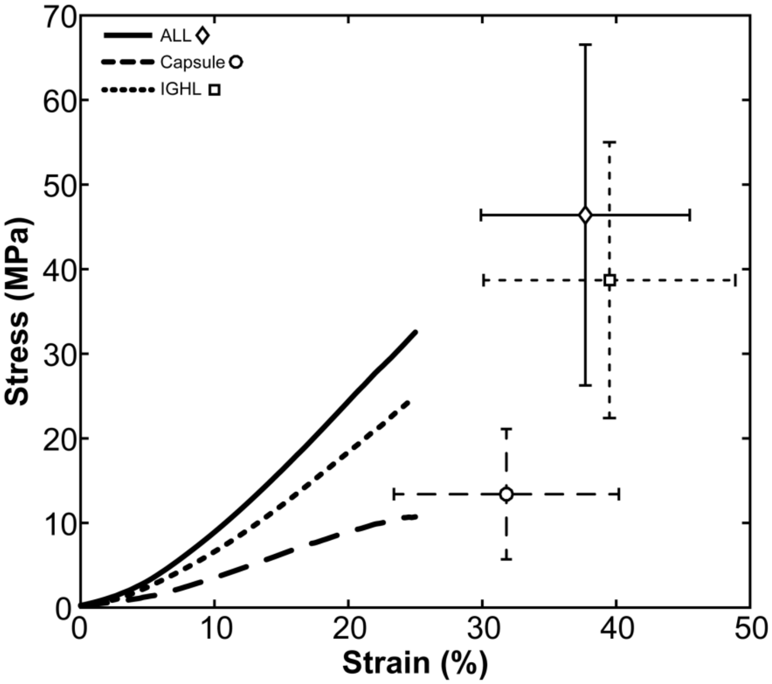

Figure 4: Average stress-strain curves for the ALL, capsule, and IGHL specimens. The final points represents the average ultimate stress and ultimate strain and the error bars indicate the standard deviation.

Histological Analysis

Histological analysis revealed substantial differences between the ALL/IGHL and the capsule (Fig. 6). The ALL was characterized by the presence of dense, parallel oriented collagen bundles with strong collagenization and regularly distributed fibroblasts. This was also illustrated by the trichrome staining, which depicts collagen as dark blue. Generally, the ALL presented as a homogeneous, hypovascular structure containing elastin bundles. On the outside of the dense collagenous structures, some nerve fibre could be noted. Likewise, the IGHL displayed structural characteristics very similar to the ALL, however, the ALL appeared to be even more strictly organized and a higher concentration of loose connective tissue separating the collagen bundles in the IGHL could be observed. In contrast, the capsule showed a disorganized architecture consisting of 'islands' of collagenized tissue, where in between fat, loose connective tissue, and neurovascular bundles are present. Although some fine and thin dense collagenized bundles and elastin could be noted in the capsule, these were not all comparable with the ALL.

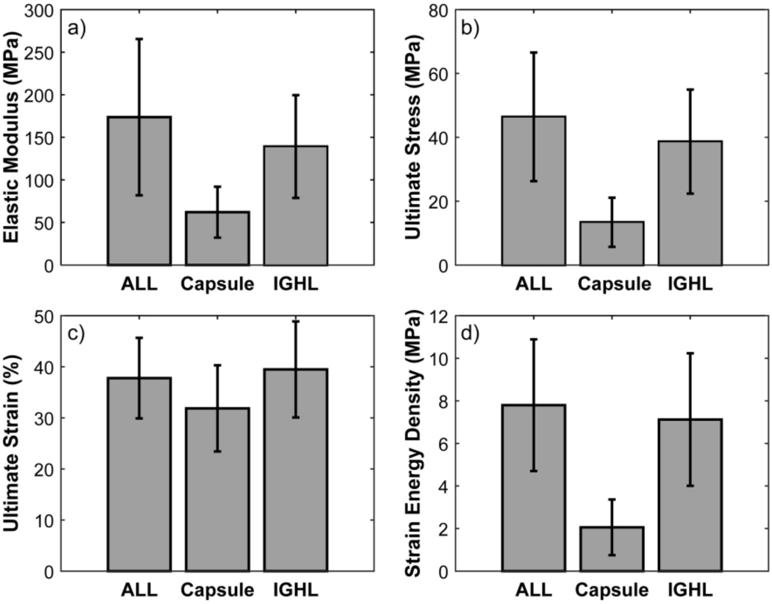

Figure 5: Results (mean ± SD) for a) elastic modulus, b) ultimate stress, c) ultimate strain, and d) strain energy density obtained from tensile testing. All measured properties were significantly ($P < 0.001$ a-b-d and $P < 0.05$ for c) higher for the ALL and IGHL relative to the capsule. No significant differences were found between the ALL and IGHL.

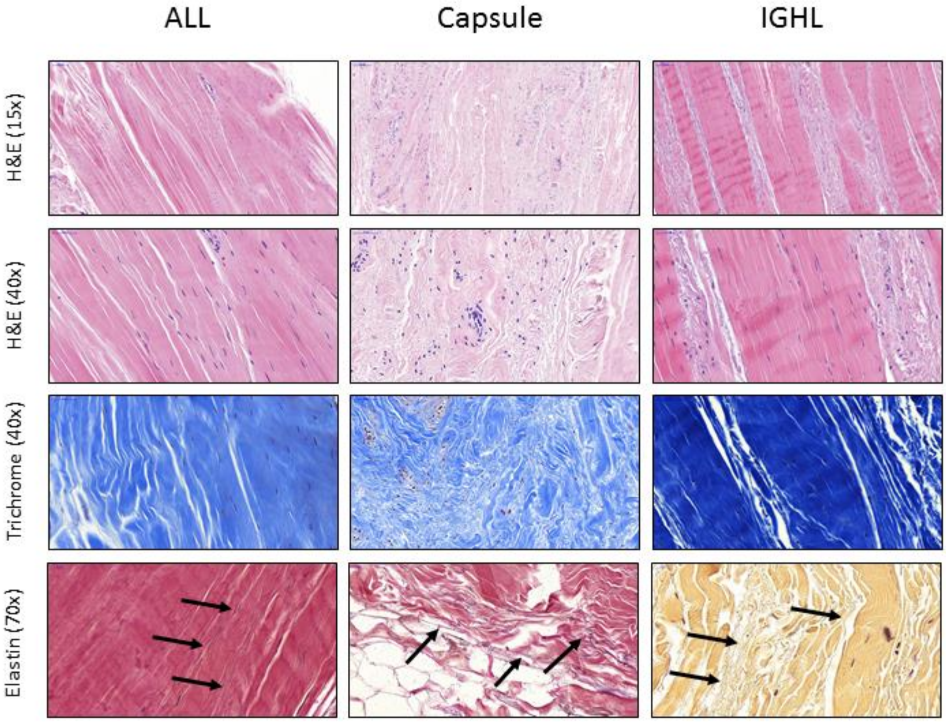

Figure 6: Representative histological cross sections of the ALL, capsule, and IGHL using three different staining techniques. The arrows represents the elastin fibers.

DISCUSSION

The primary finding of this work demonstrated that the tensile properties of the ALL are significantly higher than those of the knee capsule, while being comparable to the IGHL. This finding, coupled with the results from the histological analysis of the tissues, suggest that the ALL is a ligamentous structure that is distinct from the knee capsule; as is the case with the IGHL, one should refrain from stating that the ALL is just a simple thickening of the knee capsule.

Previously, a number of surgeons vaguely described the ALL as a 'pearly, fibrous band', the mid-third lateral capsular ligament, the anterior band of the lateral collateral ligament, the anterior oblique band or the capsulo-osseous layer of the iliotibial tract,[2,10,13,15,16] however, it wasn't until recently that a more detailed anatomic description was given.[2] Subsequently, additional anatomic studies followed and despite differences in identification of attachment sites, it is generally believed that the ALL is a well-defined ligamentous structure originating around the lateral femoral condyle and running antero-distally to its tibial attachment approximately midway between the center of Gerdy's tubercle and the anterior margin of the fibular head.[89,94,106] With internal rotation and flexion of the knee, the fibers of the ALL could clearly be distinguished from the slack and thin joint capsule lying just anterior of it.

Information regarding the mechanical properties of knee ligaments and surrounding soft tissues, in particular the ALL and capsule, are sparse. With respect to the ALL, this is surprising given the recent interest in reconstruction techniques using various types of grafts and fixation methods. The majority of studies previously performed have characterized the structural properties of these structures using pull-to-failure tests on either isolated bone-tissue-bone complexes or on entire knee cadavers.[94,144] Properties derived from these tests, such as stiffness, failure load, and toughness, are extrinsic and depend on the geometry of the tissue as well as the properties of the bony insertion sites.[135] In contrast, the mechanical properties measured in this study characterize the intrinsic behavior of the tissue. From a clinical point-of-view, an increase in a property such as the elastic modulus could be indicative of increased collagen content, larger collagen fibrils, and/or the tissue being made of a stiffer material.[135]

In this study, samples were isolated from cadavers and cut into standardized, dog-bone shaped specimens. This technique enabled for the characterization of the intrinsic mechanical, not structural, properties of the tissues. This method was chosen since replicating the loading of ligaments/tissues *ex vivo* is difficult and moreover insuring uniform load distribution to a ligament using an intact knee cadaver is particularly challenging. Cutting the tissue into dog-bone shaped-samples insured uniform loading while simultaneously mitigating potential end-effects that occur form gripping samples within the testing frame fixture.[148]

The tensile testing results obtained in this study provide strong evidence that the ALL is a distinct structure from the anterolateral knee capsule. All measured mechanical properties were significantly higher for the ALL relative to the capsule. The relative percent differences between the ALL and capsule were

95%, 110%, 17%, and 115% for the modulus, ultimate stress, maximum strain, and strain energy density, respectively. Additionally, one of the key strengths of this work relative to previous studies is the high number of specimens tested, done in an effort to mitigate the variability in biological tissue testing.

Table 1: Comparison of the mechanical properties from the current study with previously reported data. All data are presented as mean ± standard deviation. A dashed line indicates the property was not reported. Note, only mechanical properties, not structural properties (stiffness, load at failure), are reported here.

Reference	**Structure**	***N***	**Modulus (MPa)**	**Ultimate Stress (MPa)**	**Maximum Strain (%)**	**Strain Energy Density (MPa)**
Zens M.[101]	ALL	4	1.2±0.4*	32.8±4.0	36.0±4.5	---
Current study	ALL	19	174±92	46.4±20.1	37.8±7.9	7.8±3.1
Rachmat H.[149]	Capsule	15	9±11	1.8±1.9	35±10	---
Current study	Capsule	15	62±30	13.4±7.7	31.9±8.4	2.1±1.3
Bey M.[150]	IGHL	7	38±19	8.7±3.8	36±15	1.6±1.1
Ticker J.[151]	IGHL	8	115±44	13.9±7.1	17±5	---
McMahon P.[152]	IGHL	11	104±10	8.0±1.0	10±1	---
Current study	IGHL	13	139±60	38.7±16.3	39.5±9.4	4.3±2.3

*this property was 'calculated at 20% strain' and is thus a different calculation methodology than that used in the current study

An overview comparing previously reported mechanical properties for the ALL, capsule, and IGHL is provided in Table 1. Zens et al.[101] reported maximum strain values similar to those that were found in the current work, however, their calculated yield stress and modulus was lower (potentially attributable to differences in the modulus calculation technique). It should be noted that only four samples were tested in their study, cross-sectional area was measured after the specimen was tested, and no sample pre-conditioning was performed. Likewise for the knee capsule, similar maximum strain values were found in the current study and that of Rachmat H et al.[149] yet substantial differences were noted in the modulus and yield stress values. These differences in reported mechanical properties highlight the variability inherent to biological tissue testing and how variations in methodology (pre-conditioning, strain rate, cross-sectional area measurement, etc.) can influence the calculation of mechanical properties.

Several previous studies have performed histological analysis of the ALL. For example, Helito et al.[88] analyzed 20 specimens and demonstrated that the ALL possessed typical histologic characteristics seen in ligamentous structures. Similar findings were shown by Vincent et al.[18] who noted parallel, dense, collagenous fibers suggestive of ligamentous or tendinous tissue within the ALL isolated from 10 cadavers. A recent study from Caterine et al.[90] used magnetic resonance imaging, anatomical dissection, and histological analysis to characterize the anatomical properties of the ALL. They found the morphology of the ALL to be characteristic of ligament tissue and moreover described nerve innervation within of the tissue, which they speculated could be indicative of a proprioceptive role. In the current study, histological analysis agreed with previous reports and showed that the ALL consisted of a dense collagenized and mostly homogeneous ligamentous structure containing thicker elastin bundles. Similar to Caterine et al. the presence of nerve intervention was noted in the current study but was only located outside the densely organized collagenous fibers of the ALL (4/6 samples). As shown in Figure 6, the histological morphology of the ALL was remarkably similar to the IGHL, with one notable difference being thicker elastin fibers within the IGHL. In contrast, the knee capsule contained broad islands of loose collagen with proteoglycans and fatty tissue also present.

Within ligamentous tissue, elastin (elastic fibers) are one of the components responsible for providing elastic recoil to the structure[153] and the distribution of elastic fibers is considered to reflect the physiologic function of the tissue.[154] Previous work from Ticker et al.[151] revealed elastic fibers present within the IGHL and speculated that this is relevant to the ligament’s role as a static restraint within the shoulder. The presence of organized elastic fibers within the ALL suggest that it is also capable of providing restraint within the knee joint. While elastin fibers were present within the capsule, they lacked any apparent organization and thus indicate low potential for the capsule to resist tensile loads.

Similar to the ALL, the IGHL is a structure that lies in close proximity to the joint capsule. The IGHL is responsible for providing anterior stability in the glenohumeral joint in 90° of abduction and external rotation.[152,155] Failure patterns are seen in shoulder dislocations, where there can be a capsular stretching, Bankart lesions or even bony Bankart lesions.[151] Similar to the IGHL, the ALL is thought to be an important stabilizer of knee rotation at flexion angles exceeding 35° [140] and the Segond fracture is thought to be a bony avulsion of the ALL.[6] Data from this study supports the hypothesis that the ALL and IGHL are comparable structures with similar biomechanical and histological properties. It can be further postulated that ligaments are a heterogeneous group of connective tissues where subdivisions can be made. For instance, the IGHL and ALL can be classified in the same group of capsuloligamentous structures based on their similar stabilization roles and failure modes. This is in contrast to other ligaments such as the medial and lateral collateral ligaments which have different restraint functions and therefore different mechanical properties.

Limitations

Several limitations of this study should be noted. First, the mean age of the cadavers was 74±7 years which may not represent the typical patient undergoing knee ligament reconstruction. Since ligaments are known to exhibit age-related alterations in mechanical properties[156], data from this study may not be representative of ligament properties from younger patients. Secondly, all testing was conducted at room temperature, however, the mechanical properties of ligaments are known to be temperature dependent.[157,158] Since all specimens were all prepared, stored, and tested under identical conditions, any change in tissue properties resulting from the testing temperature would be carried through all specimens. Third, only the axial tensile properties of the specimens were tested although *in vivo* loading of these tissues is more complex. In this study, axial loading was applied parallel to specimen fibers, thereby approximating a worst-case scenario. Fourth, ligaments and capsular tissue are viscoelastic materials yet only the quasi-static properties were measured in this study. Fifth, the ALL as a distinct ligamentous structure was examined by comparing it to the adjacent knee capsule and an existing ligament (IGHL).

Hereby, other interesting anatomical structures, like the shoulder capsule, were not tested in this study.

CONCLUSION

The anterolateral ligament has similar tensile and histological properties as the inferior glenohumeral ligament. The tensile properties of the ALL are significantly greater than those observed in knee capsule.

Appendix: Raw values obtained from tensile testing of the ALL, capsule, and IGHL

	Elastic Modulus (MPa)			**Ultimate Stress (MPa)**			**Ultimate Strain (mm/mm)**			**Strain Energy Density (MPa)**		
	ALL	**Capsule**	**IGHL**	**ALL**	**Capsule**	**IGHL**	**ALL**	**Capsule**	**IGHL**	**ALL**	**Capsule**	**IGHL**
	389	56	77	90	12	35	0.27	0.38	0.61	11.4	2.3	9.6
	121	56	109	30	12	38	0.32	0.28	0.48	4.2	1.7	8.7
	129	68	180	27	14	47	0.31	0.24	0.36	4.5	1.6	8.1
	102	109	112	24	19	24	0.39	0.24	0.29	4.5	2.2	3.1
	130	115	168	40	31	44	0.47	0.37	0.34	7.6	5.3	7.5
	114	54	83	32	10	18	0.41	0.35	0.27	6.3	2.0	2.1
	60	21	71	20	6	19	0.50	0.35	0.42	4.5	1.3	3.5
	198	54	131	73	18	29	0.44	0.40	0.31	14.1	3.3	5.1
	211	89	147	52	27	45	0.29	0.36	0.48	6.8	4.3	8.8
	227	55	293	62	13	79	0.34	0.28	0.32	10.9	1.7	11.3
	421	8	150	90	2	39	0.28	0.54	0.39	11.1	0.7	7.1
	173	43	189	40	7	55	0.31	0.27	0.44	5.5	1.0	12.2
	150	55	101	49	11	30	0.47	0.24	0.42	11.1	1.4	5.6
	140	98		37	9		0.34	0.22		6.1	0.7	
	159	50		55	10		0.44	0.27		12.1	1.4	
	204			46			0.28			5.7		
	122			35			0.39			5.3		
	147			43			0.43			7.3		
	103			36			0.50			9.0		
Mean	**174**	**62**	**139**	**46**	**13**	**39**	**0.38**	**0.32**	**0.39**	**7.8**	**2.1**	**7.1**
SD	**92**	**30**	**60**	**20**	**8**	**16**	**0.08**	**0.09**	**0.09**	**3.1**	**1.3**	**3.1**

CHAPTER 2

Mechanical Analysis of Extra-Articular Knee Ligaments. Part One: Native knee ligaments.

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The Knee

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ABSTRACT

Purpose

To aim of this study was to provide a characterization of the tensile properties of the medial collateral ligament (MCL), lateral collateral ligament (LCL), anterolateral ligament (ALL) and medial patellofemoral ligament (MPFL). Our hypothesis was that extra-articular knee ligaments are heterogeneous in nature and possess distinct material properties.

Methods

MCL (N=12), LCL (N=11), MPFL (N=12) and ALL (N=19) samples from fresh frozen human cadaveric knees were subjected to uniaxial tensile testing to failure and analyzed for their material properties. The elastic modulus (slope of the linear portion of the stress/strain curve), ultimate stress (stress at failure), ultimate strain (strain at failure) and strain energy density (area under the stress/strain curve) were calculated.

Results

The MCL had the highest elastic modulus (441.8±117.2 MPa) and was significant greater than the MPFL (294.6±190.4 MPa) and LCL (289.0±159.7 MPa) ($P<0.05$) as well as the ALL (173.7±91.8 MPa) ($P<0.001$). The ultimate stress was significant higher ($P<0.05$) for the LCL (83.6±38.1 MPa) and MCL (72.4±20.7 MPa), relative to the MPFL (49.1±31.0 MPa) and ALL (46.4±20.1 MPa). The ultimate strain of the LCL (41.0±9.9%) and ALL (37.8±7.9%) were significantly higher ($P<0.05$) compared to the MCL (22.9±2.5%) and MPFL (22.2±5.6%). The strain energy density of the LCL (15.2±6.4 MPa) was significantly greater ($P<0.05$) than all other ligaments (ALL 7.8±3.1 MPa, MCL 7.5±2.9 MPa and MPFL 5.0±2.9 MPa).

Conclusions

Extra-articular knee ligaments are a heterogeneous group with respect to material characteristics. Each ligament has tensile properties that are significantly different from others and treatment strategies should take these findings into account.

INTRODUCTION

Injuries to knee ligaments are very common, particularly in sports related activities [159], with an estimated rate of occurrence in the general population approaching 2/1000 people per year. [160] Ruptures of these ligaments can result in chronic instability and secondary damage to other structures, such as the cartilage and meniscus. Surgical treatment often involves reconstruction with auto- or allografts [53,78,126,128,161-170] and therefore, knowledge of ligament mechanical properties is essential to elucidate their *in vivo* behavior and function as well as for selecting appropriate grafting materials used in reconstruction procedures.

The intrinsic mechanical properties of a ligament depend upon several factors including collagen composition, fiber orientation and the interaction between collagen and ground substance [135]. A wide variation of grafting materials and surgical techniques are used for the reconstruction of extra-articular ligaments such as the medial collateral (MCL) [161-163], lateral collateral (LCL) [164-167], medial patellofemoral [168-170], and anterolateral (ALL) ligament [53,78,126,128]. Despite this, there are only few studies investigating the intrinsic mechanical behavior of human extra-articular knee ligaments, and many previous studies have only characterized the structural properties of bone-ligament-bone complexes. [94,171,172] Moreover, an advantage of this study is that ligaments of the same cadaveric specimen are tested using an identic testing method.

In current clinical practice, graft materials are often chosen because of their size, structural properties, ease for harvesting, and availability [161,164,165,173-175]. To enhance the effectiveness of various treatment procedures and to deal with problems such as over-constraining versus residual joint laxity, it is essential to know the intrinsic characteristics of ligaments in order to mimic them with the appropriate graft. Therefore, the primary objective of this work is to provide a detailed characterization of the tensile properties of the MCL, LCL, ALL, and MPFL. We hypothesize that extra-articular ligaments are heterogeneous in nature and possess distinct material properties.

METHODS

Twelve fresh-frozen full body cadavers (74±7 years, 10 men, 2 women) were obtained under ethical approval from the Institutional Review Board at KULeuven. No donor had a history of knee injury, instability, or prior surgical intervention. Additionally, 3 knees were excluded because of grade III and IV arthrosis or ACL deficiency. From 12 of the 21 specimens, the anterolateral ligament (ALL), superficial medial collateral ligament (MCL), lateral collateral ligament (LCL), and medial patellofemoral ligament (MPFL) were dissected using previously described techniques [2,176]. Nine knee specimens were only dissected for the ALL and could not be used for harvesting other ligaments because of other research purposes. Consequently, a total of 21 ALL, 12 MCL, 12 LCL and 12 MPFL samples were taken by the same orthopaedic resident (KS). Once removed, the samples were wrapped in saline-soaked gauze, placed in freezer bags, and stored at -80°C until the time of testing.

Mechanical Testing

Prior to testing samples were removed from the freezer and allowed to thaw at room temperature for 24 hr. Once thawed, samples were cut into standardized shapes (dog-bone) using a surgical scalpel to form a uniform cross-sectional area in the mid-substance of the tendon, thus providing a uniform stress distribution during testing [177,178]. Samples were mounted in custom made tensile grips which had sandpaper between the grip faces to provide anchorage. Additionally, cyanoacrylate adhesive was used to provide additional protection against slippage.The tensile grips were aligned axially (i.e. in-line with the ligament fibers) within a materials testing frame (model 4467, Instron, Norwood MA, USA) equipped with a 1 kN calibrated load cell. (figure 1) A 1 N preload was applied to the samples and measurements of the cross-sectional area were taken with a digital micrometer five times and the average calculated. The distance between the grip faces was measured and was used as the original gage length. Ten preloading cycles consisting of a ramp from 1 – 10 N at a strain rate of $0.1\%s^{-1}$ was performed which were followed immediately by a ramp-to-failure test at a strain rate of $2\%s^{-1}$. Force and displacement data were measured at 100 Hz. Samples were kept wet with saline to prevent dehydration and all tests were performed at room temperature (~22 °C).

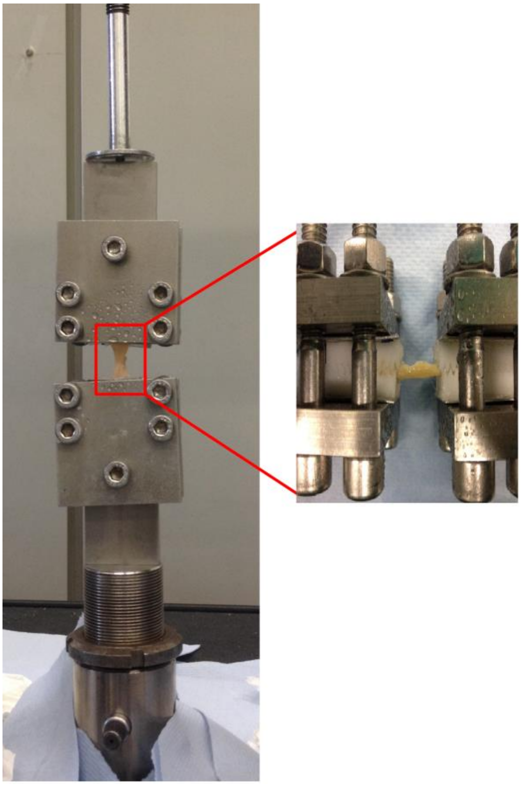

Figure 1: The clamping system used to perform tensile testing of the tissue specimen.

Only those samples that showed mid-substance failure were used for analysis. In total, data from 19/21 ALL, 12/12 MCL and MPFL, and 11/12 LCL could be analyzed. The collected force and displacement data were converted to stress (applied force/average cross sectional area) and strain (change in length/original gage length) to allow the calculation of the ligament mechanical properties: elastic modulus (slope of the linear portion of the stress-strain curve), ultimate stress (stress at failure), ultimate strain (strain at failure), and strain energy density (energy absorbed to yield).

Statistical analysis

Statistical analysis of the collected mechanical properties was conducted using commercially available software (SPSS 24, IBM, Armonk, NY, USA). Data were found to exhibit non-normal distributions using the Shapiro-Wilk test and therefore non-parametric analysis was used. Kruskal-Wallis tests with Dunn's post-hoc test were used to analyze collected tensile data. The statistical significance level ɑ was set to 0.05 for all statistical tests. Where applicable, data are presented as mean ± standard deviation.

RESULTS

All ligaments demonstrated an initial non-linear 'toe region' followed by a linear stress-strain relationship leading to sample yield/failure. (figure 2)

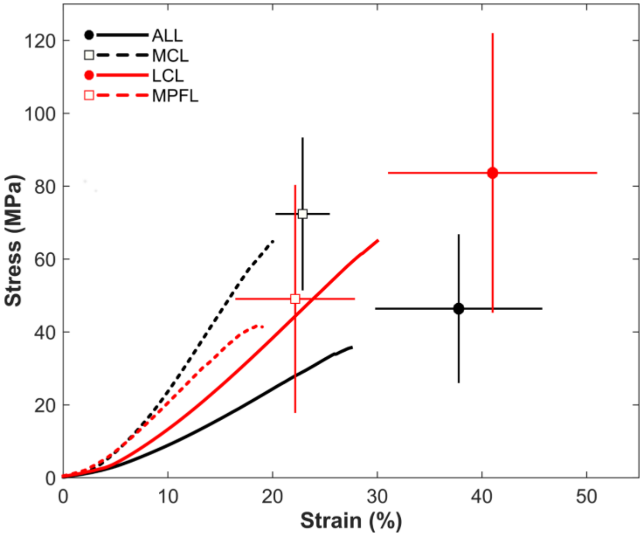

Figure2: Average stress-strain curves for the ALL, MCL, LCL, and MPFL specimens. The final points represents the average ultimate stress and ultimate strain and the error bars indicate the standard deviation.

The *elastic modulus* was highest for the MCL (441.8±117.2 MPa) and was significant greater than the MPFL (294.6±190.4 MPa) and LCL (289.0±159.7 MPa) ($P<0.05$) as well as the ALL (173.7±91.8 MPa) ($P<0.001$). (figure 3, table 1 and 2)

The *ultimate stress* was significant higher ($P<0.05$) for the LCL (83.6±38.1 MPa) and MCL (72.4±20.7 MPa), relative to the MPFL (49.1±31.0 MPa) and ALL (46.4±20.1 MPa). (figure 3, table 1 and 2)

The *ultimate strain* of the LCL (41.0±9.9%) and ALL (37.8±7.9%) were significantly higher ($P<0.05$) compared to the MCL (22.9±2.5%) and MPFL (22.2±5.6%). (figure 3, table 1 and 2)

The *strain energy density* of the LCL (15.2±6.4 MPa) was significantly greater ($P<0.05$) than all other ligaments (ALL 7.8±3.1 MPa, MCL 7.5±2.9 MPa and MPFL 5.0±2.9 MPa). (figure 3, table 1 and 2)

The relationship between the obtained mechanical properties for the tested ligaments is shown in Figure 4. The differences in patterns between the ligaments demonstrate the great variance in the mechanical characteristics.

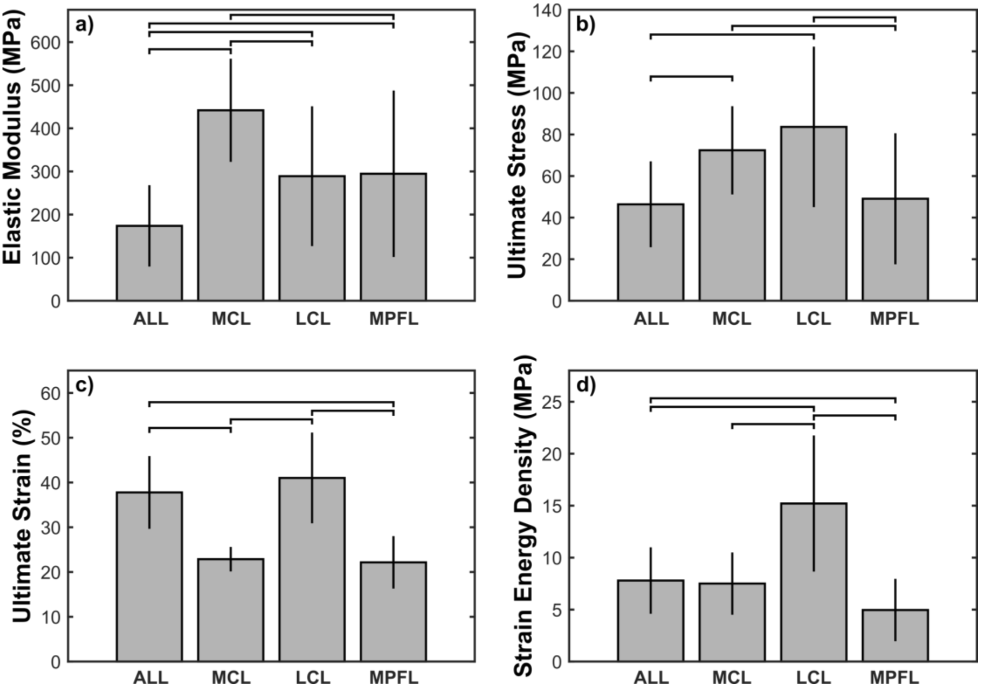

Figure 3: Results (mean ± SD) for a) elastic modulus, b) ultimatestress, c) ultimatestrain, and d) strain energy density obtained from tensile testing of the ligament specimens. A solid horizontal link between ligament types indicates a significant ($P < .05$) difference

Table 1: Mechanical property results obtained from tensile testing of each individual specimen.

Specimen	**Elastic Modulus (MPa)**				**Ultimate Stress (MPa)**				**UltimateStrain (%)**				**Strain Energy Density (MPa)**			
	ALL	**MCL**	**LCL**	**MPFL**	**ALL**	**MCL**	**LCL**	**MPFL**	**ALL**	**MCL**	**LCL**	**MPFL**	**ALL**	**MCL**	**LCL**	**MPFL**
1	389.2	281.2	171.4	99.8	90.1	44.6	57.5	26.7	27.0	21.6	43.7	34.8	11.4	4.2	12.1	4.6
2	120.7	367.3	127.7	226.1	29.8	55.7	40.7	36.4	31.8	23.1	40.6	21.0	4.2	5.2	7.7	3.5
3	129.1	600.0	239.9	613.2	27.4	99.3	54.1	89.0	31.1	22.2	35.3	18.2	4.5	10.4	9.5	7.5
4	101.7	617.5	611.7	217.8	24.3	94.1	153.7	40.4	38.7	22.6	31.2	20.7	4.5	8.4	21.5	3.7
5	129.9	257.9	185.4	647.8	40.3	47.2	51.6	115.2	47.2	22.6	42.9	20.8	7.6	4.6	10.2	11.4
6	114.4	357.4	210.7	140.2	31.7	51.3	103.4	26.5	41.0	21.6	64.9	25.4	6.3	5.7	26.2	3.2
7	60.3	496.1	396.5	256.6	20.3	84.3	98.8	31.8	49.5	22.5	32.4	17.4	4.5	8.6	16.4	2.5
8	197.5	504.9	517.8	133.2	72.8	101.0	131.0	24.7	43.8	27.6	32.4	26.8	14.1	13.2	18.4	3.5
9	210.7	528.0	348.9	367.2	51.7	76.3	102.3	52.0	28.9	22.2	41.3	16.8	6.8	7.8	19.5	4.4
10	226.9	388.0	149.0	249.2	62.0	54.9	39.5	51.0	34.5	19.9	35.8	26.0	10.9	4.0	6.2	6.0
11	420.9	503.6	220.3	110.8	90.1	79.3	87.6	12.6	27.8	20.4	50.6	14.2	11.1	7.3	19.6	0.8
12	173.2	400.0		473.1	39.7	80.5		82.8	30.9	28.1		24.0	5.5	10.6		8.4
13	150.1				49.4				47.3				11.1			
14	140.0				37.4				34.5				6.1			
15	159.1				54.7				44.3				12.1			
16	204.0				46.3				28.0				5.7			
17	121.9				34.6				38.6				5.3			
18	147.2				43.4				42.8				7.3			
19	103.2				36.0				50.0				9.0			
Avg	173.7	441.8	289.0	294.6	46.4	72.4	83.6	49.1	37.8	22.9	41.0	22.2	7.8	7.5	15.2	5.0
SD	91.8	117.2	159.7	190.4	20.1	20.7	38.1	31.0	7.9	2.5	9.9	5.6	3.1	2.9	6.4	2.9
95CI$_{UB}$	218.0	516.3	396.3	415.6	56.1	85.6	109.2	68.8	41.6	24.5	47.7	25.7	9.3	9.3	19.5	6.8
95CI$_{LB}$	129.4	367.4	181.7	173.6	36.7	59.2	58.1	29.4	34.0	21.3	34.4	18.6	6.3	5.7	10.9	3.1

avg – average, SD – standard deviation, 95CI$_{UB}$ – 95% confidence interval upper bound, 95CI$_{LB}$ – 95% confidence interval lower bound

Table 2: The obtained P-values from the statistical analysis of data obtained from tensile testing. An emrule indicates the lack of a statistical test.

Property	Specimen	ALL P	MCL P	LCL P	MPFL P
Elastic Modulus	**ALL**	–	< .001	.034	.047
	MCL		–	.040	.023
	LCL			–	.867
	MPFL				–
Ultimate Stress	**ALL**	–	.006	.002	.960
	MCL		–	.728	.015
	LCL			–	.007
	MPFL				–
Ultimate Strain	**ALL**	–	< .001	.574	< .001
	MCL		–	< .001	.795
	LCL			–	< .001
	MPFL				–
Strain Energy Density	**ALL**	–	.822	.007	.021
	MCL		–	.008	.060
	LCL			–	< .001
	MPFL				–

DISCUSSION

The main objective of this study was to provide data on the tensile properties of the MCL, LCL, ALL and MPFL. The primary findings of this work suggest that the investigated ligaments have significant differences in their intrinsic mechanical properties and are heterogeneous in nature, thus supporting our initial hypothesis. These findings may help explain differences observed in the clinical behavior of these ligaments in both healthy and injured states, and stimulate a specific treatment approach per ligament.

Data regarding the mechanical properties of human knee ligaments and surrounding soft tissues are sparse (Table 3). This is surprising given the numerous reconstruction techniques using various types of grafts and fixation methods. The majority of previous studies have characterized the structural properties (e.g. failure load, elongation, stiffness) of these structures using pull-to-failure tests on either isolated bone-tissue-bone complexes or on entire knee cadavers [94,144,171,172,179-187] and depend on the geometry of the tissue as well as the properties of the bony insertion sites [135]. Structural tests performed on bone-ligament-bone complexes can potentially underestimate the true ligament mechanical properties. For example, when testing the structural properties of the bone-ligament-bone complex of eight MCLs, Robinson et al. showed specimen failure at the bony attachment site in six samples. Re-testing of these samples after excision of the bony fragments resulted in mid-substance failure at significantly higher loads (74% higher) [172]. In contrast, the mechanical properties measured in this study characterize the intrinsic behavior of the tissue and depend on the collagen composition, fiber orientation and interaction between the collagen and the ground substance [135].

Only a limited number of previous studies have compared multiple human knee ligaments within the same specimen pool. Trent et al. [184] performed structural testing on six samples and found that the MCL was 36% stronger and 16% stiffer relative to the LCL. Similarly, Wilson et al. [171] tested 10 samples and demonstrated that the MCL is 100% stronger and requires 200% more energy to fail than the LCL. Additionally, in the study from Wilson et al. mid-substance failure of the LCL and MCL only occurred in 4 and 1 specimens, respectively. Therefore, these data are based on failures of the insertion sites and do not give a correct idea on the properties of the ligament itself. Findings from these previous studies are in contrast to the values for ultimate stress and strain energy density obtained in this study and can likely be attributed to differences in the size of the MCL and LCL; generally the MCL is a larger structure and structural testing does not take this into account when comparing properties between ligaments. Our results showed that the modulus of the MCL was significantly higher relative to the LCL, however, the ultimate stress was not significantly different between the collateral ligaments. Conversely, the ultimate strain and strain energy density was significant higher for the LCL compared to the MCL (and all other tested ligaments). Considering the LCL as the primary lateral constraint in the coronal plane [188], it is maybe not surprising that isolated LCL lesions are not as common as MCL tears. From a clinical standpoint, reconstructing the LCL with a strong, stiff graft could potentially over-constrain the lateral compartment.

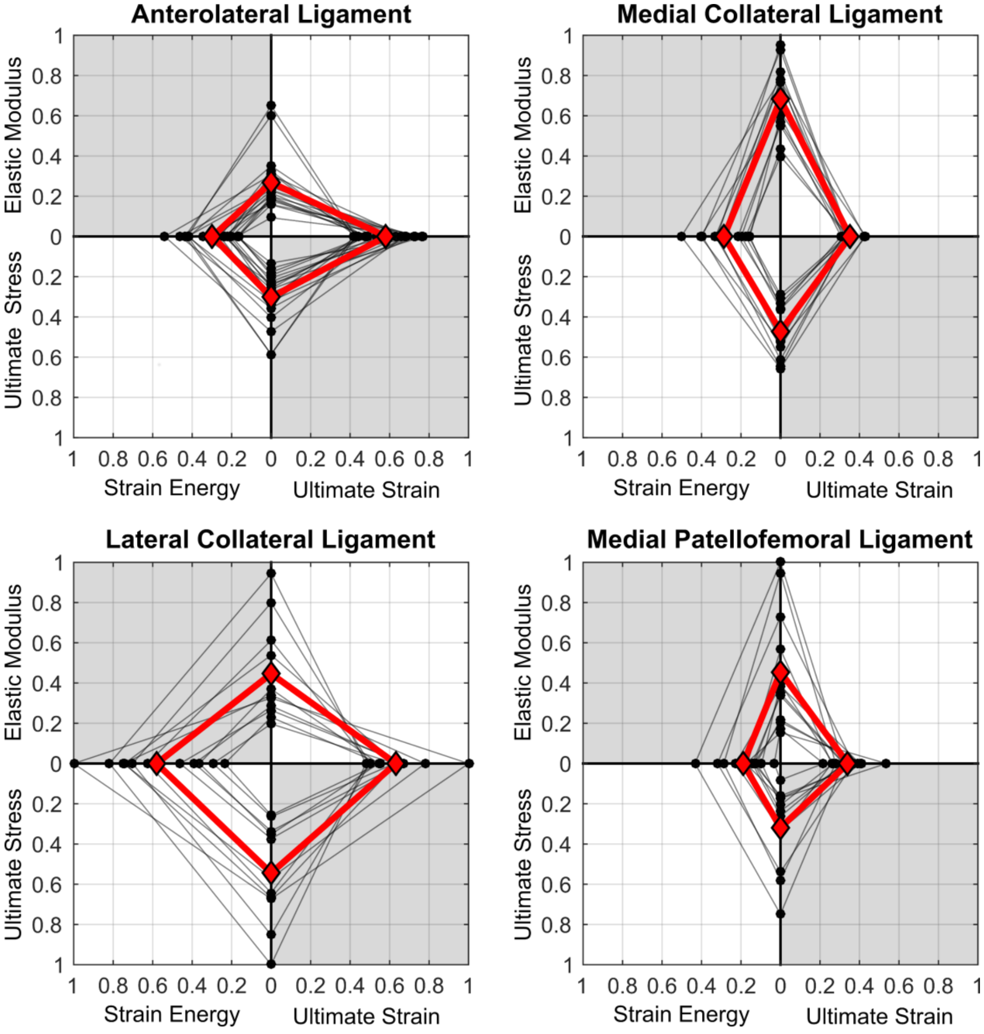

Figure 4: The relationship between the obtained mechanical properties for the tested ligaments. Data are normalized to the maximum value obtained for all tested specimens, regardless of ligament type. Black dots/lines represent the values for each individual ligament and red diamonds/lines represent the average values.

An overview comparing previously reported mechanical properties for the MCL, LCL, ALL and MPFL is provided in Table 3. These data highlight the wide variability that is often obtained in mechanical testing of biological tissue resulting from biological variation and variations in testing techniques. Zens et al. [101] performed mechanical testing on isolated ALL samples and found similar ultimate strain values as reported in this work, but a lower ultimate stress and elastic modulus. However, it should be noted the elastic modulus was calculated using a different technique, a limited number of samples were tested, and there were differences in the testing protocol. Quapp et al. [148] and Criscenti et al. [177] reported maximum strain values of for the MCL and MPFL that were similar to those that were found in this work. Nevertheless, the maximum stress was respectively 2 and 3 times higher. Possible reasons for lower mean stress values (with similar strain values) are differences in clamping techniques (e.g. failure between the clamps) and the inherent biologic variability that exists in cadaver specimens. Gardiner et al. [189] reported an elastic modulus value of 467 MPa for the MCL, which is very close to the value of 441 MPa obtained in this study. Remarkably, large differences were noted with the study by Butler et al. [190] on the material properties of the LCL. In their study, bone-ligament-bone units were isolated and the ligament was divided into two fiber bundles tested and no failure mechanism was described. Due to bony resorption of the attachment site, mid-substance failure is unlikely to happen, with an underestimation of the material properties as a consequence [172].

Several limitations of this study should be noted. First, ligament cross-sectional area was measured using a digital micrometer which can introduce errors due to the difficulty of establishing when contact is made with the micrometer knife edges. To minimize potential errors, all measurements were performed by the same person five times and the average taken. Second, inherent variability in tissue property resulting from differences in donor age, sex and physical activity are known [156], however, an effort was made to obtain cadavers from a similar age range. Third, strain measurements were based on the grip-to-grip displacement and thus represent the global strain. Previous work has shown that localized strain distributions in soft tissue undergoing tensile testing exist [149].

Table 3: Comparison of the mechanical properties from the current study with previously reported data. All data are presented as mean ± standard deviation (if available). A dashed line indicates the property was not reported. Note, only mechanical properties, not structural properties (stiffness, load at failure), are reported here.

Reference	**Structure**	***N***	**Modulus (MPa)**	**Ultimate Stress (MPa)**	**Ultimate Strain (%)**	**Strain Energy Density (MPa)**
Zens [101]	ALL	4	1.2±0.4*	32.8±4.0	36.0±4.5	---
Current study	ALL	21	173.7±91.8	46.4±20.1	37.8±7.9	7.8±3.1
Quapp [148]	MCL	10	332.2±58.3	38.6±4.8	17.1±1.5	---
Lujan [191]	MCL	4	202±37	---	---	---
Gardiner [189]	MCL	8	467.1±177.4	---	---	---
Thornton [192]	MCL	13	613±63	95.1±12.3	17.4±1.8	---
Current study	MCL	12	441.8±117.2	72.4±20.7	22.9±2.5	7.5±2.9
Criscenti [177]	MPFL	12	116±95	16±11	24.3±6.8	---
Current study	MPFL	12	294.6±190.4	49.1±31.0	22.2±5.6	5.0±2.9
Butler [190]**	LCL	6	379	35.6	13.7	2.05
Current study	LCL	11	289.0±159.7	83.6±38.1	41.0±9.9	15.2±6.4

*this property was "calculated at 20% strain" and is thus a different calculation methodology than that used in the current study

**results were obtained from three cadaver knees that were each dissected into two fiber bundles. Therefore, data represent the averages obtained from tensile testing of LCL fiber bundles, not the entire LCL. Data were digitized from graphs in the original publication

Fourth, only the axial tensile properties of the samples were tested, which simulate a worst-case loading scenario, although the in vivo loading of these tissues is more complex. Finally, ligaments are viscoelastic materials that display both time and temperature dependent properties [157,158] yet only the quasi-static properties were measured at room temperature in this study.

To our knowledge, this is the first study that compares the mechanical properties of different native knee ligaments. As the same testing technique is used, this study not only provides mechanical data of each individual ligament, but also provides information how the behavior of ligaments can differ from each other. From a clinicial point of view, those data may help in understanding the differences in injury pattern and appearance that can be seen between ligament injuries. The clinical relevance in knowing the mechanical data of each individual ligament is that it can help in understanding the function of each specific ligament, but also can serve as a guidance when looking for a graft to reconstruct it. An ideal graft has the same mechanical properties as the original ligament.

CONCLUSION

Each ligament has tensile properties that are significantly different from others and treatment strategies should take these findings into account. The elastic modulus is significant higher for the MCL than for the LCL, MPFL and ALL. While having comparable stress at failure, the strain at failure and strain energy density is significant higher for the LCL than for the MCL. There is no significant difference in ultimate stress between the ALL and MPFL.

CHAPTER 3

Do Knee Ligaments Demonstrate Different Biomechanical Properties in Low versus High Load Conditions?

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Lennart Scheys, Johan Bellemans

ABSTRACT

Purpose

The biomechanical characteristics of knee ligaments are well known under relatively high loading conditions, such as represented in later phases of the stress-strain curve. During most activities of daily life however, ligaments are loaded in the so-called "toe region" of the stress-strain curve. Little or no data are however available for these relatively low loading conditions.

The aim of our study was therefore to provide a detailed characterization of the low-load (toe region) mechanical properties of the medial collateral ligament (MCL), the lateral collateral ligament (LCL), the medial patellofemoral ligament (MPFL) and the anterolateral ligament (ALL). We hypothesized these could be fundamentally different compared to higher loading conditions, and and also fundamentally different from each other.

Methods

Fresh-frozen human cadaveric knees were harvested for the MCL (n=12), LCL (n=11), MPFL (n=12) and ALL (n=19) and subjected for uniaxial testing to failure. The obtained stress-strain curve was divided into a non-linear (toe region) and a linear region and the material properties of the toe region were investigated.

Results

The strain value where the toe region turned into a linear region was significantly higher for the LCL (10.8% ± 4.2) and ALL (9.2% ± 3.3), relative to the MCL (5.9 % ± 1.7) and MPFL (5.3 % ± 0.8). No significant differences for stress at this transition point were seen. The elastic modulus of the toe region was significantly ($P<0.05$) higher for the MCL (79 MPa ±31) than for the ALL (43 MPa ±29), but not for the LCL (57 MPa ± 27) and the MPFL (67 MPa ± 44).

Conclusion

All investigated knee ligaments behaved significantly different in low-load versus high load conditions. The strain at the transition point from the toe region to the linear region, was significantly higher for the LCL and ALL compared to the MCL and MPFL. In addition, the slope of the non-linear toe region was significantly higher for the MCL relative to the ALL.

The clinical consequence of our findings is that the low load conditions of ligaments should be taken into consideration when considering the optimal graft material for reconstruction.

INTRODUCTION

The knowledge of mechanical properties of ligaments is essential to understand their function and behavior, and to create accurate and valid joint models for a better comprehension of trauma mechanisms and pathology of related diseases. [193,194] Furthermore, this information is important for new surgical techniques restoring the original function of torn ligaments and for the selection of appropriate graft options. [135]

Investigating the biomechanical characteristics of ligaments is generally performed using uniaxial tensile loading tests to failure. [147,148,159,177,184,188,190,193,195-197] Depending on whether the bone-ligament-bone complex or the (mid-)substance of the ligament itself is analyzed, both the structural and mechanical properties can be obtained, respectively. The latter characterize the intrinsic behavior of the tissue and are typically represented by a stress-strain curve. This curve can be divided in a non-linear (toe region) and linear part. [135] Whereas, the toe region characterizes the mechanical behavior of the ligament in response to low strain activities, the linear region demonstrates the behavior in high strain activities. [198] While the linear properties are well studied [147,148,177,184,188,190,193,197], we could only find one study that specifically described the toe region properties of the patella tendon. [198] Furthermore, it has been established that the strains in the ACL during activities such as biking, squatting and other similar activities of daily living are typically of magnitudes between 2-4%. [199,200], i.e. strains that have rather been associated with the toe region than the linear region. [198]

The toe region is characterized by a process of progressive fiber recruitment in order to resist the increasing load. Hereby the curve demonstrates a non-linear part where small initial forces produce relatively large elongations. The subsequent higher stiffness in the linear part results from the fibers being stretched. [135] Provenzano et al. [201] showed in rats’ medial collateral ligaments (MCL) that structural damage is already occurring at ligament strains of 5.14%. Therefore, knowledge of the strain value at which the toe region proceeds to a linear region is important information. Unfortunately however, little or no data are available on this. [198]

The aim of our study was therefore to provide a detailed characterization of the low-load (toe region) mechanical properties of the medial collateral ligament (MCL), the lateral collateral ligament (LCL), the medial patellofemoral ligament (MPFL) and the anterolateral ligament (ALL). We hypothesized these low-load characteristics could be fundamentally different compared to those under higher loading conditions, and also could be very different amongst the ligaments that were analyzed.

MATERIAL AND METHODS

After obtaining approval from the ethical committee of the review board at KU Leuven, 12 full body fresh-frozen cadavers were collected (10 men and 2 women, average 74 years +/- 7). Three from the 24 knees were excluded due to advanced signs of gonarthrosis (grade 3 and 4) or ACL deficiency. The rest of the specimens had no history of knee injury, surgery or instability. The ALL, superficial MCL, LCL and MPFL were dissected using a previously specified technique [2,176,190] Nine knee specimens were only dissected for the ALL and could not be used for harvesting other ligaments because of other research purposes. In total 21 ALL, 12 MCL, 12 LCL and 12 MPFL were dissected by the same orthopaedic surgeon (KS) and storage of the specimens was done at -80°C after wrapping the removed ligaments in saline soaked gauze placed in freezer bags until the time of testing. [193]

Mechanical testing

After 24h thawing of the specimens at room temperature, a standardized dog-bone shaped sample was cut from all ligaments to create a uniform cross-sectional area in the mid-substance of the tendon. [147,178] The reason for this was to create a uniform stress-distribution during testing and to cause a mid-substance failure. *S*amples were anchored in custom-made tensile grips and extra prevention from slippage was provided with sandpaper and cyanoacrylate glue. [193,195] Before testing, samples were aligned axially with a preload of 1 N in a material testing frame (model 4467, Instron, Norwood MA,USA) provided with a 1-kN calibrated load cell. (Figure 1) Additionally, the cross-sectional area of the samples was measured five times with a digital micrometer from which the average was calculated. The preconditioning phase consisted of ten cycles, each inclining from 1 to 10 N at a strain rate of 0.1% s^{-1}. After the tenth cycle, a test-to-failure followed at a strain rate of 2% s^{-1}. Tests were performed at room temperature (22°C) and samples were kept wet using saline to prevent dehydration.

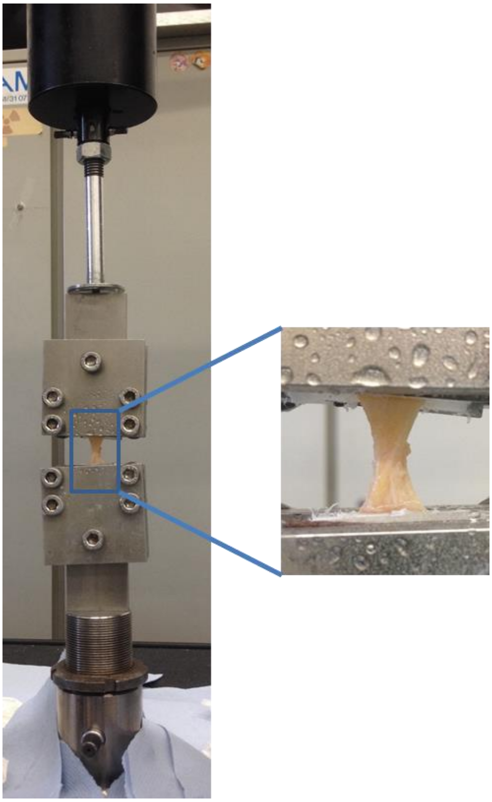

Figure 1. Specimens were cut into a standardized dog-bone shaped sample and axially aligned. Custom-made tensile grips were used to perform tensile testing to failure.

Statistical testing

Only those samples that showed mid-substance failure were included and after measuring displacement and force at 100 Hz, data were converted into strain (change in length/ original length) and stress (applied force/ average cross-sectional area). The same dataset was previously used for the analysis of the material properties of the linear region. [193] Now, for every patient, the following breakpoint regression model – described by Chandrashekar et al [198] - was used to divide the stress–strain curve into a toe region and a linear elastic region:

$$\sigma = E_0\ \varepsilon \quad \text{when } \varepsilon \le \varepsilon^*$$

$$\sigma = E(\varepsilon - \varepsilon^*) + E_0\ \varepsilon^* \quad \text{when } \varepsilon > \varepsilon^*$$

where σ is the tensile stress, when ε is the tensile strain, ε^* is the strain at the transition point between the toe-region and linear elastic region. E_0 is the modulus of elasticity of the toe region and E is the modulus of elasticity of the linear region. (Figure 2)

Next, linear mixed models, with a random patient effect, were used to investigate differences according to ligament type in average transition point and the modulus of elasticity of the toe region. A 5% level of significance was used and statistical analysis was performed using SAS for windows version 9.4.

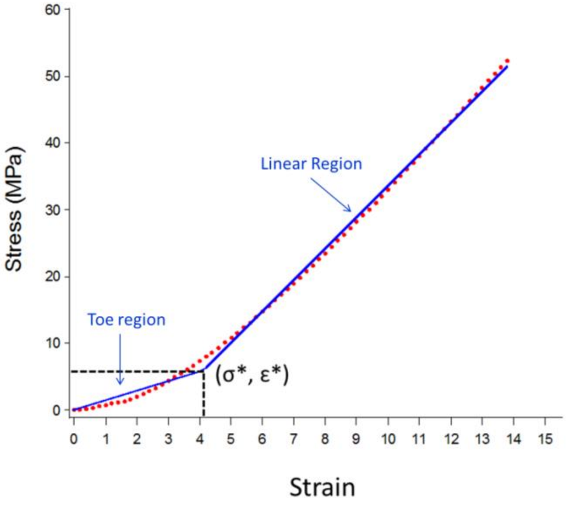

Figure 2. A representative stress-strain curve of the MCL is divided in a toe region (low load activities) and a linear region (high load activities). The point where the toe region turns into a linear region is the transition point (σ^*, ε^*). σ^*= transition stress; ε^*= transition strain

RESULTS

All ligaments showed a stress-strain curve with an initial non-linear toe region followed by a linear region, ultimately leading to sample failure. (Figure 2) Only those samples where mid-substance failure occurred were analyzed. In total, 19/21 ALL, 12/12 MCL, 11/12 LCL, 12/12 MPFL and 19/21 ALL could be used.

All analyzed mechanical properties are showed in Table 1. The elastic modulus was significantly ($P<0.05$) higher for the MCL (79 MPa ±31) than for the ALL (43 MPa ±29), but not for the LCL (57 MPa ± 27) and the MPFL (67 MPa ± 44). (Table 2) The strain value where the toe region turned into a linear region was significantly higher for the LCL (10.8% ± 4.2) and ALL (9.2% ± 3.3), relative to the MCL (5.9 % ± 1.7) and MPFL (5.3 % ± 0.8). (Table 2) No significant differences for stress at this transition point were seen between the ligaments.

Table 1: Results (mean ± standard deviation) obtained from tensile testing

	Elastic Modulus (MPa)	**Transition Strain (%)**	**Transition Stress (MPa)**
MCL	79±31	5.9±1.7	4.7±2.5
LCL	57±27	10.8±4.2	5.9±3.2
MPFL	67±44	5.3±0.8	3.5±2.3
ALL	43±29	9.2±3.3	3.8±2.6
P Value	0.0337	<0.0001	0.1358

Table 2. The obtained P-values from the statistical analysis of data obtained from tensile testing. NS = not significant (P<0.05). No significant differences were observed for stress at the transition point.

		MCL	LCL	MPFL	ALL
Elastic Modulus	MCL	/	NS	NS	0.0052
	LCL		/	NS	NS
	MPFL			/	NS
	ALL				/
Transition Strain	MCL	/	0.0002	NS	0.0031
	LCL		/	<0.0001	NS
	MPFL			/	0.0007
	ALL				/

DISCUSSION

The main purpose of this study was to provide a detailed characterization of the toe region mechanical properties of the MCL, LCL, MPFL and ALL. Our data support the hypothesis that the investigated knee ligaments demonstrate significantly different low load properties amongst each other. The principal finding is that the strain at the transition point from the toe region to the linear region, is significantly higher for the LCL and ALL than for the MCL and MPFL. Moreover, the slope of the non-linear toe region was significantly higher for the MCL relative to the ALL. No significant difference in elastic modulus was seen between the MCL and LCL. Considering the importance of the low load properties in daily activities [135,198], this knowledge is crucial for further improving our understanding of the behavior of ligaments, but also for choosing an appropriate graft in reconstructive procedures. But also in total knee arthroplasty, this knowledge could be important for how surgeons should balance a knee, and more specifically, how this knowledge effects the use of a ligament balancer.

When a ligament is loaded in tension, it responds by elongating and thus helps in maintaining normal kinematics and guiding joint motion. Hereby, the toe region is characterized by larger elongations due to progressive fiber recruitment. In the linear region, however, fibers are being stretched and the stiffness is higher [135]. Our data showed that there are significant differences between ligaments in the extent of this toe region. The strain is defined as the deformation per unit length of a ligament and for the toe region the strain for the LCL (10.8% ± 4.2) was twice as high as for the MCL (5.9 % ± 1.7). It has been demonstrated that daily living activities occur at low strain rates in the toe region of a ligament. [198,199] Considering the LCL is typically seen as a primary lateral restraint and the MCL as a primary medial restraint in the coronal plane[188], our finding seems to correspond with the natural laxity in the lateral compartment of the native knee as well as the higher prevalence of injuries of the MCL in comparison to the LCL.

To the best of our knowledge, we believe this study to be the first one to analyse the low load (toe region) properties of knee ligaments. Only one study on toe region properties was found, investigating the behavior of the patella tendon. [198] The conclusion of this paper showed that toe region mechanical properties are dependent on sex, height and BMI. It attributes these differences to the fact that people exert different magnitudes of load on the patellar tendon, which affects the properties through remodeling.

The mechanical properties characterize the intrinsic behavior of the ligament and are dependent on the collagen composition, fiber orientation, and the interaction between collagen and the ground substance. [135] Prior work on mechanical properties of knee ligaments has mainly focused on the linear region and examined elastic modulus, strain energy density and maximum stress and strain. [101,148,177,190,192,193,195] Previous work from our research group within the same specimen pool showed a significant higher elastic modulus for the MCL, relative to the LCL, MPFL and ALL. [193] Moreover, the maximum strain of the LCL (41.0 ± 9.9%) and ALL (37.8 ± 7.9%) were significantly higher compared to the MCL (22.9 ± 2.5%) and MPFL (22.2± 5.6%). If we analyze those results with the current study, it was noticed that the transition strain value varies around 25% of the maximum strain for each ligament (respectively 26.3%, 24.3%, 25.8% and 23.9%).

Our study has a number of strengths but also some limitations. In literature, strain of ligaments has been measured by different techniques and is considered one of the most challenging endeavors in biomechanical science. [135,194] In our study the deformation of the tested ligaments was determined by grip-to-grip displacement and thus only allowed to characterize the global strain behavior of the tested ligaments. However, a future analysis with the use of e.g. digital image correlation[202] could give an even more detailed view on more local differences in strain behavior. Absence of slippage of the specimen within the grips, known to affect strain readings, was confirmed by video recording during all tests. Only samples that showed mid-substance failure were included.

Secondly, accurate measurements of cross-sectional area is necessary and potential errors were minimized by performing the measurements by the same person five times and taking the mean was taken. Third, the toe region is a non-linear curve and properties were determined by approximating it by a linear function. Fourth, variability in mechanical properties for different sex, age and physical activity is known but efforts were made to obtain cadavers from a similar age range. Fifth, only quasi-static properties were measured at room temperature, whereas ligaments are viscoelastic materials that have time- and temperature dependent properties. [157,158]

Studies on the mechanical properties of ligaments are showing a wide variability in outcome and this is probably due to the biologic variability between specimens and the variations in testing methods. A strength of this study is that a standardized testing protocol was used with the same cross-sectional area calculations, strain rate and clamping technique for all ligaments. Herewith, our study showed significant differences between the investigated ligaments, suggesting that ligament fibers differ in composition and behavior. Future studies have to focus on the ultrastructural and biochemical properties to explain those differences. Furthermore, our results were compared with our previous investigations. [193] A strength is that the same specimen pool was used, which reduced the biologic variability and made the comparisons more reliable.

CONCLUSION

Our study demonstrates that knee ligaments behave significantly different in low-load versus high load conditions. The strain at the transition point from the toe region to the linear region, was significantly higher for the LCL and ALL than for the MCL and MPFL. In addition, the slope of the non-linear toe region was significantly higher for the MCL relative to the ALL. No significant difference in elastic modulus was seen between the MCL and LCL. The clinical consequence of our findings is that the low load conditions of ligaments should be taken into consideration when considering the optimal graft material for reconstruction.

PART III

RECONSTRUCTION OF THE ANTEROLATERAL LIGAMENT

CHAPTER 1

Mechanical Analysis of Extra-Articular Knee Ligaments.

Part two: Tendon grafts used for knee ligament reconstruction

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The Knee

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ABSTRACT

Purpose

The aim of this study was to provide information about the mechanical properties of grafts used for knee ligament reconstructions and to compare those results with the mechanical properties of native knee ligaments.

Methods

Eleven cadaveric knees were dissected for the semitendinosus, gracilis, iliotibial band (ITB), quadriceps and patellar tendon. Uniaxial testing to failure was performed using a standardized method and mechanical properties (elastic modulus - ultimate stress - ultimate strain - strain energy density) were determined.

Results

The elastic modulus of the gracilis tendon (1458±476 MPa) ($P<0.001$) and the semitendinosus tendon (1036±312 MPa) ($P<0.05$) was significantly higher than the ITB (610±171 MPa), quadriceps tendon (568±194 MPa) and patellar tendon (417±107 MPa). Also the ultimate stress of the hamstring tendons (gracilis 155.0±30.7 MPa and semitendinosus 120.1±30.0 MPa) was significant higher ($P<0.001$, respectively $P<0.05$), relative to the ITB (75.0±11.8 MPa), quadriceps tendon (81.0±27.6 MPa) and patellar tendon (76.2±25.1 MPa). A significant difference ($P<0.05$) could be noticed between the ultimate strain of the patellar tendon (24.6±5.9 %) and the hamstrings (gracilis 14.5±3.1% and semitendinosus 17.0±4.0%). No significant difference in strain energy density between the grafts was observed.

Conclusions

Material properties of common grafts used for knee ligament reconstructions often differ significantly from the original knee ligament which the graft is supposed to emulate.

INTRODUCTION

The use of tendon autografts for knee ligament reconstructions is extremely common. Different grafts around the knee have been used for intra- and extra-articular ligament reconstructions. Many graft materials show good clinical results and are chosen because of their size, structural properties, ease for harvesting, patient activity level, surgeon experience and preference, and availability. [161,164,165,173-175,203] Hamstring autografts are often preferred as graft because of its low donor-site morbidity [204], tensile strength [203] and its geometric properties [165]. For anterior cruciate ligament (ACL) reconstructions, the patellar tendon autograft is a widely accepted graft with good to excellent clinical results [204,205]. On the other hand, the quadriceps tendon is less commonly used for this but also have been reported with excellent results with a low rate of morbidity. [206] Finally, the use of the iliotibial band (ITB) as a graft is particularly popularized for a lateral extra-articular tenodesis in combination with ACL reconstructions to better control knee rotation [67,68,207]

Too stiff grafts have the potential to overconstrain a certain part of the joint thus theoretically predisposing the patient for detrimental long-term effects on the cartilage. [38] On the other hand, more elastic grafts can cause residual joint laxity. Knowledge about the mechanical properties is therefore important for understanding the intrinsic behavior of the graft itself and is necessary information for choosing a graft and for comparing it with the native ligament. Those properties are independent of the size or amount of tissue and are not influenced by the effect of the attachment sites. [135]

While the mechanical properties of the patellar tendon are well established [190,197,208-217], there are relatively few studies about the hamstrings [197,208,214,218], ITB [156,197,208] and quadriceps tendon [197,215,216,219]. Moreover, between those studies, a lot of variation in results is observed and comparing such studies is difficult because results can vary markedly depending on the methods of testing and the biologic variability that exists between human cadavers. [203] Therefore, the primary purpose of this study was to provide information about the mechanical properties of typical grafts currently used for knee ligament reconstructions. We hypothesize that those grafts present different mechanical characteristics. The secondary purpose was to compare those results with the previously studied mechanical properties of native knee ligaments [220]. The hypothesis was that the mechanical properties of knee ligaments are distinct from the tendon grafts used to reconstruct them.

METHODS

Eleven cadaver knees (82±24 yr) were obtained under ethical approval from Katholieke Universiteit Leuven. The knees had no history of injury, instability or prior surgical intervention. Additionally, donors with grade III or IV arthrosis or ACL deficiency were excluded. For graft harvesting, a midline incision was performed. The hamstring tendons (gracilis and semitendinosus) were identified under the sartorius aponeurosis and were cut at their tibial insertion. With a closed stripper they were detached from their muscle bodies and examined to ensure that there were no signs of damage. The middle third of the patellar tendon was cut from the insertion sites on the patella and tibial tubercle. The quadriceps tendon sample was taken by making a 10 cm long and 2 cm wide partial thickness strip and peel it off from the patella insertion. Furthermore, a 10cm long and 2cm wide ITB strip was cut out and detached from the periosteum at Gerdy’s tubercle. In total, 11 samples from each graft were dissected from the specimens by the same orthopaedic resident. Once removed, the samples were wrapped in saline-soaked gauze, placed in freezer bags, and stored at -80°C until the time of testing.

Mechanical Testing

Prior to testing samples were removed from the freezer and allowed to thaw at room temperature for 24 hr. Once thawed, samples were cut into standardized shapes (dog-bone) using a surgical scalpel to form a uniform cross-sectional area in the mid-substance of the tendon, thus providing a uniform stress distribution during testing [177,178]. Samples were mounted in custom made tensile grips which had sandpaper between the grip faces to provide anchorage. Additionally, cyanoacrylate adhesive was used to provide additional protection against slippage. The tensile grips were aligned axially (i.e. in line with the ligament fibers) within a materials testing frame (model 4467, Instron, Norwood MA, USA) equipped with a 1 kN calibrated load cell. (figure 1) A 1 N preload was applied to the samples and measurements of the cross-sectional area were taken with a digital micrometer five times and the average calculated, always done by the same researcher. The distance between the grip faces was measured and was used as the original gage length. Ten preloading cycles consisting of a ramp from 1 – 10 N at a strain rate of $0.1\%s^{-1}$ was performed which were followed immediately by a ramp-to-failure test at a strain rate of $2\%s^{-1}$. Force and displacement data were measured at 100 Hz. Samples were kept wet with saline to prevent dehydration and all tests were performed at room temperature (~22 °C).

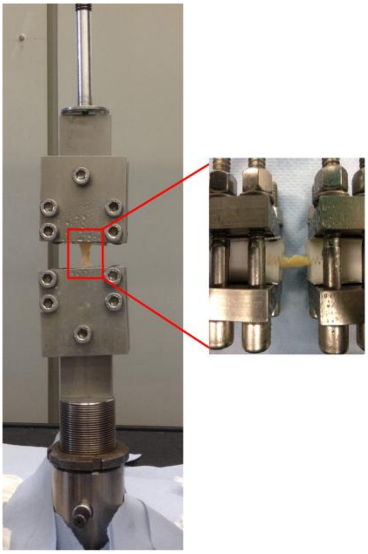

Figure 1: Custom made tensile grips were used to perform tensile testing and were integrated in the testing setup.

Only those samples that showed mid-substance failure were used. Consequently, data from 11 semitendinosus, 11 gracilis, 9 ITB, 9 quadriceps and 8 patellar tendons were analyzed. The collected force and displacement data were converted to stress (applied force / average cross sectional area) and strain (change in length / original gage length) to allow the calculation of the ligament mechanical properties: elastic modulus (slope of the linear portion of the stress-strain curve), ultimate stress (stress at failure), ultimate strain (strain at failure), and strain energy density (energy absorbed to yield).

Statistical analysis

Commercially available software (SPSS 24, IBM, Armonk, NY, USA) was used for all statistical analysis and the significance level was set to α = 0.05. Data were found to exhibit normal distributions using the Shapiro-Wilk test, therefore, parametric statistical analysis was used. Data were assessed for significance using one-way analysis of variance (ANOVA) with pairwise multiple comparisons used for post-hoc analysis (corrected for multiple comparisons with the Bonferroni adjustment). Additionally, the homogeneity of variance was assessed using Levene's test. If data were found to violate the (ANOVA) assumption of homogeneity, the Brown-Forsythe test was utilized. Where applicable, data are presented as the mean ± standard deviation.

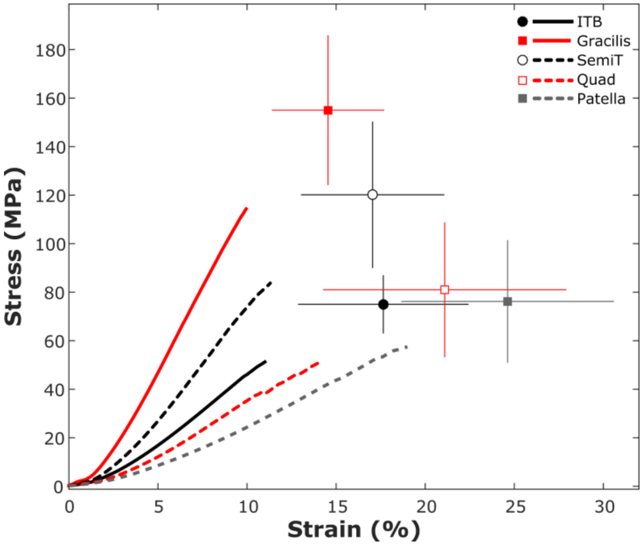

Figure 2: Average stress-strain curves for the ITB, gracilis, semitendinosus, quadriceps and patella specimens. The final points represents the average ultimate stress and ultimate strain and the error bars indicate the standard deviation.

RESULTS

All grafts demonstrated an initial non-linear toe region followed by a linear stress-strain relationship leading to sample yield/failure. For all samples, failure always occurred within the mid-substance of the sample. (figure 2)

The *elastic modulus* of the gracilis tendon (1458±476 MPa) ($P<0.001$) and the semitendinosus tendon (1036±312 MPa) ($P<0.05$) was significantly higher than the ITB (610±171 MPa), quadriceps tendon (568±194 MPa) and patellar tendon (417±107 MPa). (table 1) (table 2)

The *ultimate stress* of the gracilis (155.0±30.7 MPa) and semitendinosus (120.1±30.0 MPa) was significant higher ($P<0.001$, respectively $P<0.05$), relative to the ITB (75.0±11.8 MPa), quadriceps tendon (81.0±27.6 MPa) and patellar tendon (76.2±25.1 MPa). (table 1)

The *ultimate strain* of the patellar tendon (24.6±5.9 %) was significantly higher ($P<0.05$) than the hamstrings (gracilis 14.5±3.1% and semitendinosus 17.0±4.0%), but no significant difference was seen with the quadriceps tendon (21.1±6.8 %) and the ITB (17.6±4.8 %). (table 1)

The *strain energy density* showed no significant differences between the grafts. (table 1)

Table 1: Results (mean ± standard deviation) obtained from tensile testing

	Elastic Modulus (MPa)	**Ultimate Stress (MPa)**	**UltimateStrain (%)**	**Strain Energy Density (MPa)**
ITB	610±171	75.0±11.8	17.6±4.8	6.5±2.3
Gracilis	1458±476	155.0±30.7	14.5±3.1	10.9±3.3
SemiT	1036±312	120.1±30.0	17.0±4.0	10.3±3.3
Quad	568±194	81.0±27.6	21.1±6.8	8.5±5.5
Patella	417±107	76.2±25.1	24.6±5.9	9.0±5.0

Table 2: The obtained P-values from the statistical analysis of data obtained from tensile testing. An emrule indicates the lack of a statistical test. Strain energy density was not significantly influenced by tendon type, therefore, post-hoc testing was not conducted. NS – not significant (P > ,05)

Property	Specimen	ITB P	Gracilis P	SemiT P	Quad P	Patella P
Modulus	**ITB**	–	< ,001	,028	NS	NS
	Gracilis		–	,019	< ,001	< ,001
	SemiT			–	,012	,001
	Quad				–	NS
	Patella					–
Ultimate Stress	**ITB**	–	< ,001	,004	NS	NS
	Gracilis		–	,034	< ,001	< ,001
	SemiT			–	,020	,009
	Quad				–	NS
	Patella					–
UltimateStrain	**ITB**	–	NS	NS	NS	NS
	Gracilis		–	NS	NS	,001
	SemiT			–	NS	,020
	Quad				–	NS
	Patella					–

The relationship between the obtained mechanical properties for the tested grafts and each previous tested knee ligament is shown in Figure 3. A similar trend between the MCL-ITB-Quadriceps-Patella and MPFL- ITB-Quadriceps-Patella can be observed. Furthermore, these patterns suggest that there is no similarity between the mechanical properties of the ALL and LCL and the grafts.

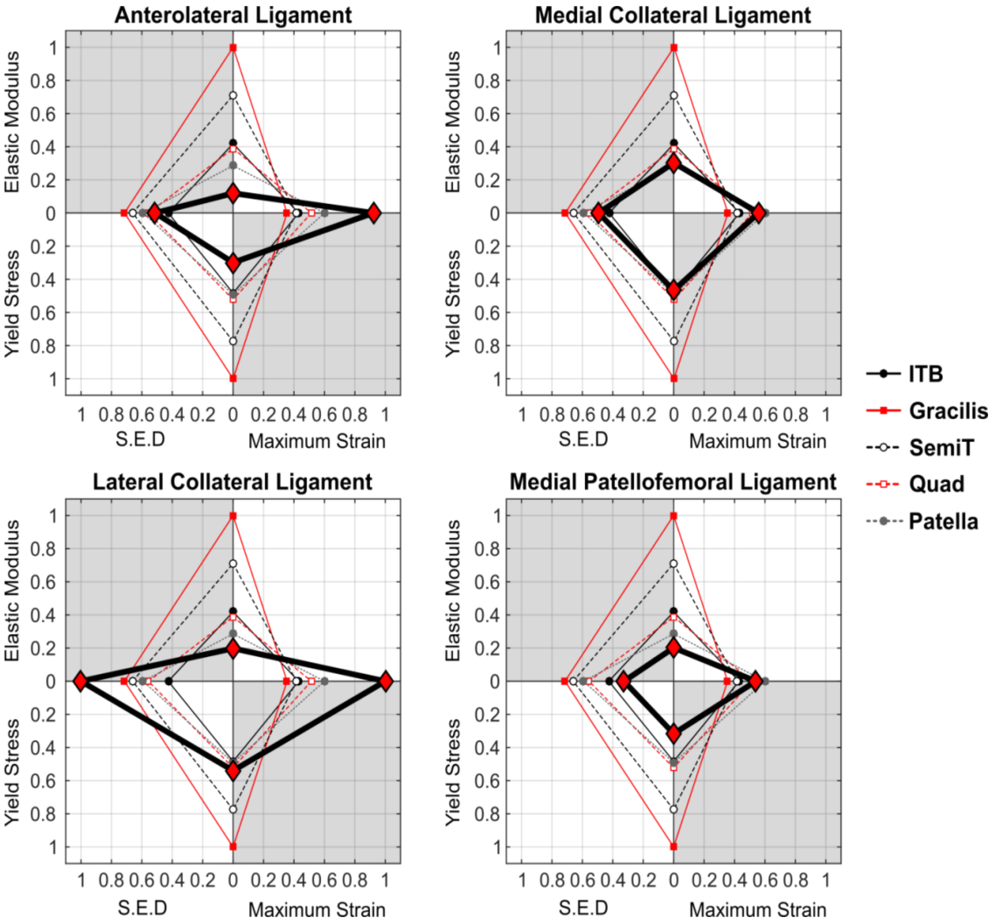

Figure 3: The relationship between the obtained mechanical properties for the tested grafts and previous tested ligaments. Data are normalized to the maximum value obtained for all tested specimens, regardless of ligament/graft type. Black lines / red diamonds represent the average value for each ligament. S.E.D. = strain energy density

DISCUSSION

The primary purpose of this study was to provide information about the mechanical properties of grafts used for knee ligament reconstructions. Our data support our hypothesis that tendon grafts possess different mechanical properties. The primary finding indicate that the elastic modulus and the ultimate stress of the hamstring tendons is significantly higher than the other grafts. Moreover, the gracilis showed a significantly higher elastic modulus and ultimate stress than the semitendinosus, while the ultimate strain and strain energy density being the same. Although higher absolute values were measured in our study – possibly due to differences in methodology for cross-sectional area and testing protocol – the same significant differences in material properties between the hamstring tendons were reported by Abramowitch et al.[218]

An overview comparing previously reported mechanical properties for the semitendinosus, gracilis, ITB, quadriceps and patellar tendon is provided in Table 3. The results of the different studies on material properties vary markedly, thus making comparisons difficult. Donor age, strain rate, biologic variability, cross-sectional area calculation and clamping technique are variables that can explain the differences between studies. Of interest in our study is that a standardized testing protocol was used, the cross-sectional area was measured by the same person and grafts were taken from the same knee. Remarkably in our data is the significant difference in modulus, ultimate stress and strain between the hamstring tendons and the patellar tendon and the same trend can be observed in previous literature. (Table 3) So from a material standpoint, hamstring grafts are stronger and less compliant than patellar tendon grafts and this is of clinical importance when choosing a graft in, for example ACL reconstruction surgery, certainly if one considers the remodeling process of the grafts whereby their mechanical properties have been shown to deteriorate. [221] On the other hand, some studies have suggested that hamstring grafts are more likely to fail than patellar tendon grafts in ACL reconstructions [222]. Many other factors influence the strength and durability of a graft, for example the biologic ingrowth and fixation method. [203,218] Although the quadriceps tendon - compared with the hamstrings and patellar tendon - is the least used autograft in ACL reconstruction, review articles showe that this is a safe, reproducible and versatile graft. [206,223] Data from our study demonstrate that there is no significant difference in material properties between the quadriceps and the patellar tendon.

The ideal graft should have structural and material properties similar to those of the native ligament. The structural properties of the grafts have been studied extensively [144,216,224-226] and are dependent on the geometry of the tissue or entire construct. Conversely, material properties characterize the behavior of the tendon itself, independent of the the size or amount of tissue and is determined by the composition and micro-architecture of the tissue. Abramowitch et al. even suggested that those data can be used within computational models to more accurately predict the behavior of constructs in response to clinically relevant loading conditions that cannot be simulated experimentally. [218]

The target of the ideal graft is to mimic the properties of the original ligament. Therefore, the secondary purpose of our study was to compare our results with data from the native knee ligaments. Hereby our hypothesis was confirmed and mechanical properties of the investigated grafts possess different characteristics as those of the native knee ligaments. Figure 3 provide information about the relationship between the material properties of the grafts and those of the knee ligaments investigated in the first part of this study. Of added value is that the same standardized testing protocol was used and that dissections and cross-sectional area calculation was done by the same person. Remarkable is that both the ALL and LCL show no similarity with the investigated grafts. The renewed interest in the ALL [2] had led several institutions to describe anatomic reconstruction techniques using ITB or hamstring tendons. [78,124,126,128,227] Although the authors recognize the role of the ALL as a secondary stabilizer against internal rotation [117,131], this study suggests that current ALL reconstructions utilizing both ITB or hamstring tendons could potentially overconstrain the lateral compartment of the knee. It should be mentioned that material properties are not the only factor that influence the structural integrity of a graft construct and that also the quantity of the tissue and the method of fixation will contribute significantly. In this view, the use of soft anchors or soft tissue fixation might be beneficial when performing ALL reconstruction with

Table 3: Comparison of the mechanical properties from the current study with previously reported data. All data are presented as mean ± standard deviation. A dashed line indicates the property was not reported. Note, only mechanical properties, not structural properties (stiffness, load at failure), are reported here.

Reference	**Structure**	***N***	**Modulus (MPa)**	**Ultimate Stress (MPa)**	**Ultimate Strain (%)**	**Strain Energy Density (MPa)**
Noyes [197]	Patella	7	305±59	58.3±6.1	26.5±2.9	---
Butler [190]	Patella	19	643±53	68.5±6	13.5±7	5.03±1.6
Haut [217]	Patella	3	191±16	26.6±2.8	26.6±10	---
Cooper [210]	Patella	5	---	95.5±16.8	15.8±4	---
Johnson [211]	Patella	15	660±266	64.7±17	14±6	---
Blevins [212]	Patella	82	310±95	35.9±10.9	---	---
Flahiff [213]	Patella	33	340±97	78.4±18.5	31.4±5.9	---
Yanke [209]	Patella	10	---	41±12.5	21±3	---
Handl [214]	Patella	21	---	40.6±7.1	---	---
Butler [208]	Patella	7	305.5±59	58.3±6.1	26.5±2.9	9.9±1.9
Staubli [215]	Patella	7	811.7±154.1	69.6±8.3	14.4±3.3	---
Shani [216]	Patella	11	337.8±67.7	33.4±9.0	11.4±2.1	---
Current Study	Patella	8	417±107	76.2±25.1	24.6±5.9	9.0±5.0
Noyes [197]	Quadriceps	6	---	16.1±1.8	---	---
Mabe [219]	Quadriceps	9	153±46	19.1±5.42	16±2	---
Staubli [215]	Quadriceps	8	462.8±68.5	38±5	11.2±2.2	---
Shani [216]	Quadriceps	12	255.3±61.4	23.9±7.4	10.7±1.4	---
Current Study	Quadriceps	9	568±194	81.0±27.6	21.1±6.8	8.5±5.5

Noyes [197]	ITB	10	---	19.1 (2.9)	---	---
Hammer [156]	ITB	38	369±191.5	35.8 (16.4)	---	---
Butler [208]	ITB	18	397.5±17.1	78.7 (4.6)	27±1.1	12.8±1.1
Current Study	ITB	9	610±171	75.0±11.8	17.6±4.8	6.5±2.3
Noyes [197]	Semitendinosus	11	---	88.5±5.0	---	---
Handl [214]	Semitendinosus	7	---	88.7±7.8	---	---
Abramowit[218]	Semitendinosus	10	484.5±124.8	48.5±11.8	14.1±2	3.4±1
Butler [208]	Semitendinosus	11	362.2±21.6	88.5±5	33.2±1.8	23.4±1.3
Current Study	Semitendinosus	11	1036±312	120.1±30.0	17.0±4.0	10.3±3.3
Noyes [197]	Gracilis	11	---	111.5±4.0	---	---
Handl [214]	Gracilis	7	---	95.1±13.1	---	---
Abramowit[218]	Gracilis	10	625.5±148	63±13.3	13.6±2.1	4.3±0.9
Butler [208]	Gracilis	11	612.8±40.6	111.5±4	26.7±1.4	17.7±1.7
Current Study	Gracilis	11	1458±476	155.0±30.7	14.5±3.1	10.9±3.3

hamstrings or ITB grafts [207,228]. Furthermore, hamstring tendons are frequently used autografts in medial patellofemoral ligament (MPFL) reconstructions [229] but shows no clear relationship with the native MPFL. (Figure 3) Reconstruction techniques using a quadriceps or patellar tendon autograft are described [230-232] and seems more appropriate based on the material properties alone. In addition, hamstring tendons are also common used grafts in MCL reconstructions [233,234], but a clear correlation could only be noticed between the material properties of the MCL and those of the ITB, quadriceps and patellar tendon. (Figure 3)

There are several limitations in our study. First, the tensile tests were performed with samples dissected from older specimens and results are possibly an underestimation of the mechanical properties of younger patients who typically undergo ligament reconstruction. [135] Second, the fixation method is a basic consideration when performing biomechanical analysis of tissue samples. All samples showed mid-substance failure and no slippage of the graft during testing was noticed. Third, variation in cross-sectional area determination could affect the results and therefore all measurements were performed by the same person 5 times and the mean was taken. Fourth, ligaments are viscoelastic materials yet only the quasi-static properties were measured in this study. It has been shown that the strength of those materials are dependent on the strain rate [235], which was kept at $2\%s^{-1}$ to minimize viscoelastic effects. Fifth, although variation in results were reduced by doing the dissections, the tensile tests and the cross-sectional area calculations by the same person, samples from the first and second part of this study were obtained from different cadaveric knees and biologic variability can play a role when comparing both data. Sixth, non-normally distributed data from different cadaveric specimens [31] were used in figure 3 to compare with the results of this study. Finally, few studies have shown that mechanical properties can differ significantly along the length of tendons, with the modulus generally increasing toward the distal attachment. [218,236] Our study examined the distal part of the hamstrings and ITB, and the central third of the quadriceps and patellar tendon.

CONCLUSION

Our data showed that different grafts possess distinct material properties. The hamstring tendons have an elastic modulus and ultimate stress that is significantly higher than the patellar and quadriceps tendon. No significant difference in material properties was seen between the quadriceps and patellar tendon. The elastic modulus and ultimate stress of the gracilis was higher than the semitendinosus.

Material properties of common grafts used for knee ligament reconstructions often differ significantly from the original knee ligament which the graft is supposed to emulate. No similarity was seen between the ALL, LCL, MPFL and the investigated grafts. Synthetic grafts were not tested and this could be an interesting topic for future studies.

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CHAPTER 2

High Risk of Tunnel Convergence During Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstruction

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ABSTRACT

Purpose

The main purpose was to assess the risk of femoral tunnel convergence in combined anterior cruciate ligament (ACL) and anterolateral ligament (ALL) reconstructions. Our hypothesis was that a more proximal and anterior orientation of the ALL femoral tunnel should reduce the risk of convergence with the ACL femoral tunnel. The second purpose was to examine the relationship between the lateral femoral condyle (LFC) width and tunnel conflict occurrence.

Methods

Fifteen fresh-frozen cadaver knees were examined. An anatomic ACL femoral tunnel was drilled arthroscopically in each specimen and ALL tunnels were made in two directions: 1) 0° coronal angulation and 20° axial angulation , 2) 30° coronal angulation and 30° axial angulation. Computed tomography scans were performed to investigate tunnel convergence and to measure the minimal distance between tunnels, tunnel length and the LFC width.

Results

Tunnel convergence occurred in 67% of cases. Convergence was significantly reduced when tunnels were drilled at 30° coronal and 30° axial angulation ($P<0.05$). The mean length of the ALL tunnel was 15.85mm and was independent of ALL tunnel angulation. The mean minimal distance between the ALL and ACL tunnel was 3.08mm. The odds ratio for tunnel convergence was 3.5 for small LFC, relative to large LFC.

Conclusion

A high risk of tunnel convergence was observed when performing combined ACL and ALL reconstructions. Aiming the ALL tunnel in a more proximal and anterior directions could reduce the occurrence of tunnel conflicts. Surgeons should be aware of this, since tunnel convergence could jeopardize the ACL reconstruction and fixation.

INTRODUCTION

An anterior cruciate ligament (ACL) tear is one of the most common sports injuries, and frequently requires surgical reconstruction. [237,238] When performing a state-of-the-art intra-articular ACL reconstruction (ACLR), a remaining pivot shift has been reported to persist in 11% to 60% of patients [33-35] and failure of the graft is seen in approximately 1.7% to 18% of patients. [237,239] This high failure rate has led to the combination of an intra-articular ACLR and lateral extra-articular tenodesis (LET) in an attempt to control anterolateral instability and to reduce tension on the ACL graft. [78,80,84,131,240]

Recent studies have shown that the anterolateral ligament (ALL) functions as a secondary stabilizer to the anterior cruciate ligament (ACL) in resisting anterior tibial translation and internal tibial rotation [4,51-54]. Therefore, anatomical ALL reconstructions (ALLR) are becoming increasingly popular among orthopaedic surgeons as a LET procedure to augment an ACLR. Several authors agree on performing ALLR in revision cases, patients with a high-grade pivot shift and high-level athletics. [126-129] Since the rediscovery of the ALL [2], clinical outcome studies of ALLR are showing promising results and a reduced failure rate. [78,133]

The current trend in ACLR is to position the femoral tunnel relatively oblique through the anteromedial portal, in order to better reproduce the native ACL anatomy and orientation for controlling tibial rotation. [5,241-243] The femoral insertion of the ALL varies [2,90,95,124,244] but the ALL Expert Group reached a consensus that the femoral attachment is posterior and proximal to the lateral epicondyle. [98] This implies that the femoral ACL tunnel is in closer proximity of the ALL origin, and so there is theoretically more chance to interfere with the ALLR. Despite the increasing number of studies on anatomic ALLR, to our knowledge no studies exist on the risk of tunnel convergence.

Tunnel convergence is seen in combined ACL and posterolateral corner (PLC) reconstructions. [245-248] Because of the close proximity of the LCL and ALL femoral origin [95], it is reasonable to expect tunnel conflicts in ALLR. In case this is correct, during drilling potential damage could occur to the reconstructed ACL femoral attachment due to the conflicting tunnels.

The main objective of this study was therefore to assess the risk of femoral tunnel convergence in combined ACL and ALL reconstructions. We hypothesize that a more proximal and anterior orientation of the ALL femoral tunnel should reduce the risk of convergence with the ACL femoral tunnel. The second objective was to examine the relationship between the lateral femoral condyle (LFC) width and tunnel conflict occurrence.

MATERIAL AND METHODS

Fifteen fresh-frozen cadaver knees (9 woman, 6 men) were studied after ethical approval from the Institutional Review Board at the University of Hasselt. Age ranged from 65 to 103 years (mean 80.9). No donor had a history of knee injury or prior surgical intervention. All specimens were stored at -40°C and thawed at room temperature for 24 hours before testing.

Femoral Tunnel Drilling

All surgeries were performed by 2 orthopaedic surgeons. The knees were placed in a custom-made rig in which they could move freely between 0° and 130°. A high parapatellar anterolateral portal was made as a viewing portal. A low anteromedial portal was established as the working portal for the femoral ACL drilling. An arthroscopic debridement of the anterior cruciate ligament and notch was performed in order to have a clear view on the medial wall of the LFC. A femoral offset guide (Arthrex) of 6mm was placed behind the LFC while the knee was flexed to 125°. Next a ACL tightrobe drill pin 4mm (Arthrex) was drilled at a 2 or 10 o'clock position and subsequently overreamed to 8 mm.

A lateral longitudinal incision of 8-10cm over the lateral epicondyle(LE) was made and subcutaneous tissue and fascia lata were removed. The ALL insertion point was identified, as described by the ALL Expert Group, just proximal and posterior of the LE. [98] From this position, two 2.4mm guidewires were drilled in 2 different orientations: 1) 0° coronal angulation and 20° axial angulation , 2) 30° coronal angulation and 30° axial angulation. (figure 1) In the coronal plane, the 0° angulation was perpendicular to the anatomical axis of the femur. In the axial plane, a 2 mm K-wire was reamed through the epicondylar axis and this was used to create the 20° or 30° axial directions with the help of a manual goniometer. Both 2.4mm guidewires were overdrilled to increase their diameter to 4.5mm.

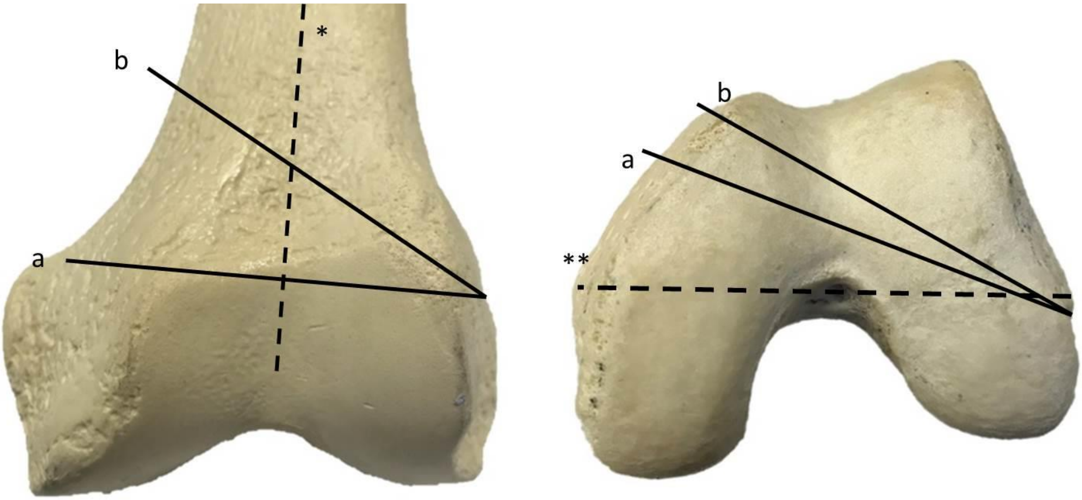

Figure 1: The ALL tunnel was drilled at (a) 0° coronal and 20° axial angulation and (b) 30° coronal and 30° axial angulation. *= anatomical axis ; **= transepicondylar axis

Computed Tomography Imaging

After the tunnels were completed, specimens were transported to the radiology department and imaged by computed tomography (CT) on a Siemens Somatom Force dual source 192-slice CT scanner (Siemens Healthineers, Erlangen, Germany) using tube voltage settings of Sn150kV and 300mAs and a bone kernel. 3D post processing of the thin slices (slice thickness 0.4 mm, isotropic voxels) was performed using bone window and level settings on Syngo.Via VB10B software (Siemens Healthineers, Huizingen, Belgium) and allowed for assessing tunnel convergence and measuring distances (figure 2).

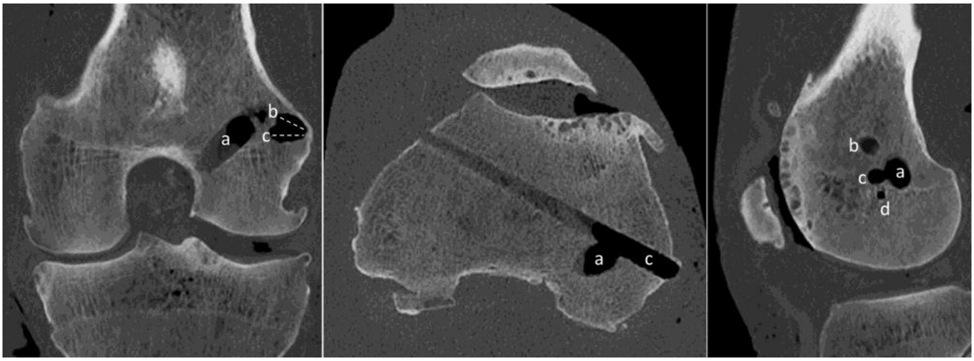

Figure 2: Computed tomography scan of tunnel convergence in the coronal, axial and sagittal plane. a = ACL tunnel; b= 30° coronal and 30° axial ALL tunnel; c= 0° coronal and 20° axial ALL tunnel; d = transepicondylar axis

All measurements were performed by an expert musculoskeletal imaging radiologist and confirmed by an experienced orthopaedic surgeon. Drilling angles were measured and matched the intended angles. The occurrence of tunnel convergence between both ALL tunnels and the ACL tunnel was noted. If convergence was observed, the length of both tunnels from the entry point to the conflict was measured. If no tunnel interference was seen, the minimal distance between the ACL and ALL tunnel was calculated for data analysis. In addition, tunnel length was measured for both tunnels from their entry point to the point where the tunnel was at his shortest distance to the other tunnel. To determine the relationship between LFC width and tunnel convergence all knees were divided in two groups, depending if there were above or below the average LFC width.

Statistical Analysis

For each knee, the outcomes are observed for both ALL tunnel angulations. As a result, the measurements cannot be treated as independent. We used a generalized estimating equations (GEE), model with an unstructured working correlation to take into account the dependency of observations. For the binary outcome (convergence of tunnels yes or no) a logit link with a binomial distribution was specified and for the continuous outcomes (distances and length) an identity link with a normal distribution was used. The effect of ALL tunnel angulation is investigated in this model by introducing ALL tunnel angulation as dependent variables in the model. A 5% level of significance is used and statistical analysis are performed in SAS for windows version 9.4.

RESULTS

The overall rate of tunnel convergence was 67%. Convergence occurred significantly more frequent (P=0.0072) when tunnels were drilled at 0° coronal and 20 axial angulation (87% conflicts) compared to 30° coronal and 30° axial angulation (47% conflicts), with an odds ratio of 7.43.

In the non-converging tunnels, the mean minimal distance between tunnels was 3.08 mm (95% ci [2.07; 4.11]), ranging from 1 to 6 mm. From that distance, the mean length of the ALL and ACL tunnels was respectively 17.46 mm (95% ci 14.36; 20.54]) and 22.95 mm (95% ci [19.95; 25.96]). When tunnel conflict occurred, the mean length of the ALL tunnel was 15.85 mm (95% ci [13.58; 18.12])] and 19.02 mm (95% ci [17.26; 20.79])] for the ACL tunnel. (Table 1)

All specimens were divided in 2 groups (large femurs / small femurs) according to the average LFC width of 28,8mm. There were 9 small femurs with a tunnel convergence rate of 77.7%. From the 6 large femurs, 50% of reaming combinations showed tunnel conflicts. There was no significant difference between both groups (P=0.1270) and an odds that was 3.5 times higher for the small femur group, relative to the large femur group.

Table 1. Tunnel length and minimal distance between ALL and ACL tunnels.

	Convergence		Non-convergence		
	ALL Tunnel Length	ACL Tunnel Length	Minimal Distance	ALL Tunnel Length	ACL Tunnel Length
0° coronal / 20° axial	15.94 (13.67-18.20)	16.70 (15.49-17.93)	1.34 (0.23-2.44)	19.73 (18.49-20.98)	17.14 (13.64-20.63)
30° coronal / 30° axial	15.58 (13.17-17.99)	22.97 (20.57-25.39)	3.34 (2.23-4.45)	16.80 (12.71-20.88)	23.79 (20.13-27.44)
P value	0.146	<0.001	<0.001	0.2246	<0.001

Notes. All data are expressed in millimeters as mean (95% CI). In non-convergence tunnels, tunnel length is measured from the entry point to the point where the tunnel is at the shortest distance to the other tunnel.

DISCUSSION

The primary finding of this work is that there is a high risk of tunnel convergence in combined ACL and ALL reconstructions. The risk of creating a tunnel conflict can be significantly reduced by drilling the ALL tunnel in a more proximal and anterior direction, supporting our initial hypothesis.

Despite the growing interest in anatomical ALL reconstructions and the high convergence rate in combined ACL and PLC reconstructions [245-248], to our knowledge, no studies were performed on the risk assessment for combined ACL and ALL reconstructions. When tunnels converge in multiple knee ligament reconstructions, it may lead to graft damage or excessively short tunnels. [246] During the last decades more attention has been drawn onto anatomical placement of the ACL femoral tunnel because of its biomechanical advantage for rotational stability. [249-251] In this study the femoral tunnel was drilled through a low anteromedial portal in the center of the ACL footprint. With this technique it was found to allow easier and more anatomical placement of the ACL tunnel compared to the transtibial technique. [252] As a consequence, the direction of the tunnel is more horizontal and in closer proximity with the ALL origin. There is some discussion about the exact femoral insertion, but experts reached a consensus that the ALL origin is just proximal and posterior to the lateral epicondyle [98], and thus this was used as the entry point of the ALL tunnel. Because of this close relation with the origin of the fibular collateral ligament (FCL), our tunnel directions were based on studies which examined tunnel conflicts in combined ACL-FCL reconstructions. Gelber et al. [246] and Moatshe et al. [248] found that 30° axial angulation and 0° coronal angulation was the most safe combination for FCL tunnel drilling. Gali et al. [245] concluded 20° axial and 20° coronal angulation as the least risky combination for tunnel convergence. Tunnel angulations greater than 40° in the axial plane were avoided because this can result in elliptical tunnels and thinned cortices. [247] In the same way, 0° directions in the coronal plane were excluded because of the risk of penetrating the posterior cortex or intercondylar notch. [245] The drilling angulation in the axial plane (20° and 30°) was referenced to the transepicondylar axis, and in the coronal plane (0° and 30°) it was referenced to a line perpendicular to the anatomical axis of the femur. This was done for a better reproducibility during real-life surgery.

The results in our study showed a significant reduction of the risk for creating a tunnel conflict when aiming the ALL tunnel in a more anterior and proximal direction. However, the direction of the ALL tunnel can also have an effect on the pullout strength of the ALL reconstruction. It has been showed that the angle between the bone anchor or interference screw and the bone surface should be 45° or less.[253] So theoretically, a more proximal and anterior direction of the ALL tunnel could result in a higher pull-out risk.

Femoral graft fixation for ALL reconstruction varies but is usually achieved by an interference screw or bone anchor, with a femoral socket diameter ranging from 4.5mm to 6mm and tunnel length of at least 20mm [98,124,126,128,240]. Our technique consists of a 1 cm wide iliotibial band strip that is passed underneath the most proximal part of the FCL and is fixed in a femoral socket of 25mm length using a 4.75mm fully threaded knotless anchor (SwiveLock PEEK, Arthrex). In this study a guide pin was overreamed by a 4.5mm drill until the medial femoral cortex was reached. In that way the length of the ALL tunnel could be measured from the lateral femoral entry point until the point where both tunnels were at the shortest distance from each other. Most authors recommend tunnel length of 20mm or 25mm for safe graft to bone tunnel healing. [246,252,254,255] Our results showed that the mean ALL tunnel length was 15.85 mm when convergence occurred. No significant difference between the different drilling combinations was noticed. (table 1) Because of the high rate of tunnel convergence and short ALL tunnel length, the authors recommend to first look arthroscopically through the ACL tunnel to see if the guide pin appears. (figure 3) If so, the guide pin can be re-drilled under arthroscopic view.

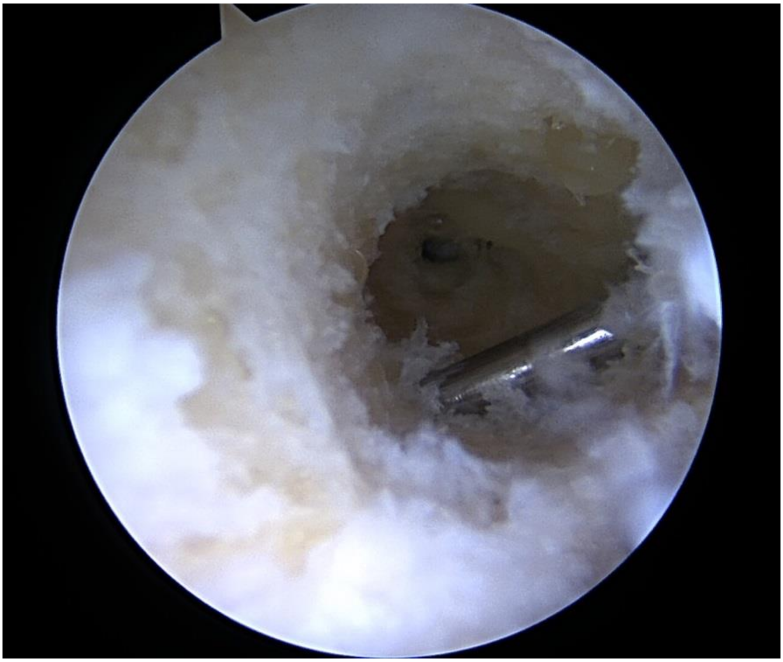

Figure 3: Arthroscopic view of a tunnel conflict between the ACL tunnel and the ALL tunnel guide pin drilled at 0° coronal 20° axial angulation.

The second objective was to investigate the LFC width as a predictive factor for tunnel conflicts. The odds to have a tunnel conflict was 3.5 times higher in knees with a small LFC relative to knees with a large LFC. The non-significant difference is probably due to the relative low sample size, although the number of cadaveric specimens in our study was higher than other papers that have used human knees to assess the risk of tunnel convergence. [245-247]

Our study has a number of limitations. A limited number of drilling combinations were tested, whereas in theory one could consider several other combinations of angulation. In addition, the ACL was drilled through an anteromedial portal in 125° of flexion using an offset guide, whereas several variations in anatomic ACL reconstructions exist. Another limitation is that only an 8 mm ACL tunnel diameter was used, based upon the most frequently used single-bundle ACL graft diameter. [256]

CONCLUSION

Our study demonstrates that a high risk of tunnel convergence exists in combined ACL and ALL reconstructions. The risk for such tunnel convergence can be reduced by aiming the ALL tunnel in a more proximal and anterior direction. The odds to have a tunnel conflict was 3.5 times higher in knees with a small LFC relative to knees with a large LFC.

CHAPTER 3

Risk Analysis of Tunnel Collision in Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstructions

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ABSTRACT

Purpose

To assess the risk of tunnel collision in combined anterior cruciate ligament (ACL) and anterolateral ligament (ALL) reconstructions.

Methods

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. An image processing program was used to simulate nine different ALL tunnel orientations with a tunnel depth of 25mm and 30mm, and potential tunnel collisions between the existing femoral ACL tunnel and the virtual ALL tunnel were examined and quantified. The minimal distance between tunnels, the ALL tunnel length, and the lateral femoral condyl (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. A significanty higher collision rate (P=0.001) was observed with a 30mm ALL tunnel. When collision of both tunnels was observed, the mean length of the ALL tunnel was 18.4 mm (95% CI: 16.6-20.1) when the ACL tunnel was drilled through an AMP.

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.

INTRODUCTION

Since a detailed anatomical description of the anterolateral ligament (ALL) was published in 2013 [2], 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. [88,91,93,95,195,257,258] In addition, biomechanical and histological studies have demonstrated that this structure displays the characteristics of a true ligament [18,88,195] 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 [4,51-54]. 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%. [107-109]

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. [84,131,259] 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. [5,98,124-130] Clinical outcome studies of combined ACL and ALLR show promising results and a reduced failure rate. [76,133]

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 [125,126,128,129], semitendinosus [124], iliotibial band [127] and polyester tape [130]. Biomechanical work has demonstrated that hamstring grafts have a 5-8x higher elastic modulus than the ALL and could therefore theoretically overconstrain the lateral compartment. [193,196] 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. [98]

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. [243,260,261] With this technique, the femoral tunnel is drilled through an anteromedial portal (AMP) which creates a biomechanical advantage on rotational stability. [242,249-251] Because of the more horizontal orientation of the femoral ACL tunnel [262], the tunnel comes in closer proximity with the ALL femoral origin, with a potential risk of tunnel collision and potential graft damage. [246] 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. [263,264]

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.

MATERIALS AND METHODS

Study Population

Thirty-two patients who underwent an ACLR were included in the study. In sixteen of them the femoral tunnel was drilled using a TT technique (9 men, 7 woman, mean 34.3±9.9y), in the other sixteen the AMP technique was used (9 men, 7 woman, mean 34.4±10.0y). All patients were randomly selected and ACLR were performed by three orthopaedic surgeons. The selection of the technique was based on the surgeon’s preference. The study was approved by the Institutional Review Board.

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; 120kV; 153 mA). Each CT-scan was processed by a medical image processing program (Mimics 17.0, Materialise, Leuven, Belgium) and 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.[98] 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, rotational variations from the neutral tunnel using 20° intervals were created to obtain 9 different ALL tunnel directions with a diameter of 4.5mm. (figure 1 and 2)

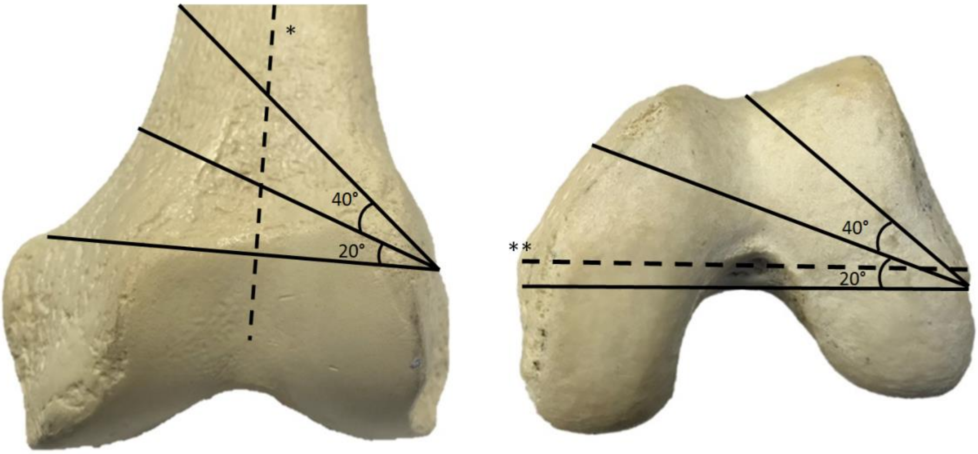

Figure 1. Nine different ALL tunnels were created by aiming the tunnel at 0°, 20° and 40° of coronal and axial angulation.

Figure 2. Medial and frontal view of a patient with an anteromedial portal (AMP) drilled ACL reconstruction and subsequent 9 different superimposed ALL tunnel orientations, eachwith 30mm tunnel length. Tunnel collision was observed in 5 of 9 combinations.

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 25mm and 30mm 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 (30mm tunnels drilled in 0° orientation in the axial plane), between the intercondylar notch and the ALL tunnel (30mm tunnels drilled in 0°coronal and 0°axial orientation) , and the trochlea and the ALL tunnel (30mm tunnels drilled in 0°coronal/40°axial orientation). Moreover, the relationship between tunnel collision and lateral femoral condyle (LFC) width was investigated by dividing all knees in 2 groups: large femurs with LFC width above average and small femurs with below average LFC width.

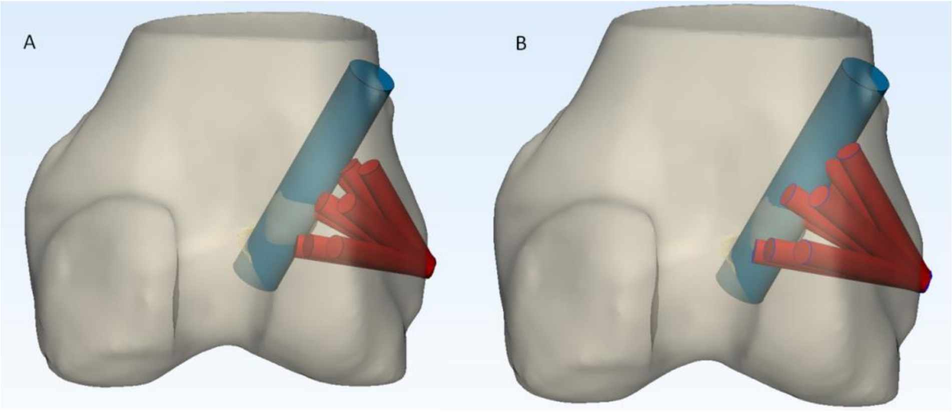

Figure 3. Frontal view of a patient with a transtibial drilled ACL and 9 different ALL tunnel orientations with 25mm (A) and (B) 30mm tunnel length.

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 tunnel) an identity link with a normal distribution was used. Univariate analysis were 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 were also investigated conditional on the drilling technique used, so separately for the ACL tunnels drilled through AMP or TT. A 5% level of significance is used and statistical analysis are performed in SAS for windows version 9.4.

RESULTS

Tunnel Orientation

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. 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)).

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 30mm, there was a significant higher collision rate relative to a 25mm length (42% vs 31%, respectively ; P=0.001). (figure 3)

No significant difference in tunnel collision was seen between a 25mm and 30mm 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 25mm and a 30mm 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 25.5mm (P<0.0001).

When no collision between both tunnels was noticed, the mean shortest length between the ACL and ALL tunnel was 6mm, but significant differences were calculated between the different ALL tunnel orientations (P<0.0001). (Table 2)

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

	TUNNEL CONFLICT (%)				
	Anteromedial Portal		Transtibial		*Total*
	25mm	30mm	25mm	30mm	
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*

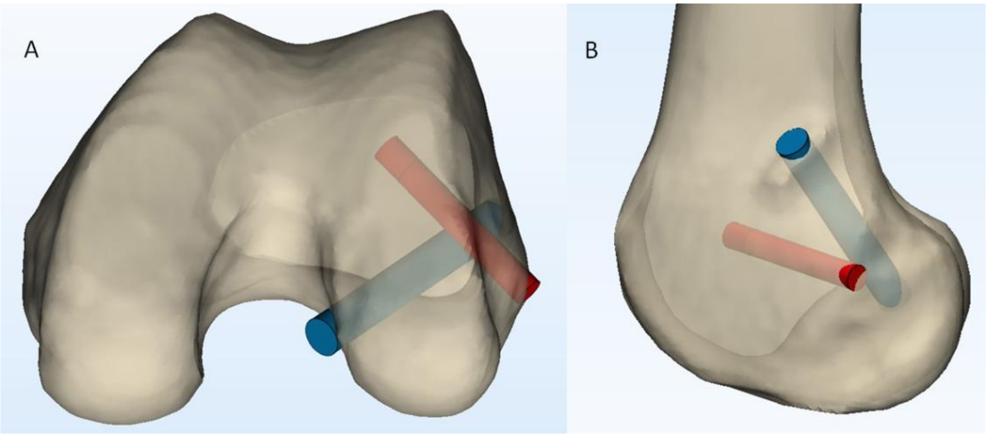

Figure 4. Anteromedial portal drilled ACL and a 30mm ALL tunnel at 0° coronal and 40° axial orientation. No collision was observed and no violation of the trochlea was noticed.

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 30mm ALL tunnel (0°-40°) to the trochlear groove was 19.9mm (range 14.5 -27.6mm).

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 7mm (range 2.2mm – 13.3mm).

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.

Lateral femoral condyle width

All patients were divided in 2 groups (large femurs / small femurs) according to the average LFC width of 22.5mm. No significant difference in tunnel occurrence was seen between both groups.

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).

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 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 14.5mm was noticed. Tunnel angulations higher than 40° in the axial plane were avoided because this can result in elliptical tunnels and thinned cortices. [247]

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. [260] Drilling the femoral ACL tunnel through an AMP, however, was found to allow easier and more anatomical placement of the ACL tunnel. [252] It has been shown that this technique creates a more horizontal graft orientation [262] 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 25mm and 30mm ALL tunnel. This is in contrast with the TT technique where the risk for collision between the ACL and ALL tunnel was halved using a 25mm ALL tunnel length.

Femoral socket depth for the ALL tunnel varies among authors between 20mm and 30mm. [98,124,128,265] Our data show that – when there was a conflict with the ACL tunnel - the mean length of the ALL tunnel was 18.4mm (95% CI: 16.6-20.1) and 25.5mm (95% CI: 24.3-26.7), for the AMP and TT technique respectively. No significant differences were noted between the different drilling orientations. For this reason, reaming a 20mm long ALL tunnel when femoral ACL tunnel was drilled transtibial can be enough to avoid tunnel collision. In the AMP technique, however, even a 20mm ALL tunnel is not sufficient to reduce the risk for tunnel collision.

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. Moatsche et al. [248] and Gelber et al. [246] demonstrated that 0° coronal and 30° axial angulation of the FCL tunnel was the most safe combination to avoid conflicts. Shuler et al. [247] recommend a 0° coronal and 40° axial orientation of the FCL tunnel. Small LFC width was in our study not seen as a predictive factor for the risk of tunnel collision. This is in conformity with the results of Camarda et al. [266] but in contrast to the outcomes of Gali et al. [245] and Shuler et al. [247].

Our study has a number of limitations. All ACL reconstructions were performed by three experienced orthopaedic surgeons who used the same surgical technique, but variability between them is likely. Femoral socket diameter for the ALL tunnel was 4.5mm in our study and therefore the number of tunnel conflicts are expected to be higher in ALL reconstruction techniques using a greater tunnel diameter. [124,129] 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 interfence screw fixation.

CONCLUSION

ALL tunnel orientation needs carefull 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.

Acknowledgment The authors thank Glenn Lamers and Bjorn Valgaeren for all their help with the medical imaging processing software and 3D reconstructions.

PART IV

CONCLUDING DISCUSSION AND FUTUR PERSPECTIVES

CONCLUDING DISCUSSION AND FUTURE PERSPECTIVES

The aim of this project was to investigate the characteristics and behavior of the ALL and to provide guidelines for surgical ALL reconstruction. In the first section of the study, the current investigators provided information about ACL treatment options and explained the problem of rotational instability. An overview of the current knowledge of the ALL was presented including current controversies surrounding this topic. In the second section, the existence of the anterolateral ligament was established and its biomechanical and histological properties were analyzed. Fresh-frozen human cadaveric knees were dissected and subjected to tensile testing and histological analysis. In the third section, technical improvements in ALL reconstruction were described. Graft choice options were investigated and guidelines provided in order to decrease the risk of complications, and more specifically the risk of tunnel conflicts between the ALL and ACL.

When interpreting this work, one should bear in mind that there are some limitations when using fresh-frozen cadaveric specimens. Differences in donor, age and sex can result in variability in tissue properties.[156] Ligaments are also viscoelastic materials and so display both time and temperature dependent properties. Therefore, an effort was made to obtain cadavers from a similar age range and all tests were performed at room temperature. Samples were kept wet with saline to prevent dehydration.

Another important limitation can be found in the testing setup of the biomechanical studies. Slippage of the specimens is a basic consideration when performing biomechanical analysis of tissue samples and can result in an underestimation of the mechanical properties. Therefore, a lot of time was spent finding an appropriate clamping technique. Only those samples that displayed mid-substance failure and no graft slippage during testing were used. Another concern was the cross-sectional area determination of the samples because this may also affect the results. Potential errors were minimized by performance of the measurements by a single person (KS) five times with the mean measurement recorded. All biomechanical tests in this work were conducted using the same routine with the same testing method and the same strain rate.

1. HYPOTHESIS TESTING

1. The Anterolateral Ligament is a distinct ligamentous structure that can be clearly distinguished from the knee capsule.

The objective was to confirm the existence of the anterolateral ligament, investigate its biomechanical and histological properties and compare it with the knee capsule. Since the first detailed anatomical description of the ALL in 2013, more than 130 studies may be found on Pubmed using the search term-term 'knee anterolateral ligament', all supporting the presence of a real and well-defined ALL. [2,11] Nevertheless, there are still authors denying the presence of a true ligament on the anterolateral side of the knee and citing the ALL as a capsular thickening.[19,38,121]

Therefore, a comparative study between the ALL and the knee capsule was necessary to prove the existence of the ALL as a distinct structure. In order to prove that the ALL has ligamentous characteristics, the current investigators compared it to another ligamentous structure, the inferior glenohumeral ligament (IGHL). It is known that both ligaments are in close relationship with the joint capsule, have comparable macroscopic and microscopic appearance and have a presumed function of restraining joint motion of in the knee and shoulder respectively. So, the mechanical and histological properties of the ALL, the anterolateral knee capsule and IGHL were compared.

It was demonstrated that the ALL is a ligamentous structure that is distinct from the knee capsule. Its mechanical properties were significantly different to the capsule and histologically the ALL showed the presence of dense, parallel collagen bundles and uniformally distributed fibroblasts. In contrast, the knee capsule demonstrated a disorganized architecture with islands of collagenized tissue, between fat and connective tissue. Thus, it was concluded that it is inaccurate to surmise that the ALL is a simple thickening of the knee capsule. Of interest also was the similarity between the ALL and IHGL. The data showed that there was no significant difference in their mechanical properties and that both structures displayed very similar histological characteristics. In both ALL and IGHL specimens, the presence of organized elastin fibers was observed. Elastin is recognised as one of the components responsible for providing elastic recoil to a structure and the distribution of elastic fibers is considered to reflect the physiological function of the tissue.[153,154] Therefore, similar to the IGHL, the ALL is thought to be an important stabilizer, providing restraint to the knee joint.

One study was found that also performed mechanical testing on isolated ALL samples and showed similar ultimate strain values as reported in the current study, but a lower ultimate stress and elastic modulus.[101] However, it should be noted that the elastic modulus was calculated using a different technique, a limited number of samples were tested, and there were differences in the testing protocol.

In the current study, only fresh-frozen cadaveric knees were used. A few other similar studies in the literature were performed with embalmed knees [2,91,96,258,267,268] and it was observed that the use of formalin may make tissue dissection more difficult.[96] However, in studies using fresh-frozen knees, the prevalence of the ALL was between 60% and 100%.[88-90,92,269] As in the study of Caterine et al. [90] and Helito et al. [88], the ALL in the current study was found in all knee specimens. Despite this, a group of authors recently suggested that the ALL is likely either a mid-third capsular ligament, the capsulo-osseus layer of the ITB, or a combination of both. [270] In fact, independent of the anatomic name that is given to the ALL, the same group concluded that this structure is a part of the anterolateral capsule.[271-273] The current study contradicts this and proves that the knee capsule and ALL are two distinct structures, both histologically and mechanically.

The conflicting anatomic findings, in relevant studies, may have resulted from variation in dissection techniques. The technique employed in the current study was based on that of Claes et al. [2], with the ITB cut transversely at a point approximately 6 cm proximal to the lateral epicondyle and so the tissue could be turned down distally. According to Seebacher et al. [274], the ITB forms the superficial layer and is only attached anteriorly at the lateral patellar retinaculum. This allowed a careful dissection without damaging underlying structures and resulted in a good overview of the deeper layer. After flexion and internal rotation of the knee, the ALL could be palpated and carefully dissected.

The current authors' histological analysis of the ALL is comparable to previous investigations which revealed parallel collagenous fibers, suggestive of ligamentous tissue.[18,88,90] One histological study was found that investigated the anterolateral capsule and did not found a ligamentous alignment. [146] However - in their published images of the lateral capsule - organized fibers with fibroblasts can be seen, which would seem to contradict the conclusion of the authors of that study.

2. The Anterolateral Ligament possesses comparable mechanical properties as other extra-articular knee ligaments.

The mechanical properties of ligaments depend upon several factors including collagen composition, fiber orientation and the interaction between collagen and ground substance.[135] These details are essential to understand the function and behavior of a ligament, as well as for selecting appropriate grafts used in reconstructive procedures. Remarkably, this information is lacking because the majority of biomechanical studies focus on the structural properties of ligaments on bone-tissue-bone complexes and depend on the geometry of the tissue as well as the properties of the bony insertion sites. [135] It has been demonstrated that tests on bone-tissue-bone complexes can potentially underestimate the true ligament mechanical properties.[172]

The principal finding was that the knee ligaments studied, have significant differences in their intrinsic mechanical properties and are heterogeneous in nature. The elastic modulus (stiffness normalized for the cross sectional area) of the ALL was significantly lower than all other ligaments. There is no significant difference in ultimate stress between the ALL and MPFL and the ultimate strain of the ALL was comparable to the LCL. From a material point of view, the current study showed that the MCL and LCL are stronger than the ALL and MPFL, and that the MCL and MPFL are less compliant than the ALL and LCL. The findings observed in this chapter provide information that may help explain differences observed in the clinical behavior of these ligaments, both in the healthy and injured state. For example, the modulus of the MCL was significantly higher than the LCL, however, the ultimate stress was not significantly different between these collateral ligaments. In contrast, the ultimate strain and strain energy density was significant higher for the LCL compared to the MCL. Considering the LCL as the primary lateral constraint in the coronal plane [188], it is perhaps not surprising that isolated LCL lesions are not as common as MCL tears.

Many ligament biomechanics testing studies are available in literature but results often show a wide variability. This is probably due to the biological variation seen in cadaveric tissue and the different testing techniques that are employed. Aside from the current study, few studies have compared knee ligaments within the same specimen pool, using the same testing methods.[171,184] In fact, those studies compared only the MCL and LCL, and only the structural properties. The data are largely based on failures of the insertion sites and do not provide a detailed impression of the properties of the ligament itself. As the same testing technique is used, mechanical data also provides information as to how the behavior of ligaments can differ from each other. From a clinical point of view, this data may help in understanding the differences in injury pattern and appearance that can be seen between ligament injuries.

Knowledge of the mechanical properties of ligaments is also important for appropriate graft selection for ligament reconstruction. As the ideal graft has the same mechanical properties as the original ligament, current data can serve as a guide. From a clinical standpoint, reconstructing the ALL with a strong, stiff graft could potentially over-constrain the lateral compartment.

In the current study, the low load properties of the ALL were also investigated and compared to other ligaments. When performing tensile tests to determine the intrinsic behavior of a ligament, data can be presented by a stress-strain curve with an initial non-linear portion (toe region), followed by a linear portion. [135] The toe region illustrates the mechanical behavior of a ligament in response to low strain activities, whilst the linear region demonstrate the behavior in high strain activities.[198] It has been suggested that biking, squatting and similar activities of daily living occur at low strain magnitudes. [199,200] The current results showed that knee ligaments also have significantly different low load properties. The principal finding was that the strain at the transition point from the toe region to the linear region, is significantly higher for the LCL and ALL than for the MCL and MPFL. The toe region is characterized by progressive fiber recruitment, in contrast to the linear region where fibers are being stretched. Larger elongations in the toe region are seen with the ALL, suggesting that the ALL has the capacity to stretch to a greater degree in response to low strain activities. Furthermore, it was noted that the transition strain value varies at around 25% of the maximum strain.

It can be concluded that ligaments are a heterogeneous group in which subdivisions can be made. Depending on the specific material properties, some knee ligaments show similarities with the ALL. The ligament with the most similar mechanical features was the IGHL and therefore it may be classified within the same subgroup of ligaments. The other knee ligaments had significantly different mechanical properties than the ALL in both low strain and high strain activities and this is probably due to the different functional requirements which they must satisfy. The MCL is described as the primary stabilizer of the medial side of the knee against valgus stress and is considered isometric. [275,276] In comparison to the ligaments located on the lateral side, the MCL showed less deformation in response to low as well as high loads. This suggests that the MCL is a more stiff ligament, responsible for the stable medial side, but more vulnerable to injuries. The lateral side of the knee displays greater mobility [277] and the stabilizing ligaments, like the LCL, tend to become slacker and non-isometric with increasing flexion angles. [275] Our data demonstrated that the LCL is not only a strong ligament, but also is capable of absorbing significant more energy than the stabilizing structures on the medial side. Even in daily activities under the same low strain magnitudes, lateral structures like the LCL and ALL tend to have a deformation that is twice as high as the MCL. This information contributes to the concept of a stable medial side, and a more lax lateral knee joint.

3. Grafts used for Anterolateral Ligament Reconstructions have different mechanical characteristics compared to the Anterolateral Ligament.

Potential grafts that could be used for ALL reconstructions (ALLR) were analysed. An ideal graft has material properties that mimic those of the original ligament. However, graft choice is often determined by the surgeon's experience, availability, patient activity level and ease of harvesting. Also the structural properties are often used as guidelines for choosing a graft, but those properties are based on tensile tests-to-failure of the bone-ligament-bone complex and can give an underestimation due to weak bony insertion sites. Therefore, knowledge of the intrinsic mechanical properties of the grafts are essential. After all, excessively taut grafts have the potential to over-constrain the joint and overly elastic grafts can lead to residual joint laxity. The current study analyzed commonly-used grafts for knee ligament reconstructions and showed that they possess distinct material properties. The hamstring tendons have an elastic modulus and ultimate stress that is significantly higher than the iliotibial band, patellar and quadriceps tendon. Moreover, the elastic modulus and ultimate stress of the gracilis was higher than the semitendinosus. From a material point of view, if grafts with the same cross-sectional area were studied, the gracilis was shown to be stronger and stiffer than all other tested grafts. One study was found which compared the structural properties of commonly used ALL grafts and demonstrated a significant higher stiffness for the gracilis compared to the ITB. [173]

Commonly used grafts for ALLR are semitendinosus[124], gracilis [125,126,128,129] and iliotibial band [265,278]. Given that the ideal graft should mimic the properties of the original ligament closely, data from analysis of the native knee ligaments was compared to data on the ALL. Of added value is the fact that the same standardized testing protocol was used and that dissections and cross-sectional area calculations were performed by one person (KS). A comparison with data from other authors is difficult because of the wide variability that exist between different biomechanical studies, biological variations and variations in testing techniques. It was notable that, in the current study, the ALL showed no similarity with the other grafts studied. In fact, it was demonstrated that the hamstring grafts have a 5 to 8 times higher elastic modulus than the ALL, and so ALLR utilizing hamstring tendons could theoretically over-constrain the lateral compartment of the knee. The ITB however, had also a higher elastic modulus than the ALL, but data showed significantly lower values in comparison to the hamstring tendons. Thus, the current authors would agree with those studies where concerns were raised as to the ability of the various ALLR techniques to safely restore native joint kinematics without causing joint over-constraint. [38,84] Schon et al. recorded the internal rotation and anterior translation of 10 fresh-frozen human cadaveric knees at 15° flexion intervals between 0° and 120°. [84] The native knee joint was investigated first in normal state and after the ACL and ALL were cut, followed by isolated ACL reconstruction and combined ACL and ALL reconstruction. The ALLR caused a significant reduction of the rotatory laxity but tended over-constrain internal rotation beyond 30° of flexion. The ALL graft that was used was a semitendinosus allograft and, with the current data in mind, the over-constraint may be explained by differences in the mechanical properties between the ALL and the semitendinosus.

As previously mentioned in the introduction section, comparative studies of ACLR with and without extra-articular lateral tenodesis failed to demonstrate superior clinical outcomes in favor of lateral tenodesis. [78] As an explanation, the authors stated that non-anatomical ACLR and LET techniques were used and that knee kinematics were not well restored. Promising results have been published with combined anatomical ACLR and ALLR but long-term studies are not available yet.[78,133] The current study demonstrated that not only is anatomical placement of the ACL and ALL graft critical, but the specific material characteristics of the graft chosen is integral to a successful reconstruction too.

4. There is a high risk of tunnel convergence between the femoral ACL tunnel and the ALL tunnel in combined ACL and ALL reconstructions.

Renewed interest in the anterolateral structures, and more specifically the ALL, has led to the publication of several new ALL reconstruction techniques. [77] However, clinical outcome studies are sparse and complications of the operation technique are not published yet. Two outcome studies by Sonnery-Cottet et al. [78,133] demonstrated that adding an ALLR is an effective procedure without specific complications.

The current authors assessed the risk of tunnel convergence in ALLR. It is known that tunnel conflicts in multiple knee ligament reconstructions may lead to graft damage or excessively short tunnels. [246] The current trend in ACLR is to position the femoral tunnel relatively oblique through the anteromedial portal (AMP), in order to better reproduce the native ACL anatomy and orientation for controlling tibial rotation. [5,241-243] Consequently, the ACL tunnel comes in closer proximity to the ALL femoral origin - just proximal and posterior to the lateral femoral epicondyle [98] - with a greater risk of interference with the ALL tunnel. The current authors investigated the risk of tunnel collision in cadaveric knees and found that the overall rate of tunnel conflict was 67%. This high proportion of conflicts could be reduced by aiming the ALL tunnel in a more proximal and anterior direction. Remarkably, when interference was noticed, the mean ALL tunnel length was only 15.85 mm. It has been advocated that a minimal tunnel length of 20 mm or 25 mm is necessary for safe graft to bone tunnel healing [246,252,254,255]. Therefore, the current authors recommend that the surgeon first perform an arthroscopically examination of the femoral tunnel to check if the ALL guide pin is visible. If so, the guide pin can be re-drilled with arthroscopic confirmation of a satisfactory new trajectory. Furthermore, it was observed that the odds of a tunnel conflict were 3.5 times higher in knees with a small lateral femoral condyle (LFC), compared to knees with a large LFC.

A limitation of investigating tunnel conflicts in cadaveric knees, is that only a few drilling combinations can be tested to preserve the knee structure. Therefore, the authors also assessed the risk of tunnel conflicts in 3D reconstructions of post-operative ACL reconstructed knees and virtual ALL tunnels were then created in nine different orientations. This analysis showed that a more anterior direction to the ALL tunnel reduces the risk of tunnel conflicts. The safest drilling angle was observed when aiming the ALL tunnel 40° anteriorly and perpendicular to the anatomical axis of the femur. Caution is advised to avoid violating the trochlea in this position, but this was not seen in our study. The mean distance from the end of a 30 mm ALL tunnel to the trochlear groove was still 19.9 mm. The highest rates of tunnel collision were seen when drilling the tunnel at 0° in the axial plane. Another observation was that drilling the ACL femoral tunnel through an AMP, resulted in almost twice as high a risk of tunnel collision, relative to cases where the transtibial technique was utilised. An explanation may be that the more horizontal positioning of the ACL tunnel with the AMP technique leads to a closer relationship with the ALL femoral origin and raises the risk of ALL-ACL conflicts. With this technique, a mean ALL tunnel length of 18.4mm was observed when interference with the ACL tunnel occurred. This data was comparable with the authors' previous work and confirmed that even a 20 mm ALL tunnel is insufficient to reduce the risk of tunnel collision. In summary, surgeons have to be aware of the high risk of tunnel conflicts in combined ACL and ALL reconstructions and careful intra-operative attention is advised.

To the current authors’ knowledge, no previous data on the risk of tunnel collision in combined ACL and ALL reconstructions has been published. Given the close relationship with the origin of the lateral collateral ligament (LCL), comparisons may be made with previous studies investigating the risk of tunnel collisions in combined ACL and LCL reconstructions. Those studies also showed a high risk of tunnel conflicts and recommended 0° coronal and 30° [246,248] or 40° [247] axial angulation of the LCL tunnel to avoid convergence.

2. FUTURE PERSPECTIVES

The main objective of this doctoral thesis was to provide greater insight into the characteristics and behavior of the ALL and related reconstruction techniques. Currently, there are very few ALLR clinical outcome studies. The ultimate goal of an ACLR is to provide the patient with a stabile knee that enables them to return to their pre-injury level with no detrimental short or long-term effects. A concern with isolated ACLR is the residual rotational instability, causing surgeons to add a LET as an augment to the ACLR. However, the superiority of combined ACLR and LET has not been proven via superior clinical outcome data. [36,74] The first clinical outcome studies after combined ACLR and ALLR are promising and they claim that this combination is an effective procedure without specific complications. [78,133] This observation has to be confirmed by other clinical studies and ultimately long-term reports.

Long-term outcome studies are necessary, especially given concerns raised about the potentially detrimental effects of over-constraining the knee, and inducing lateral compartment arthrosis. [38] The current authors' work already provides insights into this topic but more work has to be done to rule out this problem. For example, biomechanical studies comparing the different ALLR techniques would be of great scientific value.

In the execution of the project, the current authors came to realize that the material properties of common grafts used in reconstruction of ligament injuries often differ significantly from the original native ligament which the graft is supposed to emulate. Also donor side morbidity and cosmetic problems are described with the use of autografts. [78] Synthetic grafts were not investigated in this work but are part of a future research project. The ultimate objective is to design synthetic grafts with the same characteristics as the native ligament.

By investigating the biomechanical properties of the other knee ligaments, it was demonstrated that the MCL was less compliant than the LCL. Considering the

LCL as a primary lateral restraint and the MCL as a primary medial restraint in the coronal plane[188], those findings can also have implications for arthroplasty procedures. Surgeons who use a ligament balancer for setting rotation of the femoral component typically disregard the differences between the two ligaments, and equally pre-tension the medial and lateral side of the knee in order to create a symmetric flexion space. The current authors aim to conduct a future project involving an asymmetric balancer that pre-stresses the LCL less than the MCL, and analyse how much differential pre-tensioning should be applied.

In conclusion, this doctoral thesis demonstrated that the ALL has significantly different mechanical properties than the other knee ligaments in both low strain and high strain activities. Future studies should focus on the ultrastructural and biochemical properties to explain these differences.

ADDENDUM

During the last five years, the interest from the orthopaedic community in the ALL has grown exponentially and has led to the development of several new reconstruction techniques. [77,278] These techniques are commonly based on the anatomic landmarks of the ALL and the surgeon's personal preferences and understanding. Using the current data, based on our biomechanical and cadaveric studies, the authors suggest their own ALL reconstruction technique. However, there are still some issues that need further laboration. The fixation method, graft tensioning and fixation angle are potential topics for future work.

A New Technique for Combined Anterior Cruciate Ligament and Anterolateral Ligament Reconstructions

Kristof Smeets, Johan Bellemans, Jan Truijen

ABSTRACT

A new technique for combined anterior cruciate ligament and anterolateral ligament reconstructions is described. An iliotibial band strip is used as an ALL graft , leaving the distal insertion intact and fix it with a knotless anchor on the femoral origin, after tunneling it under the lateral collateral ligament.

INTRODUCTION

Anterior cruciate ligament (ACL) tears are one of the most common knee injuries with an annual incidence of 68.6 per 100.000 person-years [20] and frequently require surgical reconstruction. However, re-rupture of the ACL graft is reported in approximately 1.7% to 18% of patients[237,239] and a remaining post-operative pivot shift is seen in 11% to 60% of patients. [33-35] Therefore, several authors advocate the use of a lateral extra-articular tenodesis (LET) in combination with an ACL reconstruction and report good to excellent clinical results. [70,76]

Since a detailed anatomical description of the anterolateral ligament (ALL) was given [2], ALL reconstructions as a LET procedure are becoming more popular and several techniques are described. [124,129,278] To date, two outcome study were identified showing a significant reduced ACL failure rate [133] and good clinical results at 2-year follow-up [78]. Biomechanical studies have shown that the ALL functions as a secondary stabilizer to the ACL in resisting anterior tibial translation and internal tibial rotation.[4,51-54] In the literature however, there is no consensus on graft choice, fixation method and ALL landmarks. The aim of this article was to describe our technique for combined ACL and ALL reconstructions.

SURGICAL TECHNIQUE

The patient is placed in supine position on a standard operating table with the injured leg in an automatic leg holder (Maquet, Rastatt, Germany). The knee is able to move freely through the full range of motion and a tourniquet is inflated high on the thigh. Before the application of the povidine-iodine – coated cutaneous drape, bony landmarks, the joint level and the incisions are marked. (Figure 1) The surgical technique for a combined ACL and ALL reconstruction is performed in 5 consecutive steps:

1. ACL Graft Preparation

An 3cm long incision is made over the pes anserine parallel with the hamstring tendons. With respect to the infrapatellar branches of the n. saphenous, the semitendinosus is harvested with a closed stripper and prepared as a quadruple ACL graft of at least 8mm using a suspensory fixation system (Tightrope, Arthrex, Naples, USA). If less diameter, the gracilis tendon is taken and a six-strand ACL graft is made.

Figure 1. Patient positioning and surgical set-up. P= Patella; LE= Lateral Epicondyl; JL= Joint Line; G= Gerdy's Tubercle; FH= Fibular Head.

2. ACL Tunnel Positioning

A high parapatellar anterolateral portal was made as a viewing portal for the arthroscopic part of the procedure. A low anteromedial portal was established as the working portal for the femoral ACL drilling. An arthroscopic debridement of the anterior cruciate ligament and notch was performed to have a clear view on the medial wall of the LFC. A femoral offset guide of 5 mm (6mm if ACL graft ≥ 9mm) was placed behind the LFC while the knee was fully flexed. Next an ACL tightrobe drill pin of 4mm was placed at a 2 or 10 o'clock position (for the left and the right knee, respectively) and subsequently overreamed to the size of the ACL graft with a total tunnel length of 25mm.

Next the tibial tunnel is made by placing a drill pin within the native ACL tibial footprint and by overreaming it to the size of the ACL graft. Before passing the ACL graft, ALL tunnel preparation is performed to avoid tunnel collision.

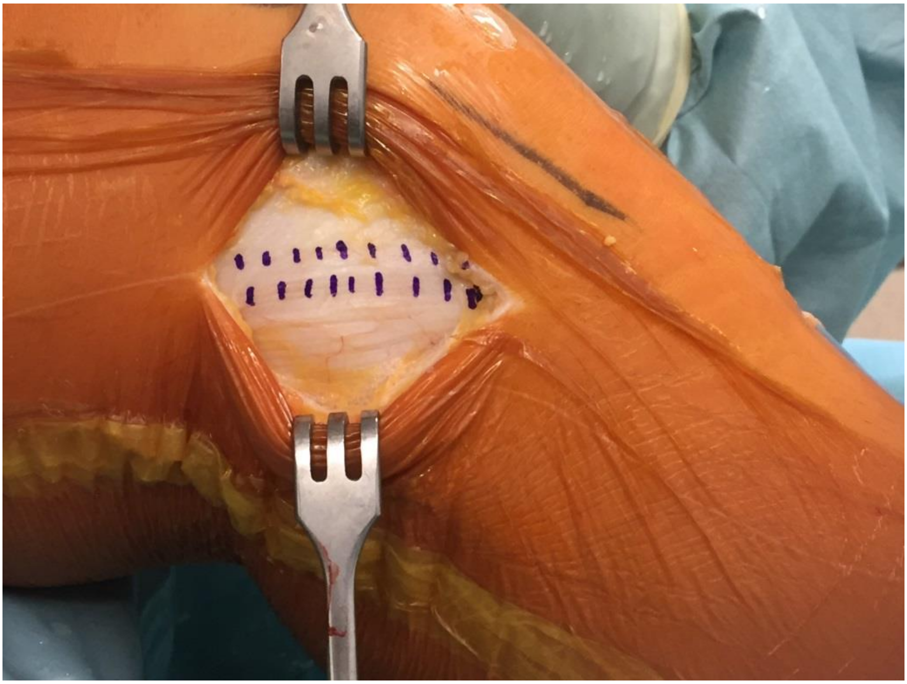

Figure 2. A straight lateral incision is established from the lateral epicondyle (LE) to a point just inferior of Gerdy's tubercle, and dissection of the subcutaneous tissue is performed until the fibers of the ITB are seen.

3. ALL Graft Preparation

A straight lateral incision is established from the lateral epicondyle (LE) to a point just inferior of Gerdy's tubercle, and dissection of the subcutaneous tissue is performed until the fibers of the ITB are seen. (Figure 1, Figure 2) A 6-8cm long and 1cm width strip is cut in the posterior part of the iliotibial band (ITB). The distal insertion of the ITB remained intact and the graft is tunneled under the lateral collateral ligament (LCL), just beneath his femoral insertion. (Figure 3, Figure 4)

Figure 3. A 6-8 cm long and 1cm width strip is cut in the posterior part of the iliotibial band (ITB).

The ALL insertion point is identified, as described by the ALL Expert Group, just proximal and posterior of the LE. [98] From this position, a 2.4mm guidewire is drilled anteriorly in the axial plane and perpendicular to the anatomical axis of the femur in the coronal plane. (Figure 5)

It is verified under arthroscopic view if the guidewire doesn't interfere with the femoral ACL tunnel. (Figure 6) If so, the guidewire is repositioned to a more anterior and/or proximal direction, with attention to not violating the trochlear groove. The guidewire is then overdrilled to increase the diameter to 4.5mm with a total tunnel length of 25mm.

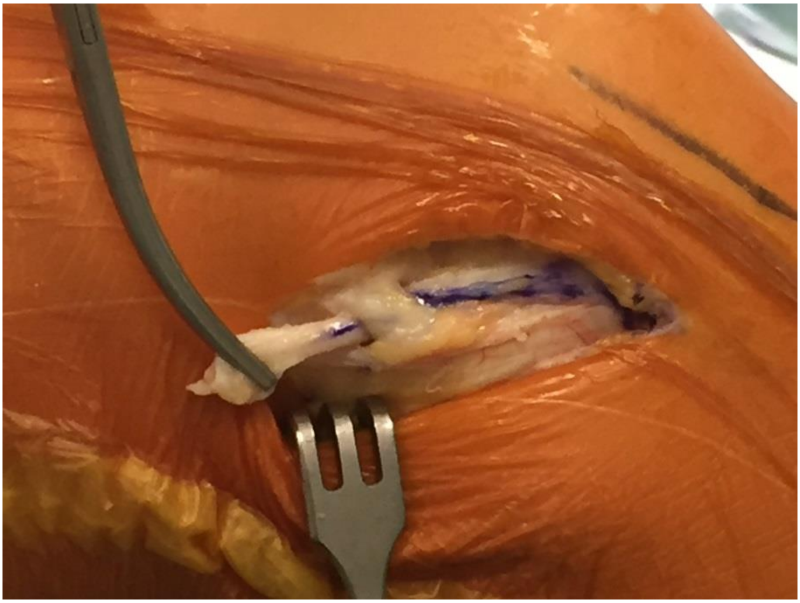

Figure 4. Tunneling of the graft under the lateral collateral ligament (LCL), just beneath his femoral insertion.

4. ACL Graft Fixation

After preparation of both ACL and ALL tunnels, the ACL graft is passed from the tibia to the femur. The femoral fixation is performed with the tightrope suspensory system. On the tibial side, a double fixation with first a post screw and then an interference screw is used.

5. ALL Graft Fixation

The free end of the ITB strip is whipstitched with No. 2 absorbable suture for a length of 1cm and the suture wires are passed through the eyelet of a 4.75mm knotless anchor (SwiveLock, Arthrex, Naples, USA). (Figure 7) Fixation of the ALL graft is performed with the knee in 45° of flexion and neutral rotation.

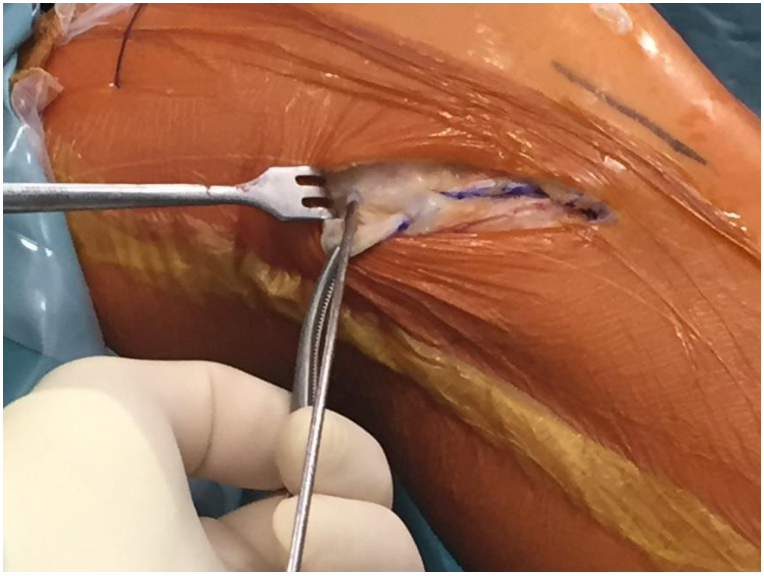

Figure 5. A 2.4 mm guidewire is drilled in the origin of the ALL, just posterior and proximal of the lateral epicondyle.

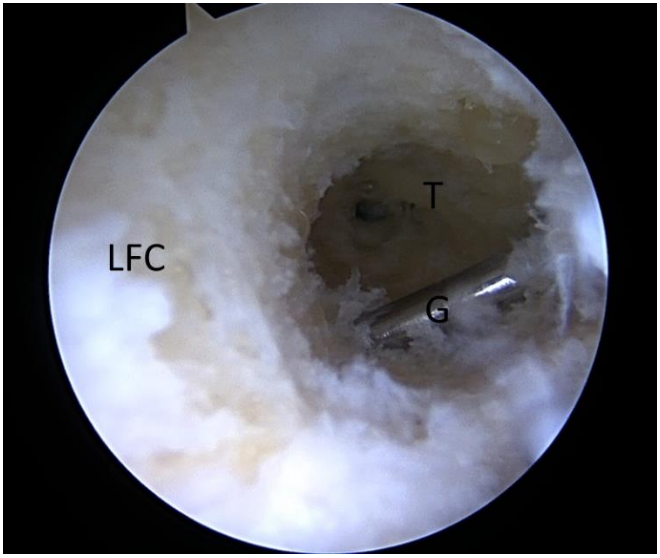

Figure 6. Example of a tunnel conflict under arthroscopic view between the femoral ACL tunnel and the ALL guidewire. LFC= medial wall of the lateral femoral condyle; G= guidewire for the ALL tunnel; T= Femoral ACL Tunnel.

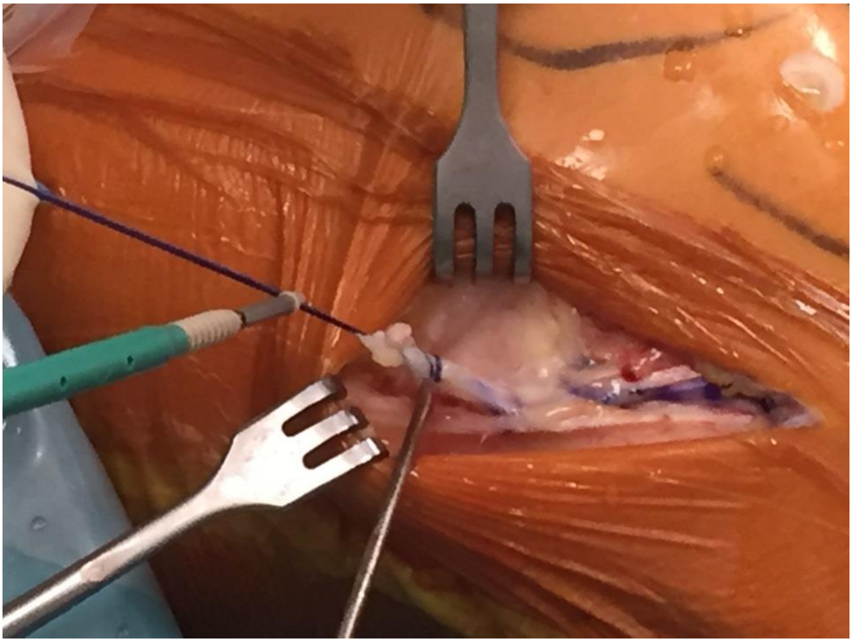

Figure 7. The free end of the ITB strip is whipstitched and the wires are passed through the eyelet of a 4.75mm knotless anchor. Fixation of the ALL graft is performed with the knee in 45° of flexion and neutral rotation.

DISCUSSION

The aim of this article was to describe our technique for combined ACL and ALL reconstructions. The renewed interest in the anterolateral compartment is largely attributed to the high number of patients with remaining anterolateral rotatory instability after isolated ACL reconstructions (ACLR). It has been demonstrated that the supplementation of a LET procedure is effective in reducing this rotational laxity. [75] Moreover, biomechanical studies highlighted the importance of the ALL as an anterior and rotational stabilizer in the knee. [51,140] As a consequence, ALL reconstructions (ALLR) are gaining popularity and several surgical techniques for anatomic ALLR are described in literature, but there is still a lack of comparative biomechanical and clinical studies.

Biomechanical studies described the potential overstuffing of the tibiofemoral joint by an ALLR [38,84,240]. Therefore, graft choice is important and commonly used graft types are gracilis [125,126,128,129], semitendinosus [124], iliotibial band [127] and polyester tape [130]. It has been demonstrated that hamstring grafts have a 5-8x higher elastic modulus than the ALL and so could theoretically overconstrain the lateral compartment. [193,196] The ITB however, had also a higher elastic modulus than the ALL, but data showed significant lower values in comparison to the hamstring tendons. [196] Another biomechanical study on the structural properties of the different ALL grafts demonstrated a significant higher stiffness for the gracilis relative to the ITB. [173] Therefore, we prefer the ITB band over the hamstring tendons to reduce the risk of overtightening the lateral compartment.

Cadaveric and radiographic studies from our group showed a high risk of tunnel collision (67%) in combined ACL and ALL reconstructions and this could be avoided by aiming the ALL tunnel anteriorly and perpendicular to the anatomical axis of the femur. (Unpublished data, January 2018) Because tunnel collision can lead to graft rupture, ALL tunnel orientation need to be adjusted. Attention should also be given to the ALL femoral fixation method. The ALL Expert Group reached a consensus about his origin, being proximal and posterior to the lateral epicondyle on the femur. [98] Because of this close proximity to the LCL origin, there is a high risk of iatrogenic damage to this ligament when a large diameter femoral ALL tunnel is drilled. [126] To reduce that risk, we prefer to create a smaller 4.5mm tunnel instead of larger diameter tunnels. [124,129] Also the positioning of the leg in ALL graft fixation has been heterogeneous in the literature, and the ALL Expert Group reached a consensus to fix the graft with the knee in full extension and the foot in neutral rotation. However, Parsons et al. [140] showed that the ALL is an important stabilizer of internal rotation at knee flexion angles greater than 35° and therefore we prefer a fixation of the ALL at 45° of flexion.

Our recommendation is to perform combined ACL and ALL reconstructions in patients participating in pivoting sports, adolescents, patients with a high-grade pivot shift, high-level athletics, hyperlax patients and revision cases. However, future studies are required to evaluate the efficacy and long-term results of the different ALL reconstruction techniques.

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CURRICULUM VITAE

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EDUCATION

Leuven University Leuven
Master in Medicine 2006-2010

Hasselt University Diepenbeek
Bachelor in Medicine 2003-2006

PROFESSIONAL EXPERIENCE

Academic Experience

PhD Researcher Hasselt / Leuven
Joint PhD University of Hasselt / University Of Leuven 2016- today

Orthopaedic Fellowship

Hospital Oost-Limburg (ZOL) Genk
3/2017- today
The Steadman Clinic Vail, USA
2/2017

Mayo Clinic	Rochester, USA
	1/2017
North Sydney Orthopaedic & Sports Medicine Centre	Sydney, Australia
	11/2016-12/2016
Hospital Oost-Limburg (ZOL)	Genk
	8/2016-10/2016

Orthopaedic Training

University Hospitals Leuven	Leuven
	2013-2016
Hospital Oost-Limburg (ZOL)	Genk
	2015-2016 (8 months)
Jessa Hospital	Hasselt
	2012-2013
KLINA Hospital	Brasschaat
	2010-2012

Sports Medicine

Team physician	
Belgian Youth Olympic Team	2013-2014
Team physician	
Belgian Youth National Soccer Teams	2011-2013

SCIENTIFIC ACTIVITIES

Oral Presentation

ABA Congress	Leuven
Torsion injuries in the knee: analysis of the frictional torque between grass field and soccer shoe	10-10-2009

K. Smeets, P. Jacobs, R. Hertogs, J-P Luyckx, B. Innocenti, K. Corten, J. Bellemans

Royal Belgian Football Association	Brussels
Football Turf	9-04-2010
Resident’s Seminar Leuven University	Leuven
Torsion injuries in the knee: analysis of the frictional torque between grass field and soccer shoe	20-09-2010
K. Smeets, P. Jacobs, R. Hertogs, J-P Luyckx, B. Innocenti, K. Corten, J. Bellemans	
Resident’s Day Antwerp Orthopaedic Surgeons	Antwerp
Acetabular fractures: case report	26-04-2011
London Conference 2012	London
Torsion injuries in the knee: analysis of the frictional torque between grass field and soccer shoe	22-04-2012
K. Smeets, P. Jacobs, R. Hertogs, J-P Luyckx, B. Innocenti, K. Corten, J. Bellemans	
Open Meeting Belgian Knee Society	Antwerp
Massive Tunnel Widening: case report	25-11-2014
EFORT Congress	Geneva
A biomechanical and histological analysis of knee Shoulder ligaments	1/3-06-2016
K. Smeets, S. Claes, J Slane, L. Scheys, J. Bellemans	
Belgian Knee Society: Jong Geweld	Gent
Can Grafts used for Knee Ligament Reconstructions Mimic The Original Native Ligament? An analysis of mechanical properties of knee ligaments and tendons	14-12-2017
Belgian Knee Society: Jong Geweld	Gent
How to avoid tunnel convergence during combined anterior cruciate ligament and anterolateral ligament reconstruction	14-12-2017

Poster Presentation

EFORT Congress Madrid
Torsion injuries in the knee: analysis of the frictional torque between grass field and soccer shoe 2/5-06-2016
K. Smeets, P. Jacobs, R. Hertogs, J-P Luyckx, B. Innocenti, K. Corten, J. Bellemans

EFORT Congress Geneva
Mechanical and histological comparison of the Anterolateral Ligament and Knee Capsule 1/3-06-2016
K. Smeets, S. Claes, J Slane, L. Scheys, J. Bellemans

EKS Arthroplasty Conference London
How should we use a ligament balancer in flexion in order to restore the natural mediolateral laxity of the knee after TKA? 20/21-04-2017
K. Smeets, J. Bellemans

ISAKOS Congress Shanghai
Biomechanical and histological differences between extra-articular ligaments 4/6-06-2017
K. Smeets, J. Slane, L. Scheys, R. Forsyth, S. Claes, J. Bellemans

AAOS New Orleans
Can Grafts used for Knee Ligament Reconstructions Mimic The Original Native Ligament? An analysis of mechanical properties of knee ligaments and tendons 6/7-03-2018
K. Smeets, S. Claes, L. Scheys, J. Bellemans

Publications

Torsion injuries in the knee: analysis of the frictional torque between grass field and soccer shoe. K. Smeets, P. Jacobs, R. Hertogs, J-P Luyckx, B. Innocenti, K. Corten, J. Bellemans
Br J Sports Med, Dec 2012;46(15):1078-83

Intra-articular shoulder infiltrations. A survey along Belgian and Dutch orthopaedic surgeons. K. Smeets, C. Dierickx
Acta Orthop Belg, Jun 2014;80(2):166-71

The anterolateral ligament has similar biomechanical and histologic properties to the inferior glenohumeral ligament. K. Smeets, J. Slane, L. Scheys, R. Forsyth, S. Claes, J. Bellemans
Arthroscopy, May 2017;33(5):1028-1035

Mechanical analysis of extra-articular knee ligaments. Part one: Native knee ligaments. K. Smeets, J. Slane, L. Scheys, S. Claes, J. Bellemans
Knee, Oct 2017;24(5):949-956

Mechanical analysis of extra-articular knee ligaments. Part two: Tendon grafts used for knee ligament reconstruction. K. Smeets, J. Bellemans, L. Scheys, BO. Eijnde, J. Slane, S. Claes
Knee, Oct 2017;24(5):957-964

Professional Membership

- Belgian Orthopaedics and Traumatology Residents Association (BOTRA)
  Board Member 2011-2015
- Belgian Society for Orthopaedics and Traumatology (BVOT)

DANKWOORD

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Yes, we did!

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Kristof

Hasselt, 13 juni 2018.

‘More surgeons must start doing basic science’

Nature, 25 April 2017