DEPARTMENT OF MECHANICAL ENGINEERING

‘THE ANTEROLATERAL STRUCTURES OF THE KNEE AND THE PIVOT SHIFT’

THESIS SUBMITTED TOWARDS THE AWARD OF MD (Res)

DEGREE

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Declaration

The work contained in this thesis is my own work, and where others have been involved they have been appropriately acknowledged. References to other works have been cited as appropriate.

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Abstract

Current standard techniques used for anterior cruciate ligament reconstruction are unable to restore normal knee biomechanics. One explanation for this is that ongoing anterolateral rotatory instability is due to damage to anterolateral knee structures that current surgical techniques fail to address. Focus had previously moved away from the periphery of the knee towards intra-articular reconstruction, however in the past rotational instability was addressed with a lateral extra-articular tenodesis, and these were widely used techniques in the 1970s and 80s before falling out of favour. A detailed review of this surgery, including the Lemaire, Macintosh and Ellison procedures has been performed in this thesis, as well as a review of the pre-existing anatomical knowledge of the anterolateral knee structures. Due to gaps in knowledge identified, an attempt to further define anterolateral knee anatomy has been made. 40 fresh frozen cadaveric knees have been dissected. A consistent structure termed the anterolateral ligament (ALL) was identified in 33 (83%) of the specimens. The ALL passed antero-distally from a femoral attachment point posterior and proximal to the lateral femoral epicondyle. It passed superficial to the lateral collateral ligament, to an attachment point midway between Gerdy’s tubercle and the fibula head. We sought to further determine the biomechanical role of the structure using length change experiments. The ALL was isometric from 0° to 60° degrees of flexion, and then slackened when the knee was flexed to 90°. Two independent musculoskeletal radiologists reviewed MRI appearances of the ALL and findings were consistent with our anatomical observations. The
ALL may be involved in resisting the pivot shift and inserts at the site of the Segond fracture. Since the experiment numerous anatomical, biomechanical and radiological investigations have been published on the ALL and these are reviewed in detail.
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Finally my thanks to my wife Louise for her support and for graciously accepting the many lost hours of family time relating to this piece of work over the years. My life has changed immeasurably since the commencement of this work, but the three most important events were the arrivals of Freddie in December 2011, Henry in September 2013, and Pippa in October in 2015, and all my work and efforts are dedicated to them.
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Presentations:
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Dodds AL, Williams AM, Gupte CM, Amis AA. The oblique lateral ligament of the knee- demonstration of a ‘new’ knee ligament. 6th World Sports Trauma Congress / 7th EFOST Congress, London 2012
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Chapter 1: Introduction

1.1 Overview of knee anatomy and function with particular reference to the anterior cruciate ligament

1.1.1 Overview of Knee Anatomy

Three bones form the knee joint- the patella, the tibia and the femur. From these structures, three distinct compartments arise- the medial tibiofemoral joint, the lateral tibiofemoral joint and the patellofemoral joint. The articulating surfaces of the joint are covered in articular cartilage, a specialized connective tissue consisting of proteoglycans in a matrix of collagen fibrils. The tibiofemoral joints contain the medial and lateral menisci, specialized crescentric fibrocartilage tissue that surrounds the tibial plateau. The knee joint is surrounded by a capsule, which in places has thickening reinforcements from other supporting structures, including anteriorly where the extensor mechanism lies.

The knee has a complex array of supporting ligaments and tendons, acting together to control and limit motion, and maintain static and dynamic equilibrium. The anterior and posterior cruciate ligaments sit intra-articularly; they stabilize the knee joint and prevent antero-posterior displacement of the tibia on the femur. Anterior to the knee joint is the extensor mechanism that consists of the quadriceps muscle group, which narrow to the quadriceps tendon, which
attaches to the patella. The patellar tendon runs from the patella before inserting into the tubercle of the tibia. The medial side of the knee consists of most superficially the sartorius, gracilis and semitendinosus muscles and tendons, and beneath this lies the superficial and deep layers of the medial collateral ligament. The lateral side of the knee consists of the iliotibial tract (ITB) and the biceps femoris, and deep to this the collection of tendons and muscles known collectively as the posterolateral corner. Posterior to the knee joint is the popliteal fossa, bounded by the biceps femoris, semimembranosus and gastrocnemius. The tibial nerve and popliteal artery sit within the popliteal fossa.

Figure 1 – The skeletal anatomy of the knee with important insertion sites illustrated
The published anatomy of the lateral structures of the knee is discussed in more detail in Chapter 3.

1.1.2 Embryology of the knee with particular reference to the development of the lateral structures

The way the structures of the knee develop early in utero will have an effect on the anatomy of the adult knee and also its function and are therefore worth studying. The complex arrangement of the knee is based on millions of years of development. The lower limb buds first appear in human embryos about 4 weeks after fertilization, and at about 5 weeks after fertilization the skeletal elements of the lower limbs begin to chondrify. The capsule of the knee joint forms at approximately 7.5 to 8 weeks, and becomes attached to the surface of the menisci. By approximately 8 weeks, the knee joint clearly resembles that of the adult, with clearly identifiable tendons and cruciate ligaments as ‘cellular oriented proliferations’. Both menisci are identifiable, but the lateral more so, and both collateral ligaments are present. At this stage the articular capsule is still visible, with densification of the condylopatellar ligaments. The knee joint has an adult appearance by approximately 12 to 13 weeks.

The lateral collateral ligament (LCL) first appears at postovulatory week 7, and by week 8 is well defined. The LCL can be seen to extend from the lateral epicondyle to the head of the fibula at week 9, and from its first appearance, can be seen to be independent of the joint.
capsule. The tendon of the popliteus muscle can also be seen to condense between weeks 7 to 8. The tendon follows the upper epiphysis of the tibia and becomes attached in a pit beneath the lateral epicondyle of the femur. It can be seen to condense at the same rate as the LCL. At week 10, synovial mesenchyme can be seen to develop between the popliteus tendon and the lateral meniscus, forming a meniscopopliteal ligament.

1.1.3 Basic biomechanics of the knee

The knee joint is capable of complex motion. There is a relative lack of conformity between the bony surfaces. Six degrees of freedom of motion can occur: medial-lateral, anterior-posterior and proximal-distal translations, and flexion-extension, internal-external and varus-valgus rotations. During extension-flexion movements, rollback occurs of the femur on the tibia, with this mainly occurring in the lateral compartment. The supporting soft tissues of the knee allow for these complex movements to occur. Knee movement plays a key role in the gait cycle, and to stabilize the knee during walking the interaction between dynamic muscle forces and forces in the passive soft tissues is critical. Before initial contact is made, the knee flexors are contracting eccentrically, and as the knee is initially loaded the ground reaction force passes behind the knee, with the quadriceps becoming activated. As further movement occurs, the ground reaction force then moves anterior to the knee joint again, with activation of the knee flexors and posterior structures. The knee flexes again at heel rise.
1.1.4 Anatomy of the Anterior Cruciate Ligament (ACL)

The anterior cruciate ligament (ACL) runs obliquely in an anteromedial direction from the medial side of the lateral femoral condyle, through the intercondylar fossa and then inserts just anterior to the tibial eminence.\textsuperscript{10,11} Cadaveric studies have shown the ACL to have an average length of 31 mm (+/-3mm), and a width of 11mm (range 7 to 17mm).\textsuperscript{12,13}

The ACL femoral attachment is centred on and then spreads posteriorly to the extended line of the posterior femoral cortex.\textsuperscript{14} The femoral attachment of the ACL on the femur consists of a direct insertion and an indirect insertion.\textsuperscript{15} The tibial insertion commences 10 to 14mm behind the anterior border of the tibia and extends to the medial and lateral tibial spines, and can be either triangular or oval in shape. The anterior horn of the lateral meniscus sits lateral to the tibial insertion, the anterior horn of the medial meniscus and the inter-meniscal ligament sit anteriorly, and the articular cartilage of the tibial plateau is medial to its insertion.\textsuperscript{16}

It has been known for some time that the ACL does not consist of one group of fibres, but contains 2 fibre bundles: the anteromedial and posterolateral bundles, although more recently this has been challenged.\textsuperscript{12,16} The bundles take their name based on their tibial insertion point. The ACL in the fetal knee has also been shown to have the same double bundle arrangement.\textsuperscript{17,18} The bundles may have different roles, with the posterolateral bundle more important in resisting anterior tibial translation in extension, and the
The structure of the ACL consists of multiple fascicles containing bundles of non-parallel collagen fibres (predominately type 1 collagen), surrounded by synovium\textsuperscript{19,20,21,22}. Elastin fibres are also present and may be involved in a mechanical role in bundle reorganization following ligament deformation\textsuperscript{23}. The primary blood supply is from the middle genicular artery, with additional supply coming from the inferomedial and inferolateral genicular arteries\textsuperscript{13}.

The recognition of this ‘double bundle anatomy’ of the ACL has influenced recent developments in knee surgery relevant to this
thesis and attempts to reconstruct the double bundle arrangement of the ACL are discussed in more detail in chapter 2.

### 1.2 Injury to the ACL – Incidence, mechanisms and clinical importance

In the United States, approximately 80,000 to 250,000 ACL injuries are estimated to occur every year.\textsuperscript{24} The rate of ACL injury has been reported at values ranging from 0.3 to 0.81 cases per 1000 inhabitants per year\textsuperscript{25,26}, and so provides a large burden in terms of healthcare expenditure. In an active military population of new recruits, there were 24 noncontact ACL injuries in a group of 895 cadets over a four year period, with small femoral intercondylar notch width, generalized joint laxity, above average BMI in females and KT-2000 arthrometer values of more than 1SD above the mean being risk factors.\textsuperscript{27}

Injuries of the ACL are often sports related and hence affect the youngest, most active members of society. Higher level sports players may be more prone to injury.\textsuperscript{25} Certain sports also predispose to ACL injury, for example there has been found to be a high incidence in recreational and professional skiers.\textsuperscript{28,29,30,31}
1.3 Tests to assess ACL laxity

A number of tests have been documented to diagnose acute ACL injury, the most commonly used of these to test are the anterior draw, Lachmanns and pivot shift.\(^\text{32}\) The anterior draw test is used to test for the integrity of the ACL, by examining its restraint of tibial anterior translation laxity when the knee is at 90° flexion. It has been shown to have a sensitivity ranging from 0.18 to 0.92, and a specificity ranging from 0.78 to 0.98.\(^\text{34}\) The Lachmanns test also tests for the integrity of the ACL, by examining its restraint of tibial anterior translation laxity, it consists of stabilizing the patient’s femur when the knee is held in 20° to 30° of flexion, and then the examiner attempts to draw the tibia anteriorly with their other hand. \(^\text{33}\) The test can be graded depending on the degree of movement; a positive test consists of visible anterior movement of the tibia combined with a soft end point. A meta-analysis which looked at nine studies which had assessed the Lachmanns test found that it had a sensitivity of 0.86 and a specificity of 0.91.\(^\text{34}\)

Another commonly used test, the ‘pivot shift’ is a very important test as it tests the complex rotational and translational instability of the tibio-femoral joint rather than anterior laxity as the other tests do. The pathogenesis of the pivot shift is a critical area for consideration in this thesis.
The rotational instability associated with tears of the ACL has been known for some time. A case report of a ‘slipping knee’ was described as long ago as 1913. Hey Groves described a ‘jerk’ as the tibia moves over the femur in an ACL deficient knee and also described an extra-articular reconstruction to counter this movement. Slocum and Larson recognised rotatory insufficiency occurring in the ACL deficient knee, noting that the runner is ‘most vulnerable when he cuts or turns away from the side of the supporting foot,’ although much of the paper is focused on the medial side of the knee, they did
devise a test for rotatory instability with an anterior draw with and without external rotation.36

‘Pivot shift’ was first used as a descriptive term in 1972.37 In its original description the authors noted ‘it is characterized by forward subluxation of the lateral tibial plateau on the femoral condyle in extension, and spontaneous reduction in flexion.’ They note that it occurred at the time of sudden directional change, and also described a method to reconstruct the ACL using a fascial strip of the ITB. Although not directly mentioning rotation in their original description, they effectively described the complex rotational and translational instability of the tibio-femoral joint, caused by combined sagittal plane laxity with axial rotatory instability. Several authors since then have suggested variations on this original pivot shift test.38 The variation in tests that have been described is a result of differences of opinion of the exact pathological movement that occurs during the pivot shift and which structures may be damaged to produce this movement.

It is now generally agreed that the pivot shift is felt as a sudden reduction of the anteriorly displaced tibial plateau as the knee is moved from extension to flexion as the ITB moves from its position in the centre of rotation anterior to the tibial plateau to posterior at approximately 30° of flexion. Clinically this instability will most commonly be felt during sudden changes in direction. The standard clinical test for this is to bring the knee from full extension to full flexion, with a valgus and internal rotation moment. The pivot shift is felt as a reduction of the anteriorly subluxed lateral tibial plateau at
about 30° of flexion. This is as the line of action of the ITB moves from its position anterior to the centre of rotation of the knee at 0° to its position posterior at 30°. A meta-analysis has shown that sensitivity of the test ranged from 0.18 to 0.48, with specificity from 0.97 to 0.99.34

The view of the exact underlying cause and the test proposed to assess the pivot shift has changed with time. Interestingly initial descriptions of the rotation occurring in an injured knee placed a greater emphasis on peripheral structures around the knee, including injuries to the capsule.39 It was later recognized in a cadaveric sectioning experiment involving 25 cadavers (50 knees) that injury to the ACL had a high correlation with the production of the pivot shift.40 The authors of this important study also noted that it was the sliding of the ITB that produced the clunk as the tibia reduced. The authors also noted that in one knee what they described as a ‘false positive’ pivot occurred- this was then the ACL was intact but the ITB had been sectioned. They also noted that sectioning of structures of the lateral side of the knee, including the ITB, LCL and popliteus tendon increased the pivot shift when the ACL was also sectioned.

Further cadaveric studies have confirmed the importance of rupture of the ACL in producing the pivot shift.41 Attempts have been made to grade the pivot shift, however the difficulty of this is that the examination findings are relatively subjective. Another difficulty is that the outcome felt when the pivot shift is undertaken is dependent on the amount of force being applied by the clinician, as well as other factors including hip position and the degree of tibial rotation.42 Another reason as already illustrated is that more than one set of soft
tissues may be involved in causing the pivot shift, allowing for variations as to what is actually been measured. The translation and rotation that occurs has been shown to be variable in vivo when knee kinematics are measured\textsuperscript{43}.

A ligament at the centre of rotation is not in the best place to act as a restraint to a rotational force, but would be better positioned on the periphery of the area resisting the force with a lever arm for controlling rotation.\textsuperscript{44} The presence of the pivot shift and its clinical tests is one piece of evidence that suggests that other, peripheral structures in the knee may be involved in resisting rotational movement. This raises the question of exactly what these structures may be and furthermore whether any attempt to repair or reconstruct them should be made if surgery is indicated for an ACL injury.

1.5 Other evidence that the anterolateral knee structures may be damaged at the time of ACL injury.

The presence of the pivot shift in both cadaveric and in vivo studies described above suggests that control of rotation may be due to factors other than the presence of an isolated ACL injury. Further evidence to support the findings that other structures may be injured at the time of ACL injury is provided by in vivo surgical studies.

Norwood \textit{et al} provided one of the earliest pieces of evidence in 1979. It is however important to note that at the time that this paper was
written and published it was not thought that tears of the ACL were important in causing the pivot shift. This may have influenced the authors' interpretation of the injuries that they saw.\cite{45} 36 knees were assessed in the study. Injuries to either the lateral capsular ligament, ACL, or both were documented in all knees with anterolateral rotatory instability. The authors noted only tears of the ITB from the tibia and therefore considered that the ITB was not involved in producing anterolateral rotatory instability. However, it should be noted that they only appeared to be referring to the direct insertion of the ITB onto Gerdy's tubercle.

The Segond fracture is a key piece of evidence that damage to anterolateral structures occurs at the time of ACL injury. (Figure 3) The Segond fracture is well known as a bony avulsion of the anterolateral tibia plateau, visible on standard radiographs and seen at the time of ACL injury. There is a strong association between the presence of a Segond fracture and damage to the ACL\cite{46,47,48}. Despite being first described by Paul Segond in 1879\cite{49}, the precise anatomy of the structures causing the avulsion is poorly described. The pathogenesis of the Segond fracture is considered in more detail in Chapter 6 in the radiology studies section of the thesis.
**Figure 4** – AP radiograph of a knee showing a Segond fracture (white arrow) – suggesting that structures in this area may be damaged during the pivot shift\(^{50}\)

Furthermore, evidence suggests that current techniques for ACL reconstructions are not able to restore normal knee biomechanics. This evidence is considered in more detail in Chapter 2 following the review of ACL reconstruction techniques.
Chapter 2 – Surgical treatment of ACL injuries and historical attempts at extra-articular reconstruction: A literature review

Material in this chapter has been published:


2.1 Treatment of ACL injuries – Rationale for surgical treatment

Tears of the ACL can either be treated non-operatively or with intervention in the form of surgical reconstruction or repair. Surgeons make decisions on whether to treat patients surgically based on individual patient factors such as degree of instability, age, sporting aspirations and presence of other associated knee injuries, as well as depending on the particular healthcare system within which they practice. Whilst surgical treatment to reconstruct the ACL is common in many Western countries, the available evidence to support surgical reconstruction in the form of randomized trials of surgical versus non-surgical treatment is poor. The literature at present still lacks a well conducted randomized controlled trial allocating patients to either surgical or non-surgical treatment following ACL tear, despite the high number of publications focusing on surgical technique and outcome. Other factors may also be important in whether a patient returns to sport following ACL injury,
including psychological profile\textsuperscript{53} and pre-injury activity level\textsuperscript{54}. Some studies have even suggested a higher rate of return to sport in non-surgically treated patients.

A further consideration when recommending surgical or non-surgical treatment is the natural history of the ACL deficient knee and the development of degenerative joint disease. Early studies suggested an increased incidence of degenerative joint disease following ACL injury, although these studies may have had a selection bias towards symptomatic patients seeking treatment.\textsuperscript{55} Older and unvalidated criteria to diagnosis arthritis were used in these studies, as well as variations in radiographs used to make the diagnosis. There is also the difficulty in producing long-term follow-up data for these patients. This led to a large variation in the rate of suggested development of osteoarthritis following ACL injury, with rates varying as much as from 24 to 86\%, although follow up was between 5 to 30 years follow up.\textsuperscript{56,57,58,59,60} The association between ACL injury and the formation of degenerative joint disease has therefore not been clearly made, as the studies referenced above contain many confounding variables. The evidence to suggest that reconstruction of an isolated anterior cruciate ligament tear will prevent osteoarthritis is also poor. Some studies suggest that there is no difference in rates of osteoarthritis development following ACL reconstruction \textsuperscript{61,62}; whilst others suggest that the rate of osteoarthritis development may even be higher compared to non-operative treatment.\textsuperscript{63,64}

Associated injuries occurring at the time of ACL injury may have a significant impact on long-term outcome regardless of whether
surgical reconstruction takes place. Alterations in the form of changes of synovial fluid cytokine and keratin sulfate concentrations have been reported. Changes to the underlying subchondral bone can often be seen on MRI imaging following ACL rupture (so-called ‘bone bruises’), and these may be relevant to the development of osteochondral lesions and osteoarthritis in the following years. Perhaps the most important factor relating to outcome in particular in relation to subsequent osteoarthritis development is damage to the menisci and subsequent menisectomy.

Certain patients may be more likely to have a successful outcome following ACL reconstruction dependent on the factors discussed. However, selection of patients has not been clearly identified. One study suggested that the most important factor in determining the need for future ACL reconstruction was the presence of a positive pivot-shift test in an awake patient at 3 months post injury.

2.2 Surgical treatment of ACL injuries

Numerous attempts have been made to reconstruct the ACL. Attempts at direct repair of the ligament have been made, including one of the first attempts using silk to repair the ACL directly. However results of direct repair have in general been poor, and surgical reconstruction is now the most commonly used technique, although recently repair has again been the focus of research.
Reconstruction using autograft tissue, allograft tissue and synthetic ligaments has been described. As well as the differences in the tissue used to perform the reconstruction; there have been some major differences in technique that may also influence outcome. There is no ‘ideal’ graft to reconstruct the ACL, although its properties would ideally include the ‘need for adequate initial mechanical properties, graft viability, accessibility, bone fixation of the grafts where possible, proper placement under correct graft tension, minimal morbidity from surgery and demonstrated function by objective criteria.’

Extra-articular reconstruction (controlling instability by reconstructive techniques outside the joint capsule) was previously widely used, either in isolation or in combination with an intra-articular reconstruction.

2.3 Intra-articular ACL reconstruction

2.3.1 Bone-patellar tendon – bone autograft

Reconstruction using the middle third of the patellar tendon has been described as the ‘gold standard’ choice of graft when it comes to ACL reconstruction. However, despite multiple randomized controlled trials and systematic reviews, there is no firm evidence to support a superior outcome using patellar tendon over hamstrings tendon graft74. Patellar tendon offers a number of potential advantages, including high strength and stiffness, consistency in the size of the graft, ease in harvesting and early graft incorporation. There are a number of potential disadvantages to the technique, including
patellar fracture and anterior knee pain potentially due to damage to the infra- patellar branch of the saphenous nerve. Modern instrumentation may avoid some of these complications such as patella fracture.

### 2.3.2 Hamstrings autograft

Harvest of autologous hamstrings tendons to reconstruct the ACL was first described in the late 1980s and has been increasing in popularity since then. It is has been suggested that it avoids causing as much donor site morbidity as patellar tendon harvest, although concerns remain including increased graft incorporation time, hamstrings weakness, increased infection rate and inferior fixation remain. Despite multiple randomized controlled trials and systematic reviews, there is no firm evidence to support a superior outcome using patellar tendon or hamstring graft. Hamstrings tendon autograft is probably the most commonly used material to reconstruct the ACL. Recent innovations have focused on varying the hamstrings technique, including placing the graft in a more ‘anatomic’ location using an anteromedial portal rather than using a more traditional transtibial technique.

Cadaveric studies have suggested that whilst conventional single bundle hamstrings or patellar tendon reconstruction techniques are effective at preventing anterior tibial translation, they are not effective as controlling rotational loads. As a result of this, other forms of ACL reconstruction to counter the pivot shift have been suggested. One recent major advance proposed using hamstring
tendons in a ‘double bundle’ reconstruction technique. This has significance for the purposes of controlling the pivot shift phenomenon and will be considered in more detail.

### 2.3.3 The ‘double bundle’ technique using hamstrings tendons to reconstruct the ACL.

The ACL consists of two distinct bundles of collagen fascicles. Attempts have been made to reconstruct both of these bundles on an individual basis, as it is known\textsuperscript{83,84,85} that conventional single bundle reconstruction is unable to restore normal biomechanics. However the technique is technically more demanding. In a systematic review involving 1433 patients in 17 trials, no evidence could be found to recommend one technique over the other.\textsuperscript{86} This included reviewing functional knee scores, and complications such as infection, hardware problems, and graft failure. Range of motion deficit was also reviewed. However, at longer term follow up, some clinician measures of knee stability as well as the incidence of new meniscal injuries were better after double bundle reconstruction. The authors of the review were unable to recommend whether double bundle ACL reconstruction improved outcome, but there was a trend to improving knee stability.

### 2.3.4 Allograft

Using allograft tissue avoids some of the potential problems associated with autograft use, principally that of donor site morbidity. However, evidence suggests that the rupture rate
associated with allograft may be higher than with autologous tissue.\textsuperscript{87, 88} Graft preparation can be time and labour intensive.\textsuperscript{89} There is also a risk of disease transmission including acquired immunodeficiency syndrome associated with allograft tissue.\textsuperscript{90}

2.3.5 Synthetic ligaments

Intra-articular reconstruction of the ACL with synthetic materials can potentially avoid many of the problems associated with using autograft or allograft tissue. They were used in large numbers in the 1980s, but due to concerns about their use including synovitis, rupture rate and tunnel widening leading to problems with revision surgery they have fallen out of favour.\textsuperscript{91, 92, 93, 94}

In summary, evidence suggests that current isolated intra-articular techniques cannot restore normal knee biomechanics. Cadaveric studies have shown that this is the case for both single bundle and double- bundle reconstruction techniques.\textsuperscript{85, 95} Clinical studies assessing rotational stability following ACL reconstruction have also shown that double bundle reconstruction is no better than single bundle ACL.\textsuperscript{96}

2.4 Extra- articular reconstruction

Extra-articular reconstruction techniques aim to prevent abnormal rotation by placing a check- rein on the lateral side of the knee. These
were used widely in the past, either in isolation or in combination with an intra-articular reconstruction. This can be achieved either with the use of a separate piece of graft or by using the same intra-articular graft outside the knee as an extra-articular graft.

Several different methods for extra-articular reconstruction have been described, and these will be reviewed in this section. The exact site of femoral attachment and tension of the extra-articular reconstruction is critical in determining the successful restoration of normal biomechanics.  

There was previously little anatomical or biomechanical evidence to help surgeons place their grafts when these techniques were in widespread use. One study suggested that the optimum site of femoral fixation is proximal and posterior to the femoral origin of the lateral collateral ligament, with an attachment on the anterolateral tibia anterior to Gerdy’s tubercle. This was suggested following a kinematic study of five adult cadaveric knees in one of the few biomechanical studies that had been conducted. Measurements between different points on the lateral side of the knee were taken at 7 different angles of flexion. They suggested that positions anterior on the tibia and posterior on the femur present an obvious restraint to anterior translation. The data were compared with commonly performed lateral extra-articular reconstructions. The attachment points showed maximal separation between 15 and 45 degrees of flexion, so as not to stretch during other portions of the motion cycle.
The authors found that variations in the femoral position had a greater effect than changes in the tibial attachment.

Extra-articular reconstruction has also been suggested to have the additional benefit of protecting the intra-articular graft during the healing phase. Engbretsen et al. 99 found that an extra-articular reconstruction decreased the forces going through an intra-articular reconstruction by 43% in vitro.

There are few studies that directly compare intra-articular only with intra-articular and extra-articular techniques. Roth et al.100 compared isolated intra- with combined intra- and extra-articular reconstruction. The authors concluded that there was no benefit in using an additional extra-articular repair. However, the methods did not indicate as to why some patients had an isolated intra-articular reconstruction and some had a combined procedure. Strum et al.101 compared a group of 43 patients who had an intra-articular reconstruction combined with an extra-articular reconstruction, with 84 who had only an isolated intra-articular reconstruction, and found no difference in outcome. However, it should be borne in mind that these studies were not based on sound anatomical or biomechanical studies.
2.5 Previous descriptions of lateral extra-articular reconstructions

These techniques were used extensively in the past. A detailed literature review was undertaken as the first part of this thesis to aid in understanding the anatomy and previous success of extra-articular reconstructions.

2.5.1 Lemaire procedure and modifications

Lemaire described one of the earliest extra-articular reconstructions in 1967\textsuperscript{102,103}. Originally this procedure was designed to control chronic rotatory instability, but did not control anterior translation of the tibia. The technique used an approximately 16cm by 1.5 cm of ITB, left attached to the Gerdy's tubercle distally. A bone tunnel was made through the lateral femoral condyle, which exited near the lateral head of the gastrocnemius. The fascia lata graft was passed under the LCL, and then through the bone tunnel. It was then passed again under the LCL before being stitched back onto the fascia lata strip.
Figure 5 – The original Lemaire procedure: a strip of ITB is taken beneath the LCL, then passed through a bony tunnel through the lateral femoral condyle near the lateral head of gastrocnemius, before being stitched back onto itself.104

Dejour et al105 described a modification of the Lemaire procedure using the gracilis tendon. The graft is attached in a tunnel located at the isometric point proximal to the LCL insertion, and then both parts passed under the LCL. They are then passed under a tunnel at the level of Gerdy’s tubercle before being sutured together.

Figure 6 - Modification of Lemaire’s original technique using a gracilis tendon graft105,106
Neyret et al\textsuperscript{107} reviewed the results of isolated extra-articular reconstruction using an isolated Lemaire technique in 33 knees of young patients (35 years old, range 15-56 years) who were all professional skiers who all had a confirmed ACL tear and a positive pivot shift test. The operation failed to control symptoms in 17 of the 33 knees, although more of the successes were in patients over the age 35 years. The authors suggest that the disappointing results in the series were due to a lack of combined intra-articular reconstruction. Lazzarone et al\textsuperscript{108} reported similarly disappointing results in 40 patients. Although a success rate of 80\% was quoted, there was a deterioration to 62.5\% after 5 years.

\textbf{2.5.2 MacIntosh procedure}

The MacIntosh procedure was the most widely used of the extra-articular reconstruction techniques. It is an extra-articular, distally based tenodesis first described in 1972\textsuperscript{109}, and is in some instances still used today. The rationale of the operation is to limit anterior movement of the lateral tibial plateau by femorotibial tension in the tenodesis, which is placed obliquely to stop the subluxation.\textsuperscript{110}

Technically, the procedure is performed via a 20 to 25 centimetre skin incision following the midlateral line of the thigh, curving across the lateral femoral condyle midway between the patella and the head of the fibula, and then extending to 2 centimetres (cms) below Gerdy’s tubercle.\textsuperscript{110} Care must be taken to avoid any fascia lata
damage during the incision. A posterior skin flap, combined with the subcutaneous fat, is raised, and the fascia lata is cleared of fat. A strip of fascia lata is then defined, approximately 15 cm long and 1 to 1.5 cms wide. This remains attached to the Gerdy’s tubercle, but is freed proximally. The authors note that the small fossa proximal to the lateral femoral condyle is cleared of fat, but ‘great care is taken to preserve the main band of insertion of the intermuscular septum into the lateral femoral condyle. Branches of the superior lateral geniculate vessels need ligation. The LCL is then defined, and although it cannot always be seen, it can be felt. A tunnel is made beneath the proximal part of the ligament, and the strip of fascia lata is passed through it. An osteoperiosteal flap, approximately 1 cm wide is made at the posterior corner of the lateral femoral condyle. The strip is looped around it several times whilst the foot and tibia are held in full external rotation. The osteoperiosteal flap is then sutured over the strip. The defect in the fascia lata is then closed in all but the distal five cms.

Of particular note with the description of the original technique is the proximal insertion of the tenodesis, 1 cm proximal to the posterior corner of the lateral femoral condyle. Also of note is the authors highlighting that the surgeon should avoid damage to the distal femoral insertions of the ITB.
Several authors reported their results using extra-articular MacIntosh reconstruction without an intra-articular reconstruction. Amirault et al\textsuperscript{111} reported results on 27 patients using this technique. Follow up was based on range of movement, arthritic change, anterior draw and pivot shift. Results were good or excellent in 52\%, fair in 26\%, and poor in 22\%. Ireland and Trickey\textsuperscript{110} reported results in 50 patients with a mean follow up two and a quarter years. In 42 of the knees the pivot shift was abolished. Taylor et al\textsuperscript{112} reported long term results in 18 patients with a mean follow up of 9.3 years. They
found that a sustained benefit was found in most cases, although many had degenerative changes. Frank and Jackson \textsuperscript{113} reviewed results of isolated extra-articular Macintosh reconstruction at 5 years (n=35). They reported that 77\% of patients had subjective improvement, and 83\% had objective evidence of either minor instability or none at follow-up. Results were poorer in patients with chondropathy at the time of surgery.

Bertoia \textit{et al} reported results on 34 patients using a combined intra and extra articular reconstruction.\textsuperscript{114} The femoral attachment of the tenodesis was posterior and proximal to the insertion of the LCL. Results were only reported using their own scoring system, although excellent results were reported in 23\%, good in 68\% and failed in 9\%. They noted that there was a 91\% conversion to a negative pivot shift post op. Dandy \textsuperscript{115} published results of several different techniques, and in the paper included a group of patients having a Macintosh repair combined with a patellar tendon or Leeds Keio intra- articular graft. Results were found to be better in the combined intra- and extra- articular group. However at 6 years, the pivot shift had returned in 38\% of these patients.

Many other authors have described variations in the MacIntosh technique, the principal differences being variations in the femoral fixation.
2.5.3 Variations on the MacIntosh procedure

Losee procedure

Losee *et al*\(^{16}\) designed an operation that was termed the ‘sling and reef’ operation. They stated that the operation was for patients who had a history of ‘intolerable instability’ of the knee and who had a positive test for anterior subluxation of the lateral tibial plateau. They recognized that in chronic cases this is a result of the ACL being torn but also due to a deficiency of the lateral capsule.

For the surgical procedure, the ITB is exposed via an incision that is made 15 cms proximal to the joint, and curving to three cms distal to the lateral margin of the tibial tubercle. Incisions are made in the ITB once it is exposed. The authors note a bifurcation of the ITB where it divides into a posterior branch running to the Gerdy’s tubercle and an anterior branch running to the patella. From this bifurcation, the ITB is incised 14cms proximal and then distally to the joint line. This strip of ITB is cut at its proximal end. A tunnel is made through the lateral femoral condyle, anterior and inferior to the lateral femoral epicondyle, using a curved osteotome. The incision should be located at the centre of rotation for the arc traversed by Gerdy’s tubercle as the knee is flexed and extended. This is determined using the strip of ITB. The tunnel is guided so that it emerges below the lateral head of the gastrocnemius. The strip of ITB is then threaded through, and it is checked to see that anterior subluxation is prevented. The strip is then sutured to the periosteum at the entrance and exits to the tunnel. The strip is then passed through the tendon of origin of the
lateral head of the gastrocnemius, entering at a point 1 cm distal and 0.5 cm medial to the posterior opening of the tunnel. It is reefed onto the muscle, before being passed to the substance of the arcuate ligament posterior to the LCL above the joint line.

**Figure 8** – Illustrations from Losee’s paper showing femoral attachment of the extra-articular reconstruction using the iliotibial band

In the original series, the authors describe the results of 50 patients who had undergone the procedure, with follow up from one to six and a half years. At arthrotomy, all patients were seen to have an ACL tear. One knee of the twelve had subluxed. No formal scores were made on the twelve patients, but a self designed system of good, fair or poor was used. The authors concluded that results were good in 41, fair in 6 and poor in 3. Of note is that the authors operated on one patient who was found to have a Segond fracture as they recognized the diagnostic importance of this for anterolateral instability. They noted that the Segond fracture was attached medially to the stretched
ITB, and in this case when a staple was inserted to fix the fracture, subluxation was prevented.

**Andrews operation**

The Andrews procedure was a mini-reconstruction, using isometric bundles in the ITB to prevent anterolateral rotatory instability\(^{117,118}\). Two ITB strips were fashioned and attached to the lateral femur, the aim of one of them to be tight in extension and the other to be tight in flexion. It was suggested that the procedure could be used in combination with an ACL repair in patients with anterolateral instability. However, when assessed on cadaveric knees the technique was found to be unsatisfactory with it being overly tight at 90° of flexion, with a suggestion that this would lead to graft stretching and the construct becoming non functional at ranges where the technique should be functional nearer to extension.\(^{119}\)

**2.5.4 Ellison’s distal ITT transfer**

Ellison’s technique \(^{120}\) was designed to prevent anterior tibial subluxation of the tibia in patients with anterolateral instability by providing a dynamic transfer. This was achieved by altering the insertion of the ITB at Gerdy’s tubercle. A further theoretical benefit suggested by the authors was that the vasculature of the transplant survived.

The technique as described by Ellison was to raise a button of bone of
approximately 1.5cm diameter at Gerdy’s tubercle. A broader proximal fascial strip is then made. The LCL is defined, and the button of bone with the attached ITB is then passed under. The tunnel under the LCL is made as proximal as possible. The authors note that the mid-third capsular ligament should be plicated. The block of bone detached from Gerdy’s tubercle is then moved anteriorly and attached using a staple. The ITB is then closed over the defect, and the author emphasizes the importance of closing the ITB in preventing further instability.

![Figure 9](image) – Ellison’s illustration of the ITB passed behind LCL and the bone block anchored with a staple

Ellison noted a number of potential advantages of his transfer. He recognized that a dynamic transfer places more stress than a simple static stabilizer on the point of transfer, and also suggested that a dynamic structure would be less likely to stretch. He also suggested that the technique would maintain vascular supply to the graft.
In his original paper, Ellison described the first 18 cases, and had excellent or good results in 15 of the patients. Results for extra-articular repair alone were mixed in other series. While Marston\textsuperscript{121} reported good or excellent results in 77\% of patients, Kennedy \textit{et al.}\textsuperscript{122} using the same Ellison procedure, reported that a positive pivot-shift sign was still present in 24 of 28 patients at a minimum follow-up of six months. Comparison with modern techniques is difficult, as many of the studies did not report their results using validated outcome measures.

\subsection*{2.5.5 Combined intra and extra articular reconstruction}

Marcacci\textsuperscript{123} described a technique to use hamstrings graft as an intra-articular reconstruction, and then used the same graft as an extra-articular augment to prevent anterolateral rotational instability after the reconstruction. The semitendinosus and gracilis tendons were passed through the tibial and femoral tunnels, before being passed laterally and then deep to the ITB to be fixed onto Gerdy’s tubercle. This technique had the benefit of avoiding some of the problems associated with using an ITB graft, such as donor site morbidity and cosmesis. Their post-operative regime consisted of proprioceptive exercises and strengthening, and was associated with an average time to return to sports at four months. Their ten-year results do not show significant degenerative changes of the lateral compartment. They concluded that a combined extra- and intra-articular procedure is a valid surgical option. Others have described similar techniques.
using extra-articular tenodesis with the same hamstrings grafts\textsuperscript{124}.

\textbf{Figure 10} – Marcacci’s combined intra and extra-articular reconstruction

\section*{2.6 Problems with previous extra-articular reconstructions}

Extra-articular reconstruction fell out of favour in the United Kingdom in the early 1990s. Some of this may be due to the introduction of new techniques with perceived benefits, for example
synthetic ligaments, which have since themselves again fallen out of favour. Some areas of concern existed with the reconstructions themselves. These included increased rates of degenerative changes in the lateral compartment of the knee, although this may have been a reflection on not being performed with a combined intra-articular reconstruction.\textsuperscript{100,125} Cosmesis was also previously a concern due to the long incisions needed to harvest tissue.\textsuperscript{126} Finally, concerns about failure rate could be reduced by identifying a more anatomically and biomechanically sound reconstructions with a greater understanding of tissues in this area.

Despite these concerns about their use, a role for extra- articular tenodeses in modern knee ligament surgery can still be identified. The past knowledge gained from extra-articular tenodesis needs to be applied to new techniques, and similarly this is the case when considering previous descriptions of the anatomy of the anterolateral structures. Previous interpretations of lateral knee anatomy and the link with previous extra- articular procedures are considered in Chapter 3.
Chapter 3: Summary of published literature relating to anterolateral knee anatomy

The lateral aspect of the knee consists of a complex and variable set of structures. This has led to confusion in previously published literature with a number of different names being applied to describe the structures. However, these reports are still useful to help guide anatomical dissection work in this thesis. A detailed review of these publications follows, broadly divided into two sections; the first a historical review of terminology in relation to the ITB and lateral capsule, followed by a review of the modern interpretations of the anatomy of the anterolateral structures.

3.1 Historical descriptions of the anterolateral structures including the ITB

The ITB had been described in very early anatomical texts including by the Paduan anatomist Vesalius in 1543. The eponymous name for the ITB was previously ‘Maissiat’s band’, named after the French anatomist who described the ITB in 1843, although this name is no longer in common use. ¹²⁷ Gerdy had previously described the tubercle on the tibia where the ITB inserts in 1829.¹²⁸ One of the most widely quoted historical works in relation to the anatomy of the anterolateral knee structures is a paper by the French surgeon Paul Segond who described the eponymous avulsion fracture of the tibial...
plateau that occurs at the same time as an ACL injury. He described a ‘pearly, resistant, fibrous band’\textsuperscript{129}

Further descriptions of this structure were provided by Milch\textsuperscript{130} who presented a case series of 3 cortical avulsion fractures of the lateral tibial condyle. By the time of this case series several attempts at extra-articular reconstructions had already been made. In 1948 RJ Last published a paper on the anatomy of the knee\textsuperscript{131}. He noted ‘the ribbon like condensation which constitutes the ITB is received into a smooth non-pitted facet which stands out prominently in the front of the lateral tibial condyle.’ He did not provide any more detail of the surrounding structures. The final surgeon who lends an eponymous name to a structure in this area is Kaplan who in a descriptive study in 1958 noted that the ITB acts as a stabilizing ligament between the lateral femoral condyle where it is attached at a fixed point and Gerdy’s tubercle\textsuperscript{132}.

3.2 The mid third capsular ligament – and the first use of the term ‘anterolateral ligament’

In the 1970s there was a surge in interest in extra-articular reconstruction techniques and in conjunction with this the anatomy of the area was also studied. Part of the reason for this area of work may have been the inability to fashion an intra-articular reconstruction due to arthroscopic surgery having not been sufficiently well developed. Hughston’s group provided much of the work detailing the anatomy of the lateral knee structures.\textsuperscript{39,133}
group described ‘capsular ligaments’ which were thickenings of the capsule. They subdivided the lateral compartment into three portions: anterior, medium and posterior. The middle third of the lateral ligaments, composed of the ITB, the capsular ligaments deep to it, extend posteriorly as far as the collateral ligament. The ITB reinforces the mid-third capsular ligament. They noted that these structures are strong and are a ‘major lateral static support’ for the knee at around 30° of flexion. Anterolateral rotatory ligament instability (ALRI) was thought to be produced by a tear to this lateral capsular ligament. Attachments of this structure were described as being from the lateral epicondyle to the distal tibial joint margin. Interestingly the authors acknowledge that a standard lateral capsulotomy, which was in use at the time for open lateral meniscal repair or menisectomy, did not normally lead to ALRI. They thought that this was due to in the majority of times a standard repair of the capsular ligaments not leading to residual instability.

A number of studies at this time also looked at in vivo anatomy in relation to ALRI. Norwood et al reviewed 36 knees with ALRI. They found that the ACL and mid third of lateral capsular ligaments was torn in 21 knees, the lateral capsular ligament alone in 6 knees, and the ITB with ACL and capsule in 3 knees. This is an important observation as it suggests that ALRI may occur with an intact ACL.134

Johnson et al135 reviewed 7 clinical cases of avulsion of the ‘lateral capsular ligament’ and reproduced this finding in 6 cadavers. They described the lateral capsular ligament complex as having vertical and horizontal components. They suggested that a pivot shift could
be caused by a lateral capsular release, a complete section of the ACL and a partial tibial collateral ligament release. They suggested an operation to improve stability, by moving the ITB with Gerdy’s tubercle anteriorly and inferiorly.

The term ‘anterolateral ligament’ first appears in a paper by Terry et al in 1986. They describe 5 parts of the ITB, the aponeurotic, superficial, middle, deep and capsule-osseous layers by dissecting 17 fresh frozen knees. They suggest that the superficial layer of the ITB, combined with the deep and capsule-osseous layers, effectively functions as an anterolateral knee ligament.

Clinical work from this group also supports the hypothesis that the ITB may be critical in knee stability. The paper looked at 82 patients with an acute knee lesion with either anteromedial or anterolateral instability. 98% of patients had ACL tears. They noted a variation in grade of Lachmann test and pivot shift tests that did not correlate to the ACL. They found that 93% of patients had an injury to the ITB.

3.3 Division of the lateral structures of the knee into three layers

Seebacher et al proposed a classification system for the anatomy of the lateral structures of the knee, dividing the knee into three distinct layers. The paper was primarily focused on the anatomy of the posterolateral corner of the knee. The deepest layer, which consisted of the lateral part of the capsule, splits into two laminae posterior to the ITB, and these encompass the LCL.
3.4 The anterior oblique band

A number of studies have used the term ‘anterior oblique band’ in relation to the anatomy of the anterolateral structures. Irvine et al. carried out a prospective study of 8 patients found to have a Segond fracture, before dissecting 7 cadaveric knees. They described the area of avulsion identified as being the Segond fracture as being ‘the attachment of an anterior oblique band of the lateral collateral ligament.’
Figure 12 – Cadaveric dissection showing the AOB (black arrows) and LCL (white arrow) and a schematic showing the Anterior Oblique Band (AOB)

The term was also used in a paper used by Campos et al. Three cadaveric knees were dissected, and these and a further three non-dissected cadaveric knees had MRI scans performed. This was also combined with a retrospective review of a further 17 clinical MRI scans. They noted a broad insertion of the ITB, with fibres extending
posterior to the Gerdy’s tubercle. The anterior oblique band was described as extending from the fibular collateral ligament to the midportion of the lateral tibia. They described the lateral capsular ligament as appearing as a thickening of the capsule.

3.5 Recent descriptions of the ITB

The anatomy of the ITB is complex. It is formed from the more proximal tensor fascia lata, gluteus maximus and gluteus medius muscles. Its major insertions are into the lateral femoral condyle and Gerdy’s tubercle. Three papers published in 2006-7 reviewed the anatomy of the ITB.

3.5.1 Fairclough et al’s description of the ITB

The first of these was Fairclough et al’s paper, whose primary aim was to review ITB syndrome, including its anatomy, histology and magnetic resonance imaging findings. ITB ‘friction syndrome’ is an overuse injury causing knee pain, and runners and cyclists are commonly affected. Anatomic dissection of 5 cadavers showed that the ITB was anchored at the lateral epicondyle by strong fibrous bands that were obliquely orientated, and although the attachment could be at the epicondyle it was more often proximal to the site. No bursa was identified but a region of adipose tissue was seen between the fibrous strands and intervening ITB. The region between the ITB and lateral aspect of the femur was seen to be filled with a highly vascularized and innervated mass of adipose tissue. Fairclough et al emphasise that the ITB is firmly attached to the distal femur and can be considered a tendon enthesis. They also state that
the ITB can be divided into a proximal ‘tendinous’ and a distal ‘ligamentous’ part below the lateral epicondyle. They suggest that this part of the ITB could be involved in limiting internal rotation of the tibia.

3.5.2 Sanchez et al

This article summarised concepts of anatomy of the lateral side of the knee. The authors divide the ITB into superficial, deep and capsule-osseous layers of the knee. The deep fibres are described as being seen when the superficial layer of the ITB is split, adhering to the lateral supracondylar tubercle of the femur. Other authors have termed these the ‘Kaplan’s fibres’. The authors state that the deep layer of the ITB connects the medial border of the superficial iliotibial layer to the distal termination of the lateral intermuscular septum of the distal femur.

The authors state that the capsulo-osseous layer is medial and distal to the deep layer, and originates from the region of the lateral intermuscular septum and fascia over the postero-lateral aspects of the lateral gastrocnemius and plantaris muscles. This structure blends with the short head of the biceps femoris. This area of the knee is described as forming a sling and the authors describe it functioning as an anterolateral ligament of the knee. The authors acknowledge that this is what most surgeons attempted to reconstruct with an extra-articular ACL reconstruction.
The authors also review the midthird lateral capsular ligament. They divide the joint capsule into superficial and deep laminae, which are separated by the inferior lateral geniculate artery. The authors state that the deep capsular lamina is a result of the fibula receding from the lateral femur. They divide the joint capsule of the knee into 3 sections, anterior, lateral and posterior. The anterior section extends from the patella tendon to the anterior border of the popliteus on the femur. The midthird lateral capsular ligament is a thickening of the lateral capsule of the knee, divided into 2 components: the meniscofemoral and meniscotibial. The authors state that this
structure is an important secondary stabilizer to varus but there is no reference given to support this.

3.5.3 Vieira et al’s description of the ITB

Vieira et al’s study aimed to define the anatomy of the ITB.\textsuperscript{143} Ten fresh cadaveric knees were used in the study. The knees used in the study were younger than those in many other studies, with an age range of 33 to 66 years. Several different incisions were made through the ITB to show the underlying structures.

The results were presented in three layers, the superficial, deep and capsule osseous layers. The authors note that the ITB did not have just one insertion at the Gerdy’s tubercle but defined insertions. These were the insertion at the linea aspera, the insertion on the lateral epicondyle, the patellar insertion, the direct insertion (Gerdy’s tubercle) and the capsular-osseous insertion. They state that this is also known as the lateral femoro tibial ligament (figure 14).

The deep layer is defined as having a wide fixation from the linea aspera and attaching to the lateral epicondyle via a strong ligament. The capsular osseous layer has a very well defined ligament structure starting from the lateral supraepicondylar region, bordering the lateral epicondyle. They state that this acts a true anterolateral ligament of the knee.
3.6 Modern interpretations of the anterolateral structures – Summary and critique of work

Since 2012 a number of research groups have sought to clarify the attachments of the anterolateral ligament of the knee. These papers are summarized and critiqued in the following section.
3.6.1 Vincent et al’s Anterolateral ligament

Vincent et al published the first of the more recent works focusing on the anterolateral structures of the knee. The goals of this study were to define the incidence of the anterolateral structure that they had noticed during total knee replacement (TKR) surgery, its anatomical location and histological composition. The incidence of the structure was determined by identifying it during surgery on 30 patients undergoing TKR for medial compartment osteoarthritis. The authors identified the ALL in all 30 specimens. However, identification would have been limited as additional dissection would not have been possible in the clinical setting. No quantification of the size of the structure or attachments was made. It is difficult to say what the structure identified was, as a fold of capsule could give the appearance of a capsule thickening. Results of this part of the study should be treated with caution.

The second part of this paper was a cadaveric anatomical investigation, using ten fresh frozen knees. The authors again identified the ALL in all 10 specimens. The ligament was thought to originate from the lateral femoral condyle; it was anterior to the popliteus tendon in nine and arising from the popliteus tendon in another. It was noted in each case to be closely associated with the lateral meniscus. The final tibial attachment was approximately 5 mm from the articular cartilage on the proximal anterolateral tibia. The authors performed gross manual stressing of the ligament, noting that anterior tibial dislocation resulted in a more oblique course. They also noted that flexion of the knee to 90 degrees resulted in a
tightening of the structure. The structure was relatively flat, with an average width of 8.2 +/- 1.5mm, thickness of 2-3 mm and an average length of 34.1 +/- 3.4mm. Illustrations of the structure from their paper are shown.

Figure 15 – Diagram from Vincent et al’s paper to show the position of the ALL as they described

The final part of the study used histological analysis of sections through the ALL from the cadaveric specimens. This revealed it to be a strip of connective tissue surrounded by loose synovial tissue. The dense fibrous tissue in the core of the structure accounted for
approximately 20% of its cross sectional area. Structures proximally showed a common origin with the insertion of the femoral popliteus tendon. Distally fibres came close to the meniscal tissue, but continued without interruption to the tibial plateau. It is not clear how many specimens underwent histological analysis.

In the discussion section, the authors conclude that the ALL was ‘quite consistently present’ in all 40 specimens. As already discussed, this cannot be said to be definitely the case in the 30 knees undergoing TKR. It is unclear from the descriptions whether all 10 knees had histological analysis performed or just one of the knees. It should also be noted that the dissection technique for identifying the ALL was much more destructive than in other studies. In Vincent et al’s study the whole knee other than the lateral structures were removed and the structure was identified ‘inside out’. This must raise the question as to whether they have identified structures that would be superficial to the capsule when dissected normally as being in the capsule. From the description, it does not seem that the structure that Vincent et al, and subsequent papers in this chapter identified, is the ‘anterolateral ligament’ that had previously been described by other groups including Terry et al and Vieira et al.136,143

I contacted Vincent et al’s team to clarify aspects of the anatomy. (personal communication). Interestingly the structure they originally described as the anterolateral ligament was termed the ‘menisco-popliteal’ ligament, but it was only after the histological analysis that the attachments to the tibia were described. The authors in the conclusion note that no biomechanical analysis of the structure has
been performed, but do suggest that the structure may prevent anterior translation of the tibia. They also do not attempt to draw conclusions as to whether the structure may be involved in the formation of the Segond fracture. However it is difficult to imagine, with their anatomical description of the ALL and of it becoming tight at 90° of flexion, how the structure could be considered biomechanically ‘useful’ in preventing the pivot shift, as an attachment anterior and at the level of the lateral epicondyle is unlikely to do this; the ligament as drawn by them would not be isometric and would slacken with knee extension.

3.6.2 Claes et al’s Anterolateral ligament

Claes et al’s anatomical description of the anterolateral ligament of the knee was the second of the recent papers on the topic.\textsuperscript{145} Due to a social media campaign by the group it was also reported in the popular press.\textsuperscript{146} The aim of this study was to provide a detailed anatomical characterization of the ALL. To do this 41 unpaired, embalmed human cadaveric knees were dissected. Specimens with a damaged ACL or gross lateral tibio- femoral osteoarthritis were excluded from the study.

Unlike Vincent et al’s study\textsuperscript{144}, the dissection protocol was from superficial to deep. A large cutaneous flap was created, before the ITB, extensor apparatus and short head of the biceps femoris were cleared of subcutaneous fat. The ITB was then cut 6cm proximal to the lateral femoral epicondyle, and released from the tibia at Gerdy’s
tubercle, cutting the deep ITB and Kaplan's fibres. The capsule could then be seen. The LCL was then identified and with the knee subjected to internal torque, fibres could be identified running from the region of the lateral condyle to an area posterior to Gerdy's tubercle. Origins of the ALL, LCL, ITB and popliteus tendon were then identified. A digital caliper was then used to identify the attachments and their relationships.

A criticism of the study is the use of embalmed human knees. Other studies described in this chapter used fresh frozen cadavers and the anatomy as seen by Claes et al would not have been as clear as if they had they used fresh frozen cadavers, limiting conclusions they could draw.

The authors identified a ‘distinct ligamentous structure’ in 40 of the 41 knees (97%). The anatomical description of the knee where the ALL was not identified is not recorded. Where it was found, it could be easily distinguished from the thinner joint capsule lying anterior to it. The origin of the ALL could be found on the prominence of the lateral femoral epicondyle, anterior to the LCL origin, but posterior and proximal to the origin of popliteus. They note that the superficial fibres of the ALL continue over the lateral aspect of the distal femur in the direction of the lateral intermuscular septum of the thigh. The posterior fibres of the ALL were seen to blend with the proximal part of the LCL. The ALL was seen to run in an oblique course to the anterolateral side of the proximal tibia, with a strong connection to the lateral meniscus. The lateral inferior geniculate artery could be seen between the lateral meniscal rim and the ALL at the level of the
joint line. The insertion on the tibia was seen to be posterior to Gerdy’s tubercle, with no connection to the ITB. *(Figure 15)* The length of the ALL was 41.5 +/- 6.7 mm in 90° knee flexion and 38.5 +/- 6.1 mm in extension. Mean width at the femoral attachment was 8.3 +/- 2.1 mm, narrowing slightly to give an average width of 6.7 +/- 3.0 mm at the joint line, and at the tibia having a width of 11.2 +/- 2.5 mm. The tibial attachment was 21.6 +/- 4.0 mm posterior to Gerdy’s tubercle and 23.2 +/- 5.7 mm anterior to the tip of the fibular head. The authors give detailed information on the anatomy of all of the specimens.

*Figure 15 – Anatomical dissection from Claes et al paper illustrating the ALL*
Figure 16 - Anatomic drawing from Claes et al to show the position of the ALL – the femoral attachment is anterior and distal to the lateral femoral epicondyle

Claes et al conclude that the ALL is a distinct ligamentous structure on the anterolateral aspect of the human knee. They however note that the conclusions in the study do not support Vincent et al’s earlier anatomical study. One explanation for this could be that the fibres originate over a wider area and hence the difficulty in determining the exact site of the attachment. Neither author state how they determine where the origin is taken from, whether it is the furthest attaching fibres or where the bulk of the fibres attach. They note as discussed previously that Vincents et als ALL would be anisometric. The authors criticize Vincent et als work as they are not clear whether the structure is part of the ITB. Claes et als work could
be criticized due to the destructive nature of the dissection, in particular the removal of Kaplan's fibres and deeper layers of the ITB without careful dissection.

The authors then hypothesised that the ALL could be a stabilizer for internal rotation, however they did conclude that further biomechanical work was needed. This did not prevent them from advertising a method for reconstructing the ALL shortly after the paper’s publication, despite the lack of biomechanical evidence.\textsuperscript{147}

\textbf{3.6.3 Helito et al.}

Helito \textit{et al} presented their interpretation of the anatomy via a descriptive laboratory study performed in 20 human cadavers.\textsuperscript{148} Exclusions from the study were a history of infection, previous surgery of the lower limbs, or ‘other conditions’ that could alter the anatomy of the region. It is not clear whether the cadavers were fresh or frozen.

A standardized anatomical dissection was used, initially removing skin and subcutaneous tissue before a tenotomy of the quadriceps tendon was performed. A medial parapatellar approach was performed and an osteotomy of the tibia to allow the patella to be moved. The ITB was excised at Gerdy’s tubercle, and a biceps femoris tenotomy was performed at the fibular head. The popliteus was cut at its muscle. The lateral structures were then viewed in isolation. Length, thickness and width measurements were made using
standard calipers. The ALL was also studied, with histological analysis in 10 cases.

The authors identified what they termed the ALL in all 20 of the knees that they studied. The attachment of the ALL was found to be anterior and distal to the attachment of the LCL, near to the articular cartilage of the distal region of the lateral femoral condyle. The authors described a 'bifurcation', one proximally to the lateral meniscus in the peripheral portion of the transition between the anterior horn and the body, and the other to the tibia more distal between Gerdy’s tubercle and the head of the fibula. The tibial attachment was found to be approximately 4.4 +/- 1.1 mm from the distal portion of the anterior articular cartilage of the proximal tibia. Measurements of the ligament were mean length 37.3 +/- 4.0, width 7.4 +/- 1.7 and mean thickness 2.7 +/- 0.6 mm. The presence of dense connective tissue with arrangement of fibres was found in all specimens.

*Figure 17* - Helito’s ALL marked with an asterisk, lateral collateral ligament (LCL), fibular head (FH), Gerdy’s tubercle (Gt)
The main criticism that can be leveled at this study is that the authors have again only focused straight in on the capsule. The ITB has been removed immediately without paying attention to its attachment. Not all of the previous work has been referenced in this study and the authors have focused on the work of Vincent et al.\textsuperscript{144}

\textbf{3.6.4 Caterine \textit{et al}}

Caterine \textit{et al} sought to further determine the anatomy and histology of the ALL due to inconsistencies in the other papers as previously highlighted.\textsuperscript{149} The authors also used MRI to review the anatomy although this part of their study is reviewed separately in chapter 6 of this thesis. Nineteen (three of which were paired) fresh frozen cadaveric knees underwent anatomical dissection. A standard dissection technique was used. This was similar to that described as a technique by Claes \textit{et al}.\textsuperscript{145} Skin was removed on the lateral side of the knee, with the ITB then cut at the level of the mid thigh and reflected inferiorly to its distal insertion. The authors do not record how the ITB was removed or to what extent the deep layers and Kaplan's fibres were removed or damaged during the procedure. Once removed, a varus and internal rotation load was applied between 30° and 60° knee flexion to highlight structures coming under tension. Any tissue not coming under tension was removed, leaving what the authors presumed to be the ALL. The LCL and popliteus tendon were then left exposed. These were then individually isolated. If the ALL was identified, an evaluation of its anatomical characteristics was then performed. Anatomical
measurements were taken using calipers, including the width of the structure.

Histological analysis was then performed on the ALL from four knees. It is not clear why these four knees were chosen and if they were selected randomly. Three of the samples were used to identify the microscopic structure of the ALL and the fourth was used to investigate the bony attachments of the ALL. Immunohistochemistry was performed on one specimen to determine the ALL’s peripheral nervous innervation.

The authors identified the ALL in all 19 of the specimens. They noted that it was ‘often difficult’ to locate the specific origin of the ALL on the lateral femoral epicondyle. It was often difficult to distinguish between the proximal attachments of the ALL and LCL. However ‘it was evident that both had their own attachment points to the femur.’ The authors found that the ALL inserted into the femur either anterior- distal or proximal- posterior to the LCL attachment. They stated that this was in contradiction to previous reports although this does not seem to be the case when compared with previous descriptions. They also described how in one case the ALL did not attach to the proximal tibia. The three variations they described are summarized in table 1.

In all cases, the ALL was found to attach to the lateral meniscus. The ALL was measured as showing a femoral attachment mean width of 4.8 +/- 1.4mm, a mean tibial insertion width of 11.7mm +/-3.3mm, and mean thickness of 1.4 +/- 0.6mm. Insertion of the ALL was, apart
from one case, at the midpoint between Gerdy’s tubercle and the LCL.
In a final statement that contradicts some of their earlier comments
the authors state that five of the specimens did not undergo
anatomical measurements as the ALL ‘is a difficult structure to
visualise’.

**Table 1** - *Three anatomical variations of the ALL femoral attachment found during
dissection by Caterine et al*[^49]

<table>
<thead>
<tr>
<th>Variations</th>
<th>Number of specimens (19)</th>
<th>Origin / insertion (full extension)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11*</td>
<td>Origin Lateral femoral epicondyle anterior–distal to FCL, Insertion Tibia posterior to Gerdy's tubercle</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>Origin Lateral femoral epicondyle posterior–proximal to FCL, Insertion Tibia posterior to Gerdy's tubercle</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Origin Lateral femoral epicondyle posterior–proximal to FCL, Insertion Medial fibular head</td>
</tr>
</tbody>
</table>

*All three paired knees had both the left and right knee classified as variation*

In the three specimens that underwent histological analysis, the ALL
was seen to have a dense regular collagen structure, similar to other
ligamentous structures including the ACL. This arrangement differed
markedly from the tissue making the joint capsule. Analysis of the
femoral attachments points showed that the LCL, ACL and popliteus
tendon had almost identical morphologies. The authors suggested
that this shows that the femoral attachment point is anatomically
distinct from the LCL and popliteus, as it has a transition from

[^49]: Caterine et al.
ligamentous tissue to mineralized cartilage and to bone. Attachment at the tibia suggested a large, broad expansion over the tibia. Immunohistochemistry was found to show mechanoreceptors indicating that the ALL had a neurological innervation.

In discussion, the authors state that the most important finding of the study was that the ALL was seen to be a distinct ligamentous structure. However, this is based only on the histological appearance of three of the specimens. It is not clear how these specimens were chosen, and furthermore the authors admit later in their results that the ALL can be difficult to identify. The authors go on in their discussion to consider whether reconstruction of the ALL will improve ACL reconstruction results although with no biomechanical support these statements were not justified. They do not acknowledge how the structure they describe inserting into the fibular head could resist the pivot shift phenomenon.

3.6.5 Stijak L et al

Stijak et al sought to determine the anatomy of all layers of the lateral part of the knee, using 14 cadaveric knees. In this study the knees were formalin fixed so the anatomy would not be seen as clearly as if the knees were fresh frozen. Skin and subcutaneous fat were removed before the lateral region of the knee was dissected from the patella to the posterior cruciate ligament. The ITB superficial layer was raised from the distal insertion on the tibia to be folded over the patella.
The authors found that in all of the dissected knees, behind the lateral patellofemoral ligament (and transverse retinaculum and patellotibial band) there was a thin translucent and broad fibrous band (dimensions 49 +/- 4 mm in length, width 11 +/- 2). In the third layer of the knee, the capsule of the knee was thickened. This area of the knee showed a different morphology, in 2 knees the proximal end had a joint initial insertion with the LCL, before running midway between Gerdy’s tubercle and the head of the fibula. In 7 (50%) of the knees a thickening of the joint capsule was found with fibres running from the lateral condyle of the femur in front of the LCL insertion to lateral tibial condyle midway between Gerdy’s tubercle and the head of the fibula. The dimensions of this structure were 41 +/-3 mm, while the width was 4 +/- 1mm. This structure was termed the anterolateral ligament. In seven cases, no clearly defined ALL was found. The authors described a clearly detectable thickening of the capsule but did not feel that they could differentiate it enough from the remaining capsule to term it a separate ligament structure.

The authors state that their most important conclusion is that they identified that what they termed the ALL was present in approximately 50% of cases. They note the difficulty in defining whether the ALL is present or not. The authors hypothesise that the presence of the ALL may be dependent on the strain that the knee has been put under in vivo, and this accounts for its varying appearance. The authors for this reason suggest that the ALL that they describe should not be considered as a separate ligamentous structure. They also wonder about the necessity of an isolated reconstruction of a capsular ligament 4x 1mm thick.
The authors also note the anterior oblique band was seen as a separate structure, as part of the LCL with a separate attachment on to the tibia.

**3.6.6 Kosy et al.**

Kosy et al highlighted confusion in the previously described studies.\(^{151}\) They attempted to clarify this by dissecting eleven fresh frozen cadaveric knees. This number is less than many of the previously published studies, suggesting that their results may be underpowered. They only dissected the anatomical specimens and did not provide any histological or biomechanical analysis. Their dissection technique was based on that already described by Caterine et al,\(^{149}\) meaning that their results are unlikely to differ from that research group. A digital caliper was used to determine the attachments and size of the structure.

The study found that the ALL could be found in 10 out of 11 specimens. They make note that the specimen that did not have an intact ALL also did not have an ACL. Mean dimensions were length 40.1 and thickness 0.9 mm. The femoral origin was found to be posterior and proximal to the LCL in 6 knees, anterior and distal in 3 knees, and the same site in one knee. The tibial attachment was a mean of 17.7 (+/- 3mm) from the greater trochanter. The authors state that they had found it difficult to determine the borders of the ALL tissue.
The work in this study merely repeats the earlier dissection study of Caterine et al and does not add any new knowledge.\textsuperscript{149}

\subsection{3.6.7 Runer et al}

Runer et al again attempted to identify the ALL and its attachments using embalmed knees.\textsuperscript{152} They dissected 44 techniques using the dissection technique of Claes et al.\textsuperscript{145} However, they identified the ALL in a much lower number (45.5\%) of specimens. The femoral attachment also varied from Claes et al's paper, with 45\% attaching at the LCL and 55.0\% posterior and proximal to it. The tibial attachment was located midway between the tip of the fibular head and the Gerdy's tubercle. They did not find any attachment of the structure to the meniscus. They noted in some specimens fibres derived from the LCL inserting onto the lateral tibia, and did not count these as being part of the ALL.

\subsection{3.6.8 Daggett et al}

Daggett et al used 52 embalmed knee specimens, all of which were free of previous surgery or ACL injury, to identify the anatomy of the ALL.\textsuperscript{153} They used the dissection technique of Claes et al\textsuperscript{145} and identified the ALL in 100\% of specimens. They were primarily interested in identifying the femoral insertion of the ALL. The ALL was again seen to insert around the lateral epicondyle, with the
location directly onto the lateral epicondyle in 12 specimens (23%), a shared lateral femoral condyle origin but slightly proximal and posterior in 30 specimens (58%), and a completely separate posterior and proximal origin in 10 specimens (19%). These findings differ from those of Caterine et al (Table 1) who identified a femoral attachment anterior to the lateral epicondyle in some specimens although using fresh frozen specimens.149

Figure – The relationship of the ALL to the LCL was found to be consistent, with the ALL ‘overlapping’ the LCL

3.6.9 Parker and Smith

This recently published anatomy article sough to determine the anatomical relationships of the ALL in preserved cadaveric specimens.154 The authors describe the preserved cadavers used as being ‘stiff’ and in some of them the knee was unable to move and to access the ALL they had to incise the quadriceps femoris tendon. Although this paper may be of interest as it shows that the ALL can be found in preserved specimens, the specimens used and dissection
technique mean that scientific conclusions regarding the attachments of the ALL can not be made.

3.7 Summary

A great degree of variability can be seen in the descriptions of the anterolateral knee anatomy. In particular the definition and interaction of structures that are 'ITB' or 'capsule' is an area of confusion. At the time that the dissection work took place, the work of Vincent et al\textsuperscript{144} and the older work on the anterolateral knee anatomy were the only dissection work available, and the context of the dissection work in this thesis in relation to the subsequently published anatomy work is discussed later in the thesis.
Chapter 4 – Anatomical investigation of the anterolateral knee structures

Material in this chapter has been published:

Acknowledgements:
Joint dissections were performed with Mr Andy Williams and Mr Chim Gupte on some of the specimens in this series. Interpretation of the anatomy and results was discussed with Mr Andy Williams, Mr Chim Gupte and Prof Andrew Amis.

4.1 Anatomical investigation of the anterolateral knee structures

Ethics approval

Ethics approval was successfully obtained via Research and Ethics Committee Approval (12/EM/0247).

The study was performed at the Department of Mechanical Engineering, Imperial College, London and the Smith and Nephew Surgical Skills Centre, York. Specimens were all fresh frozen cadaveric knees. The specimens at Imperial were obtained from the USA, via the International Institute for the Advancement of Medicine, part of the Musculoskeletal Transplant Foundation and air freighted on dry ice.
4.1.1 Aim of the study

The aim of this study was to investigate the anatomy of the anterolateral structures of the knee, in particular to identify structures that may be responsible for resisting the ‘pivot shift’. At the time of dissection as well as the older works described in Chapter 3 the work of Vincent *et al*¹⁴⁴ had been published.

4.1.2 Cadavers

Forty fresh frozen cadavers were included in the study. Fresh frozen rather than embalmed cadavers allow for a better visualization of anatomy as structures can be more easily identified. All cadavers were free from any previous surgery on the lateral side of the knee and had no major features of osteoarthritis. Some of the knees used at the Smith and Nephew centre had had previous sham surgery performed on them but were only used where the lateral structures of the knee had not been damaged.

The knees used in the study were approximately 300mm long. They were removed from a freezer and thawed overnight before dissection. The specimens consisted of 21 male and 19 female cadavers. There were 18 left sided and 22 right sided knees. Mean age at death was 75 years (range 58 to 90).
4.2 Dissection technique

The dissection technique used by Vincent *et al*[^1][44] was used on some early cadaveric specimens that are not included as part of the series presented here. The technique used by this team as outlined in Chapter 3 was felt to be too destructive to the soft tissues to allow adequate conclusions to be drawn, and also meant that the anatomy of the lateral structures would have been viewed from ‘inside out’ – i.e. deep to superficial with the capsule being viewed first.

*Figure 19 – Initial early dissection using Vincent’s dissection technique shows the ALL in front of the LCL and destruction of surrounding knee tissue however a newer less destructive technique was developed.*
Therefore after further practice dissections on other knees a standardized superficial to deep technique was used. Most other authors who have subsequently published work in this area have adopted a similar approach to ours.

During the technique developed at Imperial, overlying skin and subcutaneous fat were initially removed. The interval between the biceps femoris and the ITB was opened near where the biceps femoris enters the deep plane, with the two structures then separated from proximal to distal.

![Image of dissection showing superficial fat, ITB, and biceps femoris](image)

**Figure 20** – Incision of the skin and fat allows identification of the fibres of the ITB and the biceps femoris.
Figure 21 – In the standard dissection technique, an incision was made near the biceps femoris in its plane with the ITB, allowing the deeper structures to be studied after the ITB had been retracted anteriorly.

The ITB was carefully removed from posterior to anterior off Gerdy’s tubercle so that deeper structures could be viewed. Internal rotation of the tibia at a low degree of knee flexion allowed structures that may prevent the pivot to be identified. Any fibres running anterodistally from around the lateral epicondyle were of particular interest. Multiple photographs were taken during the dissection, with the addition of a ruler and coloured pins to aid identification of landmarks. Photographs were taken using a high-resolution digital camera with the knee in a true lateral position. The knee was aligned using the posterior condylar axis. In eight of the knees a digital image analysis program (Image J; US National Institute of Health, Bethesa,
Maryland) was used to measure the size of relevant structures and also to relate structures to the surrounding anatomical landmarks.

Figure 22- Structures deep to the ITB can then be studied. This figure shows how pins were used to mark the attachments of structures

Further deep dissection of the knees was carried out to allow the structures to be viewed from the medial side of the knee, so that the anterolateral structures alone could be viewed. Transillumination was also used to display the capsule itself once the ALL was removed.

4.3 Results

With the ITB carefully removed, the anterolateral structures of the knee could be clearly studied. An extra capsular structure could be
seen passing over the LCL obliquely, and this was present in 33 of the 40 knees. It was more distinct in some specimens than others.

*Figure 23 – Dissection to demonstrate the ALL*

*Figure 24 – A further specimen demonstrating the ALL*
The femoral attachment of the ALL was a mean of 8 mm (-2 to 12) proximal and 4.3 mm (0 to 12) posterior to the most prominent part of the lateral epicondyle. The femoral attachment was difficult to identify, and rather than being a single point was a fan like condensation of fibres. The width of the ALL was relatively constant along its length. It crossed over the proximal to mid third of the LCL when the knee was flexed, and could be seen as a separate structure. It was adherent to the capsule of the knee distally but could be separated. The tibial attachment of the ALL was broader than its main body, and was posterior to Gerdy's tubercle.

Figure 25 – A further specimen shows the ALL (arrow) clearly seen overlying the LCL (star)
**Figure 26** - In other specimens, such as the one shown here, the ALL could not be clearly identified running over the LCL

Once the structure that we termed the ALL was removed, we observed a thickening of fibres that ran antero-distally from the insertion of the popliteus tendon to the anterolateral rim of the meniscus. They continued onto the tibia but inserted near the lateral edge of the patellar tendon. These fibres could be seen more clearly with the use of trans illumination.
**Figure 27** – In this diagram the ALL has been removed and the specimen is being viewed from posteromedially, with the lateral joint capsule seen from inside to outside. The capsule beneath the ALL is thin (point of arrow). A condensation of fibres can be seen running more anteriorly (held with forceps)
Figure 28 – In this figure the ALL has been removed. The capsule lying below between the meniscus and tibia is thin as revealed by trans illumination.
**Table 2** – Anatomical measurements (mm) of the ALL (8 cadavers-
mean (+/- SD (range min- max))

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean (Standard Deviation; Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALL length</td>
<td>59 (4; 51 to 63)</td>
</tr>
<tr>
<td>Lateral collateral ligament length</td>
<td>60 (5; 50 to 7)</td>
</tr>
<tr>
<td>Distance from Gerdy’s to most prominent fibula</td>
<td>34 (4; 28 to 42)</td>
</tr>
<tr>
<td>Distance between Gerdy’s to tibial ALL</td>
<td>18 (3; 14 to 25)</td>
</tr>
<tr>
<td>Distance ALL tibial attachment to Fibula</td>
<td>17 (3; 13 to 21)</td>
</tr>
<tr>
<td>Width LCL</td>
<td>5 (0; 5 to 6)</td>
</tr>
<tr>
<td>Width ALL</td>
<td>6 (1; 5 to 8)</td>
</tr>
<tr>
<td>Distance ALL attachment to tip lat epicondyle</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>8 (5.2; -2 to 12)</td>
</tr>
<tr>
<td>Posterior</td>
<td>4.3 (4.9; 0 to 12)</td>
</tr>
<tr>
<td>Distance from tibial joint line to attachment ALL</td>
<td>11 (2; 9 to 15)</td>
</tr>
</tbody>
</table>
4.4 Discussion

We termed the structure that we identified as the anterolateral ligament (ALL). The structure passed in an oblique orientation antero-distally, from femoral attachment point posterior and proximal to the lateral epicondyle. The ALL was tensed by tibial internal rotation. The lateral joint capsule was seen to contain a thickened band of fibres that were deep to the ALL, but these fibres
were seen to merge into the lateral meniscus rather than continuing straight to the tibia.

**Results of this study in relation to other previously published work**

Previous descriptions of the anatomy of the region, as well as ones that were written after the publication of this work, have not led to a consistent description of the anatomy or terminology to describe it. There may be a number of reasons for this.

A problem when discussing the anatomy of this region is the variability of the anatomy. This means that different knees can appear to have different structures. The variability of structures around the knee has been well described. This is true even for structures that are given a relatively well-fixed ‘textbook’ attachment. Zeng et al.\textsuperscript{155} reviewed the popliteus tendon insertion in 43 cadaveric knees, and despite the relatively widely held belief of a fairly constant femoral attachment found a wide difference in the attachment of the structure, with three different attachment points either anterior inferior to the LCL, below the LCL, or posterior to the LCL. It would therefore be a surprise if other structures on the anterolateral aspect of the knee, including the ALL as described by Claes\textit{et al.},\textsuperscript{145} were present in the same position in all knees.

One problem with any dissection is that there are few discrete structures. Structures blend and merge with each other and identifying where one structure ends and another begins is
sometimes operator dependent. The way the dissection is carried out can also influence what is seen, because separating structures means that a plane has to be developed between them and where this is made depends on the operator’s dissection technique. I found that once the skin and superficial fat were removed I was presented with a continuous area of tissue. With no discrete break between the biceps femoris and the ITB, even the initial incision into these tissues will have violated the deeper structures and caused damage.

4.5 Analysis of this paper’s findings in relation to other published work

The dissection technique in this paper was to start as far posterior to the biceps femoris as possible and lift anterior, whereas other studies chose to make a window directly behind the Gerdy’s tubercle to lift the ITB. This may have had an influence in what was described as being part of the superficial ITB and what has been described as being deeper tissues. Clearing tissue to identify structures, in particular those around the LCL, will influence which structures are seen to be potential restrictors of anterolateral instability. In this study I dissected to look in particular at structures that are arising from proximal and posterior to the LCL origin as this is likely to be the isometric point of any structure as identified by Krackow et al. Subsequent attempts at dissection by other investigators may have been influenced by the publicity surrounding the original ‘anterior and distal’ attachment point proposed by Claes et al, and it can be seen that many of the subsequent dissection works listed in Chapter
3 state that they follow the dissection technique of Claes et al –i.e. they may be looking for the same attachments as already published.\textsuperscript{149,151,152,153} It should be noted that Claes has subsequently moved the attachment point of his anterolateral ligament to be more posterior and proximal than in the original description.\textsuperscript{156} This is despite originally advocating an ALL reconstruction technique that was non-anatomical and had no biomechanical evidence to support it.\textsuperscript{147}

We have seen the ALL as a discreet structure that does not have any direct attachment to the iliotibial tract. The mid third capsular ligament has been described as being an integral part of the capsule itself. We did identify these fibres, but found them to be merely a thickening that seemed unlikely to provide any structural support.

We invited members of Vincent et al's team\textsuperscript{144} to dissect in the laboratory and discuss anatomical terms with us in an attempt to reconcile differences in the interpretation of the anatomy. They revealed that in the original descriptions that they gave the structures, they termed the ALL the ‘menisco-popliteal’ ligament as there was no connection between the meniscus and the tibia. However, they renamed the structure when they found on histology ligament fibres below the meniscus. The structure that they have termed the ALL is more likely to be the collection of fibres running more anteriorly in the capsular dissection that we saw.

Blending of many structures occurs in the area that we have described, as well as the ITB the short head of the biceps femoris also
inserts in this area. Due to the complex nature of the anatomy and disagreements about structures in this area when presenting this work I urged caution when asked about potential reconstruction of these structures. Further determination of in particular the biomechanics is necessary and a biomechanical test is described in chapter 4.
Chapter 5 – Biomechanical investigations of the anterolateral ligament

Material in this chapter has been published:

Acknowledgements:
Camilla Halewood, Post Doctoral Research assistant and Prof Andrew Amis helped with study design and set up and LVDT data interpretation.

Length change experiments

5.1 Aim of this study

The aim was to investigate how the structure described as the ‘anterolateral ligament’ in chapter 4 functioned and whether its behaviour would support its function as an anterolateral stabilizer of the knee by assessing its change in length during movement of the knee.

5.2 Method

5.2.1 Ethics approval

Ethics approval was successfully obtained via Research and Ethics Committee Approval (12/EM/0247).
The study was performed at the Department of Mechanical Engineering, Imperial College, London using fresh frozen cadaveric knees. The specimens were obtained from the USA, via the International Institute for the Advancement of Medicine, part of the Musculoskeletal Transplant Foundation and air freighted on dry ice.

5.2.2 Cadavers

Eight frozen cadavers were included in the study. These had been used in the anatomical dissection part of the study (Chapter 4). Fresh frozen rather than embalmed cadavers allow for a better visualization of anatomy as structures can be more easily identified. All cadavers were free from any previous surgery on the lateral side of the knee and had no major features of osteoarthritis. The knees used in the study were approximately 300mm long. They were removed from a freezer and thawed overnight before dissection and investigation.

5.2.3 Dissection technique

The standard dissection technique as described in Chapter 4 was used. The overlying skin and subcutaneous fat were removed. The interval between the biceps femoris and ITB was opened near to where the biceps femoris enters the deep plane, with the two structures then separated from proximal to distal. The ITB was carefully removed from posterior to anterior off Gerdy's tubercle so
that deeper structures could be reviewed. The ALL as described in Chapter 4 was then identified.

5.2.4 Testing

A technique previously described in the laboratory was used. \(^{157}\) Length changes of other structures in the knee have previously been investigated, including the stabilizing structures of the patella, and the collateral ligaments of the knee. \(^{157, 158}\) A modified pneumatic extension rig was used. The femur was held fixed in position with an intramedullary rod held using polymethylmethacrylate (PMMA) bone cement that then allowed it to be placed rigidly into a knee extension rig. \((\text{Figure 30})\) The femur was aligned in internal-external rotation using the posterior femoral condylar axis and at 6 degrees of valgus to allow the tibia to hang vertically. The femur was secured as it was critical that no movement could occur here. Tibial movement was unconstrained other than in flexion and extension. The femur could be moved by hand from vertical to horizontal allowing a range of movement from 0 to 90 degrees flexion. The extensor mechanism was dissected and the quadriceps had a 100 N tension applied to it to replicate physiological tension with a pulley and weight. \(^{157}\)

The ALL was identified. Its proximal (femoral) and distal (tibial) attachments were marked with two small metal eyelets. The points chosen were taken to be those that formed the most central point of the insertion of the ligament.
**Figure 30** – Attachment of the femur to the testing rig

**Figure 31** – Cadaveric specimen to show identification of the ALL being marked with eyelets
A single monofilament suture (Ethilon 2/0; Ethicon Co, Somerville, New Jersey) was threaded through the tibial eyelet and tied to the femoral eyelet. The free distal end of the suture was connected to a linear variable transducer or LVDT (Solartron Metrology, Bognor Regis, United Kingdom). It was checked that uninterrupted movement of the suture could occur. This device is accurate at identifying very small changes in length using a measurable change in voltage and is used practically in industry for example to inspect the thickness of metal sheets. The LVDT had been confirmed to be accurate to +/- 0.01 mm. The suture was allowed to slide freely between the femoral and tibial eyelets. Lengthening of the suture (greater distance between the eyelets) would suggest tightening of the structure, whereas slackening of the structure would be suggested by a reduction in suture length (eyelets moving closer together). Changes in length were then measured using specialised Solartron ‘Orbit’ Excel software. Three measurements were taken and the mean was then calculated from these. The experiment was then repeated in the same manner, but with an internal rotation torque of 5Nm, and an external rotation torque of 5 Nm applied to the mobile tibia.
5.2.5 Statistical analysis

One way analysis of variance (ANOVA) with pairwise comparisons, with significance and 95% confidence intervals having Bonferroni adjustment for multiple comparisons were used to examine changes in the length of the ALL caused by changes in knee flexion. Length changes in the ALL were examined using two way repeated measure ANOVA, the two primary variables being flexion of the tibia and rotational torque, with the dependent variable being the length of the ALL. Paired t tests were used to view differences of length at specific angles of flexion, with Bonferroni correction for the three way comparison between internal, neutral and external rotation modes (p-value <0.05).
5.3 Results

As the knee was moved into extension with the tibia free to rotate, the distance between the attachments of the ALL was observed to be longer than in flexion (*Figure 33*). The ALL was isometric from 0° to 60° of flexion, although there was some inter-specimen variability. The mean change in length from 0° to 60° knee flexion was a reduction (that is: the ALL tended to slacken) of 1.7 mm (SD 1.1; 95% CI -2.3 to 5.7) (p = 0.980), followed by further shortening of 4.1 mm (SD 0.9; 95% CI 1.0 to 7.2) (p = 0.011) from 60° to 90° of flexion.

The length between the attachments was increased with tibial internal rotation, and external rotation reduced the length (*Figure 33*). When the knee was in extension (0° flexion) a 5 Nm torque in tibial internal rotation was not sufficient to cause significant changes in the length of the ALL (p > 0.26). At 30° of flexion, internal tibial rotation increased the mean length between the ALL attachments by a mean of 3.6 mm (SD 0.7; 1.5 to 5.7) (p = 0.003). At 90° of flexion, internal tibial rotation increased the mean length between the ALL attachments to 9.9 mm (SD 1.4; 5.7 to 14.2) (p < 0.001). The mean length between the attachments of the ALL was reduced by tibial external rotation, meaning that the external rotation caused the ALL to slacken. At 90° of flexion of the knee the length between the attachments of the ALL reduced by 5.9 mm (SD 0.7; 3.7 to 8.1) during tibial external rotation (p < 0.001).
5.4 Discussion

This study suggests that length changes observed in the structure termed the ALL in Chapter 4 would support a hypothetical role in resisting the pivot shift phenomenon. Nearer to extension the structure became tighter, with an increase in length observed during LVDT testing. It was also found that internal rotation of the tibia produced tensioning of the structure, whereas external rotation produced slackening of the structure. Although previously extra-articular reconstructions have been in widespread clinical use, and surgeons still use these techniques, there has been little biomechanical data to support use of this surgery and this study.
provides one of the few pieces of published work to support this type of reconstruction.

Krackow *et al* published the only previously published study that had attempted to look at extra-articular reconstructions in a similar way at the time of experimentation. They studied five adult cadaveric knees and measured the distances between attachment points on the tibia and femur. They found that the most favourable attachment points for resisting the pivot was for a femoral attachment point proximal and posterior to the lateral epicondyle. They also noted that moving the tibial attachment point anterior to Gerdy’s tubercle also produced a more favourable attachment point, although it had less of an effect than varying the femoral attachment. The authors suggested a number of reasons why they thought these attachment points were favourable, first that the check rein seemed to be in obvious position to act as a major restraint, and secondly that the attachment points demonstrated maximum separation between 15 and 45 degrees.

As discussed in chapter 4, the anatomy of the ALL is variable. Exact attachment points can be difficult to identify, due to inter-specimen differences in where the structure attaches, and difficulty in identifying exact attachments due to the fan like insertions in particular on the femur. In this study, the central point of the insertion of the fibres was identified and used as the point where the metal eyelet was placed. However there was a degree of subjectivity in identifying the exact position, which could affect results as minimal movements are being investigated. Despite this, the overall results are still useful in identifying whether an attachment point could
potentially have a role in resisting the pivot shift. Other anatomy works published on the ALL have suggested a constant tibial attachment point, but a variable attachment point on the femur.

This work gives an idea of how the ALL may behave and from this suggestions can be made about a potential role in resisting the pivot shift. However, it is not possible to extrapolate further on a role for the ligament from this, or to suggest that a reconstruction be performed, as other groups have, based on the anatomy work that they have published. This study cannot draw any conclusions about the likely ability of the structure to resist the pivot shift in vivo, as the strength of the ALL has not been investigated. To get further information on this aspect of the ALL, sectioning studies would have to take place to identify its contribution relative to other structures including the ACL. It may also be that rather than acting as isolated restraint, it may have a role with other structures in preventing tibial internal rotation.

A relatively small numbers of knees were used in this study. A larger number of knees could be used to assess more accurately how variability in position either around the femoral attachment (in particular around the lateral epicondyle) or on the tibia may change the behaviour of either the ALL or a reconstruction of it. The role of other structures in resisting the pivot shift, including the ITB, needs further consideration and length change experiments could be used as method to assess this. Attachment points of reconstructions and tenodeses which have previously been described (see chapter 2) could be tested in this manner to see if they potentially could provide
a role in resisting the pivot shift. Despite many of these procedures being used extensively in the past, and some still being in use today, work to support their use has not been done.

5.5 Interpretation of this work in relation to other more recently published biomechanical studies.

Since the completion and publication of this work, additional studies have been completed which address some of the questions posed in the further studies area of the conclusions. Kittl et al\textsuperscript{160} used the same LVDT technique to assess how altering the position of the femoral attachment affected the behaviour of the ALL or an extra-articular reconstruction. They chose different attachment points, including the ones described in this work, as well as investigating the attachment points of different reconstructions. The authors found that altering the femoral attachment point had a significant effect on length change patterns. The authors found that the attachment point as described in this study in chapter 4 was the most isometric of the various ligament attachment points. The attachment point of the ALL as described by Claes et al\textsuperscript{145} led to the structure becoming slack in low flexion angles, suggesting that a structure with an insertion point in this area would not be able to resist the pivot.
Chapter 6: Magnetic resonance imaging of the anterolateral knee structures.

Acknowledgments
The MRI imaging interpretation work was performed by Dr Monica Khanna and Dr Miny Walker of Imperial College. Because the imaging interpretation work reported in this chapter was not performed by the author, it should not be considered as a part of the thesis. It has, however, been included because it helps to complete the clinical picture of anterolateral knee injuries, and informs the final discussion of the thesis. The final literature review and discussion which conclude this chapter were the work of the author.

6.1 Aim

The aim of this part of the study was to investigate the anatomy of the anterolateral structures of the knee using magnetic resonance imaging (MRI), in uninjured knees and also to assess whether these structures are damaged at the same time as the ACL.

6.2 Introduction

This study was originally timetabled to run at the same time as the anatomy and biomechanical studies as detailed in Chapters 4 and 5,
however due to delays this was not the case. As a result of emerging literature, the attachments of the ITB were also studied as well as the ALL. To continue using the same nomenclature used elsewhere in this thesis, I have termed the structure being described by the radiologists as the ‘anterolateral ligament’ (ALL).

6.3 Materials and Methods

A retrospective cross sectional study of two different groups of patients was performed. Patients in the study were identified from a list of consecutive MRI scans performed on a single 3T MRI scanner in a hospital with a specialist knee unit, from December 2012 to November 2013. Group 1 consisted of 20 consecutive patients with a variety of knee symptoms, however none of this group showed evidence of an ACL tear or a pivot shift pattern of bone injury. Group 2 consisted of 20 consecutive patients identified as having a pivot shift bone marrow oedema pattern with ACL injury. Exclusions for the study were individuals who had undergone previous knee surgery, and anyone who had suffered a direct impact injury to the anterolateral or lateral aspect of the knee in the history.
<table>
<thead>
<tr>
<th></th>
<th>Group 1 (Non pivot shift injured knees)</th>
<th>Group 2 (pivot shift injured knees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
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<td>20</td>
</tr>
<tr>
<td>Right : Left</td>
<td>11 : 9</td>
<td>9 : 11</td>
</tr>
<tr>
<td>Age (Median, range) Years</td>
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<td>35.5 (18- 54)</td>
</tr>
<tr>
<td>Male : Female</td>
<td>11 : 9</td>
<td>10 : 10</td>
</tr>
</tbody>
</table>

**Table 3 - Demographics of groups**

All of the scans reviewed were performed on a Siemens 3T Skyra scanner using standard sequences used in clinical practice (*Table 4*). Two consultant radiologists reviewed the MRI scans prospectively with a specialist interest in musculoskeletal imaging (each reviewing greater than 800 MRI scans per year). Interpretation was reached by consensus between the two radiologists. A standard data capture sheet was used to retrieve data and specific structures including those identified in Chapter 4 were viewed. The radiologists have supplied the images provided here as examples of the anatomical structures seen during the investigation.
<table>
<thead>
<tr>
<th>Sequence</th>
<th>PDFS TRA</th>
<th>PD TRA</th>
<th>PDFS COR</th>
<th>PD COR</th>
<th>PDFS SAG</th>
<th>PD SAG</th>
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<td>29</td>
</tr>
<tr>
<td>SLICES</td>
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<td>30/3mm</td>
<td>25/3mm</td>
<td>25/3mm</td>
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</tr>
<tr>
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<td>0.6mm</td>
<td>0.3mm</td>
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<td>2</td>
<td>1</td>
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<td>1</td>
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<td>461 x 512</td>
<td>518 x 576</td>
<td>461 x 512</td>
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</tr>
<tr>
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<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>VOXEL SIZE</td>
<td>0.3 x 0.3 x 3.0</td>
<td>0.3 x 0.3 x 3.0</td>
<td>0.3 x 0.3 x 3.0</td>
<td>0.3 x 0.3 x 3.0</td>
<td>0.3 x 0.3 x 3.0</td>
<td>0.3 x 0.3 x 3.0</td>
</tr>
</tbody>
</table>

Table 4 – MRI sequences and parameters used during the study. MRI scanner used was a Siemens 3T Skyra scanner. (Abbreviations TR – time to recognition, TE – time to echo, FOV- Field of View, VOXEL – Volume Element, PD – Proton Density, FS- Fat Saturated, TRA - transverse, COR- coronal, SAG – sagittal)

6.3.1 Protocol for the assessment of anatomical structures

The proximal and distal attachments of the structure termed the ALL in chapter 4 were reviewed, and the relationship of this to the surrounding structures was noted. The tibial attachments and distal femoral attachments of the iliotibial band were also reviewed, specifically the ‘proximal’ and ‘condylar’ distal femoral attachments. They were assessed for visibility, and where present for anatomical insertion.
6.4 Results

6.4.1 Anterolateral ligament

6.4.1.1 Group 1 – “Normal” non pivot shift injured knees.

The ACL appeared normal in all of these MRIs. In 18 of the 20 knees the ALL could be identified. In all of these cases there was a distal attachment that was posterior to the ITB. The distal attachment was normal in 12 knees, but 5 showed some altered signal around the tibial insertion. In one knee the ALL was thickened and underlying bone marrow oedema was visible.

The proximal femoral attachment was less distinct. In the knees where the ALL could be seen, in 3 cases the proximal attachment could not be clearly seen, and in 15 it could be seen to be attaching around the LCL.
**Figure 34** – Axial cut to show the ALL (marked) as it passes over the lateral side of the tibial plateau.

**Figure 35** - A coronal cut shows the ALL (marked with yellow arrow) at its tibial insertion. A sagittal image would show the course better but is difficult to obtain in the correct MRI slice.
6.4.1.2 Group 2 – Pivot Shift Injured Knees

18 knees had a complete tear of the ACL, with the remaining 2 showing a high grade near complete tear. The ALL could be visualized in all 20 knees. No Segond fracture was identified in any of the cases. However 5 MRIs showed bone oedema at the expected Segond site, which corresponded to the distal attachment of the ALL, which was always posterior to the ITB and was visible in all of the knees. There was abnormal high signal in the distal ALL in 17 of the knees, with 3 appearing normal. The proximal attachment was again harder to identify, and it was not possible to identify it in 5 knees. In 12 cases, the ALL appeared to blend with the LCL. However, in 3 cases it appeared that it blended with the fascia posterior to the ITB.

![Figure 36](image) – *in this coronal image the ‘pivot shift’ pattern of bone marrow oedema can be clearly seen. The ALL is marked and bone marrow oedema can be seen at its insertion that would be the site of the Segond fracture*
**Figure 37** - In this axial cut at the distal femur, the ALL is marked between the ITB (shown as ITT) and LCL (FCL).

**Figure 38** - Axial cut at the level of the distal femur to illustrate the ALL.
6.4.2 Distal insertions of the iliotibial band

6.4.2.1 Group 1 – Non pivot shift injury knee group

Tibial insertion of the ITB

The distal ITB showed subtle abnormal increased intrinsic high signal in 3 of the “normal” non pivot shift knees.

Distal femoral insertions of the ITB

The MRI showed two distal femoral attachments of the ITB that could be seen repeatedly on the images. The first of these was a supracondylar band. It could be seen inserting at a point superior to the lateral geniculate vessels. It then followed an oblique course, running inferiorly and posteriorly attaching to the linea aspera after running posterior to the vastus lateralis. Due to the routine sequences performed for MRIs of the knee, the proximal attachment of this structure could sometimes not be viewed on the images.
In this group, this proximal femoral attachment of the ITB was visible in 17 out of 20 knees. There was evidence of injury in 1 of the 17 bands, and in this case an injury to the vastus lateralis was also visible.

*Figure 39 – in this coronal cut the supracondylar band can be seen in relation to the ITB*
Figure 40 – a sagittal cut demonstrating the supracondylar band

Figure 41 – the close relationship of the supracondylar band to the superior geniculate vessels is illustrated here
A further band could also be identified routinely. This was a curved structure that attached in the lateral recess proximal to the lateral femoral condyle. This was termed the ‘condylar’ band. This structure could be more easily identified when an effusion was present. The condylar band attachment could be seen in 13 of the scans. 3 of these showed evidence of injury. 1 of these was associated with a vastus lateralis injury.

In 3 cases, neither of the bands could be seen.
Figure 42 – the epicondylar band can be seen attaching the ITB to the distal femur

Figure 43 – the epicondylar band is better illustrated when there is an effusion present. In this figure, the LM appears to be strongly attached to the ITB.
6.4.2.2 Group 2 – ACL pivot shift injured group

Tibial insertion of the ITB

No abnormality of the distal ITB insertion was seen in the ACL pivot shift injury group.

Distal femoral insertions of the ITB

In this group the proximal femoral attachment (Supracondylar) of the ITB could be seen in 17 of the knees, with it being damaged in 14 of them (82%). In all 14 of these there was localised oedema surrounding the band, but in in 4 cases there was also diffuse oedema in the lateral fat pad. In 3 cases the proximal band was normal. In 3 cases the proximal band was not clearly visible but there was lateral fat pad oedema in 2 of these cases.
**Figure 44** – Sagittal image showing supracondylar band

**Figure 45** – Axial MRI to show supracondylar band to ITB
The condylar band was visible in 17 cases, but could not be defined in 3 cases. In 5 of the 17 visible condylar bands, there was intrinsic altered signal and thickening consistent with injury. Of the 5 in the pivot shift group 4 had associated injury in the region of the proximal band.

6.5 Discussion

The ALL could be consistently seen in this study in both non injured knees and knees with an ACL injury. The inability to identify it in all knee MRIs is a similar finding to that of the anatomical study. The radiologists reporting the MRIs were made aware of the anatomical dissection work presented in Chapter 4 of this thesis. This may have
presented some bias in the study as they may have looked specifically for the structure described rather than a more open interpretation of the anatomy. The findings of this MRI study in terms of interpretation of ALL anatomy support the descriptions of the structure that we have made in the anatomical dissection work. Whilst the tibial insertion was fairly constant and proved easy to identify, the femoral attachment of the ALL was more difficult to identify, and was variable when the radiologists reviewed it. The radiologists did note that in some cases the ALL inserted at the lateral epicondyle, however with a less distinct femoral attachment seen both at anatomical dissection and MRI the attachment may still have continued to blend posterior and proximal as we saw in Chapter 4. A concern of this study is that some of the control group did show some altered signal at the ALL tibial insertion reflecting that a rotational injury may have occurred, although in these cases the ACL was intact.

MRI has been used to study the distal attachments of the ITB for the first time in this study. This area was not originally planned to be reviewed when this part of the study commenced. However, new studies suggested that the ITB was also likely to have role in resisting the pivot shift and hence was also studied here. The work suggesting a role for the ITB in preventing the pivot shift is considered in more detail in Chapter 7. One of the problems with looking at the ITB is the complex nature of its insertion, and interestingly what many people consider to be the major attachment at Gerdy's tubercle did not show any change in signal in the pivot shift injured group. For the first time this study has shown that attachments of ITB at the distal femur (supracondylar and
epicondylar bands) are consistent attachment sites that can be identified by MRI. The change in signal to these structures suggests that they may have a role in preventing the pivot shift but the ITB may be acting more proximally than at the Gerdy's tubercle insertion. Damage to these structures may also be used as a potential marker of injury for a radiologist reviewing MRIs looking for ACL injury.

The number of knees reviewed in this study was relatively low (40) and this is a potential weakness in the study. However, it was a time consuming study for the radiologists involved as they needed to be brought up to speed with the current scientific literature in the area and reviewing the MRI scans in detail was a time consuming process. 40 knees is still enough to spot potential trends; however, more knees need to be studied in order to confirm the initial findings reported here.

Numerous studies have been published detailing the MRI anatomy of the ALL since this study was started, and these have been summarised in Table 5. A number of these are studies initiated by groups who have performed anatomical dissections studies, and as in this study they tend to be reviews by 2 radiologists interpreting the MRIs independently, however they may still have been influenced by the anatomical description of their respective groups. A total of 15 MRI studies are summarised in table 5, and this number probably reflects the relative ease in reviewing these scans versus the cost of cadaveric specimens. However this means that some of the studies may have been carried out by non expert reviewers who may
not have fully understood the complexities of the anatomy in the region.

As for the anatomical dissections performed and reviewed in Chapters 3 and 4, it can be seen from Table 5 that there is again a very wide variation in the description of the ALL in the published work. The rate of identification ranged from 38.6% to 100% in these studies, and in particular it was the femoral attachment that led to increased variability in reporting. This is not a surprise from what we saw in our anatomical dissections. It should also be remembered that the authors in these studies may not all have been attempting to identify the same MRI structure as the ALL, accounting for some of the variability seen. None of the authors had looked at the ITB attachments as in this work, and it may be the case that some authors identified the ITB attachments such as the epicondylar band as part of the ALL.

Claes et al\textsuperscript{162} claimed to publish the first MRI study on the ALL. From the anatomy study\textsuperscript{145} they described the attachment point of the ALL as being anterior and distal to the lateral epicondyle and this would have affected the MRI interpretation they made. They identified the ALL in 76% of knees in their anatomical study, this was much lower than the rate they described in their anatomy paper, and nearer the percentage that was found during the dissection in this study. In the knees where they identified the ALL, it was abnormal in 78.7% of knees. They noted a 2% rate of Segond fracture in the study. They found that in the knees with ALL injuries, proximal injuries occurred in 20.4% of knees, and distal in 77.8%. This compares to our study
with 17 of the 20 knees in the pivot shift group having distal ALL abnormalities, and none having proximal ALL abnormalities. It could be speculated that some of the proximal ALL injuries identified by Claes et al may in fact have been injuries to the femoral insertions of the ITB that were identified in our study. Other authors\textsuperscript{163} have shown a higher rate of injury (72% of ALL injuries as proximal) to what they describe as proximal ALL, however again they may have been reporting injuries to ITB distal femoral insertions.

Few other MRI studies (Table 5) have used a control group of normal knees, instead focusing on knees with a pivot shift pattern of bone injury. Devitt et al\textsuperscript{164} reviewed 63 ACL injured knees and 64 controls, and found that 15/64 (23%) of the control group showed injuries to the ALL. This is a similar finding to some of the control group in this study, suggesting either selection may not have been appropriate or ALRI injuries may be more common than thought.

More recently Shaikh et al\textsuperscript{165} have published a series where they question the presence of the ALL. In the description they provide they look at fibres and categorise as either arising from solely the ITB or the capsule. This is a reflection of a more far reaching question on anatomical description rather than on the MRI interpretation itself, and this is considered and addressed further in Chapter 7.
<table>
<thead>
<tr>
<th>Type of study</th>
<th>Number of knees studied</th>
<th>% of knees where ALL identified</th>
<th>Femoral attachment</th>
<th>Tibial attachment</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilfeld 2017&lt;sup&gt;166&lt;/sup&gt;</td>
<td>Prospective study of 30 patients with suspected ACL tear. Injured and contralateral knees evaluated with MRI. Reviewed by 2 radiologists independently.</td>
<td>30</td>
<td>96% (29/30)</td>
<td>Visible in 40%</td>
<td>Torn in 4 cases (13%), all at tibia</td>
</tr>
<tr>
<td>Shaikh 2017&lt;sup&gt;165&lt;/sup&gt;</td>
<td>MRI to review attachments to Segond fracture</td>
<td>36</td>
<td>ITB attached to 34 of 36 and capsule to 34 of 36</td>
<td>Not investigated</td>
<td>Segond area identified</td>
</tr>
<tr>
<td>Devitt 2017&lt;sup&gt;164&lt;/sup&gt;</td>
<td>Retrospective review of 63 with ACL vs. 64 without ACL knee MRI by one radiologist</td>
<td>63 in ACL injured group, 64 in control group</td>
<td>41/64 (64%) in control group vs. 45/63 (72%) in ACL injured group. 15/64 (23%) control and 13/63 (32%) ACL injured in its entirety</td>
<td>Identified in 17 of 63 (27%) in ACL injured group</td>
<td>Identified in 40 of 63 (63%) in ACL injured group</td>
</tr>
<tr>
<td>Cavaignac 2017&lt;sup&gt;167&lt;/sup&gt;</td>
<td>2 experienced radiologists using USS and MRI in ACL deficient patients</td>
<td>30</td>
<td>96% (along entire length)</td>
<td>MRI Segond fracture visible in 13%. All injuries at tibial attachment</td>
<td>Injured in 53% of cases</td>
</tr>
<tr>
<td>Helito 2017&lt;sup&gt;148&lt;/sup&gt;</td>
<td>Assessment of acute knee injuries (less than 3 weeks post ACL injury)</td>
<td>101</td>
<td>87.1% (88 knees)</td>
<td>24 (72%) showed proximal lesions</td>
<td>7 (21%) showed distal lesions</td>
</tr>
<tr>
<td>Author</td>
<td>Study Type</td>
<td>Methods</td>
<td>Number</td>
<td>Result Notes</td>
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<tr>
<td>Song 2016</td>
<td>Retrospective series of</td>
<td>injured in 33 (32.6)</td>
<td>193</td>
<td>38.9% (75) showed abnormalities of ALL Not recorded Only recorded injury, not whether present or not.</td>
<td></td>
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<tr>
<td></td>
<td>patients with pivot shift</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>bone bruising</td>
<td></td>
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<td></td>
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<tr>
<td>Hartigan DE 2016</td>
<td>Retrospective, aimed to</td>
<td>Retrospective, aimed to identify ALL in known ACL injured knees, 2 independent MSK radiologists. Used Helito technique to identify ALL</td>
<td>72</td>
<td>100% Not stated although used Helito technique to identify ALL Not stated although used Helito technique to identify ALL Difference in opinion between 2 radiologists as to whether injured - 26% vs. 62%. Unable to reliably determine whether structure intact or torn at any site</td>
<td></td>
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<td></td>
<td>identify ALL in known ACL</td>
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<td>injured knees, 2 independent</td>
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<td>MSK radiologists. Used</td>
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<td></td>
<td>Helito technique to</td>
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<td></td>
<td>identify ALL</td>
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<tr>
<td>Macchi 2015</td>
<td>Retrospective MRI study of</td>
<td>Retrospective MRI study of patients with a ‘normal’ MRI</td>
<td>50</td>
<td>93% (47) Lateral epicondyle Lateral aspect proximal tibia Almost constantly depicted in routine 1.5T MRI</td>
<td></td>
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<td>patients with a ‘normal’</td>
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<td></td>
<td>MRI</td>
<td></td>
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<tr>
<td>Taneja AK 2015</td>
<td>Independent review of MRIs</td>
<td>Independent review of MRIs by 2 MSK radiologists</td>
<td>70</td>
<td>51% - Completely visible in 11%, partially in 40% Not always identified In all visible cases the tibial attachment was seen, mean distance 5.7mm to the tibial plateau High inter-observer reliability (k=0.7), trend to be more visible in men</td>
<td></td>
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<td></td>
<td>by 2 MSK radiologists</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Porrino J 2015</td>
<td>Retrospective MRI review</td>
<td>Retrospective MRI review</td>
<td>53</td>
<td>19/20 cases exhibited attachment of the structure to the Segond Ill defined sheet like structure, Individual component s are inseparable in routine MRI</td>
<td></td>
</tr>
<tr>
<td></td>
<td>‘Normal’ knees, 20 with</td>
<td>53 ‘Normal’ knees, 20 with Segond Inseparable from the fibular collateral ligament proximally</td>
<td></td>
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<td></td>
<td>Segond</td>
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<tr>
<td>De Maessener 2015</td>
<td>Reviewed MRI in 13 Segond</td>
<td>Reviewed MRI in 13 Segond fractures</td>
<td>13</td>
<td>10 of 13 ITB (11 of 13), ALL (10 of 13) inserted on Segond ITB and ALL may be involved in Segond fracture</td>
<td></td>
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<td></td>
<td>fractures</td>
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<tr>
<td>Kosy JD 2015</td>
<td>Retrospective study one MSK</td>
<td>Retrospective study one MSK</td>
<td>100</td>
<td>94% partial Discreet in only 57% of 7.64 +/- 1.36mm</td>
<td></td>
</tr>
<tr>
<td>Study</td>
<td>Methodology</td>
<td>Patients</td>
<td>Sensitivity</td>
<td>Description</td>
<td>Specificity</td>
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<td>------------</td>
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<tr>
<td>Claes 2014&lt;sup&gt;162&lt;/sup&gt;</td>
<td>Scans of unilateral ACL injured patients</td>
<td>271</td>
<td>76%</td>
<td>ALL identified if fibres seen from lateral epicondyle of distal femur, and running slightly oblique to anterolateral border of proximal tibia</td>
<td>Anterolateral border of proximal tibia</td>
</tr>
<tr>
<td>Helito CP 2014&lt;sup&gt;175&lt;/sup&gt;</td>
<td>Review separately by 2 radiologists</td>
<td>39</td>
<td>97.8% (part of ALL visible); entirety in 71.7%</td>
<td>Anterior and distal to lateral femoral condyle</td>
<td>7.0 +/- 1.0mm below tibial plateau</td>
</tr>
<tr>
<td>Wodicka R 2014&lt;sup&gt;176&lt;/sup&gt;</td>
<td>Retrospective study of ACL injured knees from 2 year period</td>
<td>50</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 5* - Recent in vivo MRI studies investigating the ALL
Chapter 7 Discussion

7.1 Introduction

Since the commencement of this thesis, the anterolateral aspect of the knee has been the focus of unparalleled interest. At the start of this work in 2011, minimal work had been published in this area in comparison to the multitude of publications that now exist on the topic. Despite this, the anterolateral knee has long been an area of interest, with the most notable early publication being the work of Segond. Although I identified previously published work on extra-articular reconstructions from the 1970s and 1980s when I conducted a literature review (Chapter 2), there was limited anatomic or biomechanical work to base these reconstructions on, and as a result they were non-anatomic with little evidence for their use. A lack of good quality photography in older publications to help aid anatomical description did not help to identify structures. For a scientist looking at the area now, there is a vast amount of published work to consider. Despite this, mechanism of injury to the structures of the anterolateral aspect of the knee, what these structures actually are, and how they should be treated, remains a highly controversial area in modern knee surgery. In an attempt to reconcile differences in opinion, several consensus groups have now met to try and provide unified guidance in this area.
7.2 The anatomy of the anterolateral knee and the ALL.

7.2.1 Overview

At the start of this study, we questioned whether there was a discrete anterolateral ligament of the knee. Despite the multitude of anatomical descriptions, the existence of the ALL as a discrete structure is still questioned by authors.\textsuperscript{165} Where authors acknowledge its existence, there is no clear consensus as to the anatomy of the structure. An understanding of the anatomy is the key to all further interpretations of function of the structure. We identified and described a structure that appeared to have the correct orientation and a biomechanical basis to act as an anterolateral stabilizer to the pivot shift.

The anatomy of the anterolateral knee is complex, as the anatomy of the posterolateral corner area that has been more thoroughly studied and documented is also acknowledged as being.\textsuperscript{142} It is difficult to describe discrete structures in the anterolateral area, as structures blend and merge. Despite the confidence with which some authors have described the anterolateral knee anatomy, any description of the area will therefore to a degree be subjective. In this thesis the femoral attachment of the ALL was harder to define. The manner of dissection is also critical in revealing structures and how they are interpreted. Different dissection techniques were used in Chapter 4 to try to identify the one that would cause the least damage to the structures being identified, and for this reason we used a superficial to deep approach when performing dissections. One of the criticisms
that can be leveled at the current literature on the anterolateral knee anatomy is that teams in isolation have performed most of the dissections that have taken place. We did attempt to reconcile differences in anatomical dissection by meeting with Vincent et als team\textsuperscript{144} who at the time we performed the dissection had published the only other work on the anatomy of this area.

A further point that may have caused variability in the published descriptions is the type of specimens used in the studies. We used fresh frozen rather than formaldehyde preserved and these are more likely to have allowed an accurate picture of the ALL anatomy.

### 7.2.2 The femoral attachment

The area of greatest debate regarding the authors who have described the ALL relates to the femoral insertion. Broadly speaking all published authors have suggested the attachment is somewhere near the lateral epicondyle. Perhaps one statement that can be made without controversy is that authors have had difficulty identifying the exact site of the femoral attachment, and as we have said in our dissection work, its insertion is much less distinct than the tibial insertion. We found in this thesis that the ALL inserted at a point proximal and posterior to the lateral epicondyle. Authors describing the femoral insertion of the ALL may be divided into four groups, those who suggest that it is anterior and distal to the femoral epicondyle, those who suggest that it inserts mainly on the lateral epicondyle itself, those who have described an insertion posterior and proximal, and those who have found a mixture of all of the attachments.\textsuperscript{144,145,148,149,150,151,152,153} A recent consensus group
meeting of some of those involved in research on the ALL has suggested that as in this thesis the attachment of the ALL is proximal and posterior to the lateral epicondyle.178

7.2.3 The tibial insertion

Reviewing the anatomical dissection part of the thesis in relation to recently published work, most authors agree on the tibial insertion site of the ALL, at a point midway between the Gerdy’s tubercle and the fibula head. This area corresponds to the site of the Segond fracture. In this study the ALL inserted in this area of the tibia consistently.

7.2.4 Attachments to other structures

Other authors have noted attachments to the meniscus. In this study, we were able to separate the overlying ALL from the capsule and meniscus to show that it was an extracapsular structure. However, we did not formally describe any attachments to the meniscus. Other authors have described these attachments in more detail, and we could possibly have altered the dissection technique to look at these attachments in a coronal plane.

7.2.5 The anatomy of the iliotibial band

Perhaps the single biggest factor that has led to confusion when interpreting the anterolateral knee anatomy has been the ITB. It is a complex structure,141,143 and although the superficial portion of the
ITB with its insertion onto Gerdy’s tubercle seems relatively clear, the deeper structures and their interaction with the capsule are critical in anatomical dissection. Vieria et al\textsuperscript{143} have previously described the capsule osseous layer and also a deep layer of the ITB, and it may be this deep layer and its capsule interactions are what are being confused in some descriptions in modern literature. Older descriptions of the literature are difficult to interpret due to the lack of high quality diagrams in the text. These anatomical differences are important as they play a key role in determining functional aspects of the structure. Biomechanical evidence for the roles of these structures will be considered in more detail later in this chapter, however caution for interpreting this work must still be given when the anatomical descriptions are not clear.

7.2.6 Embryology of the ALL

At the start of this thesis, consideration was given to the embryology of the knee. Knowledge of how the ALL may develop may inform understanding of adult anatomy. Some authors been unable to identify the ALL when studying cadaveric specimens, and have suggested that development of the ALL in adulthood may be related to repeated stresses put on the knee.\textsuperscript{180} However, other authors have reported the ALL to be present. When 40 fetuses aged 28 to 36 weeks were dissected the ALL could be identified in 100\% of cases.\textsuperscript{181} The authors were able to identify an extracapsular structure running in an oblique course, inserting midway between the Gerdy’s tubercle and the fibular head. They found the femoral attachment to be variable, identifying it to be proximal and posterior to the LCL in 55\%
of cases, combined with the LCL in 25% of cases, and anterior and distal to it in 20%. The authors cited the anatomy publication related to the work in this thesis to confirm that they supported our findings of an extracapsular ligament rather than as a capsular thickening as some authors have suggested.\textsuperscript{149,150,151}

7.2.7 Comparative anatomy

There has now also been a comparative anatomy study to look at the ALL. The authors looked at the presence of the ALL in 58 fresh frozen knee specimens from 24 different species.\textsuperscript{182} The authors were unable to identify the ALL in any of the specimens dissected. The conclusion from the authors was that precaution is needed before assessing the need to reconstruct the ALL in humans. However, the outcome of this study would be dependent on the method of dissection. The same group of authors was also the only ones unable to identify the ALL in anatomical dissection work and of the published MRI studies.\textsuperscript{183}

7.2.8 Variability of the presence of the ALL in dissected specimens and published work

We were unable to identify the ALL in all of the specimens that we dissected in Chapter 4. Some authors have found the ALL to be present in 100% of specimens, but most of the publications on ALL anatomy or MRI appearance have reported a lower and variable rate. (Table Chapter 6) We found in dissections that in some specimens
the ALL was a clear structure, but in others much less distinct. One potential explanation of this has been that the ALL develops as a stress response during life, however embryology work\textsuperscript{181} where it has been consistently described seem to suggest that this is not the case. It may be that the ALL may only be present in those knees where the anatomy requires it to be so – for example the fibula is known to have a variable insertion around the tibia, and it may be that the interaction between the ITB and structures inserting on the fibula (including LCL and biceps femoris) necessitate whether the ALL has to play a role in resisting the pivot shift. Small operator dependent variations in dissection technique may also have changed how the ALL was viewed. For example in the technique described in this thesis the interval chosen between the ITB and biceps femoris may have been critical in determining how the deeper structures were viewed. Other authors have suggested that meticulous dissection is needed as deeper structures may be adherent to the more superficial ITB unless separated carefully.\textsuperscript{143}

7.3 Are structures of the anterolateral knee including the ALL injured at the time of the pivot shift?

A further question posed at the start of this thesis was to whether these anterolateral structures were injured at the time of the pivot shift.

The presence of the Segond fracture has always led to a strong suspicion that anterolateral knee structures may be injured at the time of the pivot shift. Furthermore, a centrally placed lever arm is
not best placed to act as resistance to more peripherally placed rotation. Evidence exists that patients will have ongoing instability even after an ACL reconstruction using current techniques, and it has been recognized that more sophisticated techniques may be needed to restore more normal biomechanics.85

Whilst some evidence of injuries occurring to anterolateral structures is circumstantial, the MRI portion of this thesis has shown an injury pattern of both the ALL and the distal femoral insertion of the ITB, supporting a theory for in vivo damage to these structures at the time of the pivot shift.

7.4 Investigating the biomechanical role of the ALL

I attempted to carry out sectioning experiments using both a knee rig and robot during my full time period of registration but was unable to make these fully work and produce meaningful results due to time constraints. However, work of this type has now been published, as well as other studies adding knowledge to the function of the ALL.

Following the length change experiment detailed in Chapter 5, Kittl et al produced further length change experiments to investigate length change patterns at different insertion points on the femur and tibia.160 The experimental set up was as described in Chapter 5 of this thesis using 8 fresh frozen cadaveric knees. This was an important paper as it showed that the anterior femoral insertion, which was advocated by some ALL authors, was not likely to be able to act to
resist the pivot shift. The ALL attachment points as described in this thesis were the nearest to isometric of those tested. Reconstructions with attachment points proximal to the LCL showed significantly lower total strain range than those located anterior. The dramatic effect on length change by varying position of the femoral attachment around the lateral epicondyle is illustrated in Figure 47.

**Figure 47**- Point A was tibial insertion of ALL as described in this thesis, point G was Gerdy’s tubercle, E1 midthird lateral capsular ligament as described by Hughston et al/ Claes et al/ Anterior part of the Losee reconstruction, E3 as defined in this thesis, E6 posterior fibres of ITB

The anterior fibres of the ITB displayed a significantly different length change pattern to the posterior fibres. The authors found that the most isometric of all potential combinations tested corresponded to that previously described for the Macintosh procedure.

Sectioning studies have also been performed to assess the role of the anterolateral knee structures. Sixteen knees (8 ACL intact and 8
ACL deficient) were investigated using an industrial robot with a 6 axis universal force moment sensor. A simulated pivot shift test was performed at different flexion angles to assess response to anterior–posterior, internal-external and internal rotational laxity. The ITB and ALL were sectioned sequentially. It was found that the ALL and anterolateral capsule provided only a small resistance at 30° when compared to the ITB. In the ACL deficient group, the ITB provided 72% of the restraint at 45°. This experiment suggests the role of the ITB is more significant than the ALL and capsule in resisting the pivot shift, and hence cautions against trying to design an ‘anatomical’ ALL reconstruction.

**Figure 48** – Reproduced from Kittl et al 2016. Relative contribution of structures in restraining a 5Nm internal rotation torque at 0’, 30’ 60’ and 90’ of flexion (Superficial ITB - sITT, Deep/capsuloosseous ITB - dclTT, ALL, Capsule – Cap)

Spencer et al performed a sectioning study to investigate the effect of ALL transection on rotational knee kinematics and to determine the effects of anatomical ALL reconstruction in comparison with
lateral extra-articular reconstruction. They investigated 6 knee states in 12 cadaveric knees: 1) ACL intact, 2) AM bundle of ACL sectioned, 3) Complete ACL sectioned, 4) ALL sectioned, 5) Anatomical ALL reconstruction, 6) lateral extra-articular reconstruction, testing each for simulated anterior draw, Lachman tests and pivot shift. They found that sectioning the ALL made a significant difference to internal rotation during the pivot shift test. However performing an anatomical ALL reconstruction did not make a significant reduction to either internal rotation or anterior translation during the simulated pivot shift. The lateral extra-articular reconstruction however did have an effect on both anterior and rotational laxity. This is an important finding as it is one of the papers that has questioned whether ALL reconstruction alone is enough to resist the pivot shift, and led debate towards further reconsideration of the extra-articular reconstructions as described in Chapter 2.

The behaviour of the ALL in cadaveric knees has also been assessed using continuous passive movement (CPM). Drews et al. used 8 cadaveric knees to test ACL intact, ACL resected and ACL and ALL resected states. The ALL dissection and landmarks were as described in this thesis. AP translation and a static pivot shift under 134 N anterior shear load were recorded. During CPM with no load, there was no significant difference between ACL resected and ACL and ALL resected conditions. No strain on the ALL was shown. The authors concluded that the ALL had no function during passive movement, and cautioned against reconstruction of the ALL.
Tensile tests have also failed to support a role for the ALL alone to resist the pivot shift. Zens et al\textsuperscript{186} dissected the ALL from four fresh frozen cadaveric specimens, using the dissection technique described by Claes et al.\textsuperscript{145} Uniaxial tensile failure tests were then performed. They found an ultimate load to failure of 49.90 N and an ultimate tension of 32.78 MPa. The authors concluded that the ALL can not be considered a primary stabilizer of the knee joint as the tensile strength is lower than of other primary stabilisers. However, in a similar experiment Kennedy et al\textsuperscript{187} found that the mean maximal load was 175 N (95% CI, 139-211N) and stiffness was 20N/mm (95% CI, 16-25 N/mm). Differences in biomechanical behaviour may be explained by differences in what the authors considered to be the ALL due to unresolved differences in anatomy.

As for the anatomy of the ALL, scientific opinion has not been unanimous in its rejection of the ALL's ability to resist the pivot shift. Bonanzinga et al used a knee rig with a navigation system to investigate 10 fresh frozen cadaveric knees with intact, ACL resected and ACL and ALL resected conditions.\textsuperscript{188} Anterior displacement at 30° and 90° of flexion with a manual maximum load, internal rotation at 30° and 90° with a 5Nm torque and internal rotation and acceleration during a manual pivot shift test. They found that resecting the ALL produced a significant increase in terms of internal rotation at 30° (but not at 60° or 90°. Resection also produced a significant increase in acceleration during the pivot shift (p <0.01). They concluded that the ALL played a significant role in resisting static internal rotation and acceleration during the pivot shift. Reconciling this study to the rest of the ALL literature is difficult as
they appeared to investigate the same structure as other authors, one explanation is that they may have damaged the ITB during sectioning of the ALL and this may be the effect that was noted during the study.

7.5 Published clinical results of ALL reconstruction

Despite disputes over the exact anatomy of the ALL, and the extent of its biomechanical effect as detailed previously, some authors have already published results of attempts at clinical reconstruction. Surgery relating to older reconstruction techniques using extra-articular reconstruction has already been reviewed in Chapter 2 of this thesis.

Sonnery–Cottet et al. have published a minimally invasive technique for a combined ACL and ALL reconstruction using hamstring (semitendinosus and gracilis) tendons. A combined femoral tunnel for the ALL graft is used, an isometric point around the lateral epicondyle having been identified using a suture to the tibial ALL attachment.
Sonnery-Cottet et al.\textsuperscript{190} have published a retrospective review of their results using this reconstruction. Of 396 ACL reconstructions over a one year period, 23% had an ACL plus ALL reconstruction, and 83 of these were available to follow up. The authors listed indication for follow up as being an associated Segond fracture, chronic ACL lesion, grade 3 pivot, high level of sporting participation, participation in pivoting sports and a lateral femoral notch signs on radiographs. As it was a retrospective review there was no randomization between whether the patient had an ALL reconstruction in addition to ACL reconstruction, and the reasons for performing an ALL reconstruction can be seen to be subjective. Outcome was judged with Knee Injury and Osteoarthritis Outcome Score (KOOS) and instrumented knee testing. Follow up was 32.4
months (+/- 3.9 months). The authors report similar results to standard ACL reconstruction techniques, however they were unable to confirm that ALL reconstruction conferred any benefit. Of note, 19 of the group and a grade 3 pivot at final follow up and 23 had a grade 2 pivot at follow up, suggesting that in a significant number of their patients the ALL reconstruction was not performing its intended role.

Another study has been published reporting clinical outcomes following combined ALL and ACL reconstruction. They randomized 60 patients to receive either standard single bundle ACL reconstruction using an anteromedial portal technique, double bundle ACL reconstruction or combined ACL and ALL reconstruction. The 60 patients only had confirmed ACL rupture as an indication, and there is no data provided on the degree of pivot shift within the groups. A major weakness of this study is that the authors chose a femoral attachment point which was anterior to the lateral epicondyle, a position which most experts would now agree is non-anatomical and biomechanically unable to resist the pivot shift. The authors conclude that outcome measures (knee stability assessment plus return to sport measures) were better for the ACL and ALL and double bundle ACL group when compared to the single ACL group. However, there was no blinding or randomization of results and the anterior tunnel position of the ALL means that no meaningful information can be gained from this study.
Figure 50 - Zhang et al’s ‘anatomical’ ALL reconstruction: a: skin landmarks, b: harvest of ITB, c: ALL graft, d: femoral and tibial tunnels, e: ALL being implanted, f: 3D CT analysis of tunnel position, showing the anterior femoral position.

Although other authors have published their technique of ALL reconstruction,\textsuperscript{192,193} there are no further clinical outcome studies. Even if published in the near future, they are unlikely to provide any meaningful data due to rapid changes in knowledge about the function of the anterolateral knee.

Although the clinical indication for when a lateral extra-articular reconstruction should be used in addition to a standard intra-articular reconstruction is unclear, an algorithm for its use based on the work performed in this study is suggested in figure 51.
7.6 The role of the iliotibial band in resisting the pivot shift

There has been increasing focus on the ITB having an important role in resisting the pivot shift. The biomechanical evidence reviewed already suggests that the ALL appears to have a less significant role.
than the ITB in resisting the pivot shift. Further evidence for a role for the ITB has been described in this thesis via injury to the structure on MRI investigation. Whilst there were minimal changes at the principal insertion of the ITB on Gerdy’s tubercle, there were changes visible on the distal femoral attachments of the structure. This must be borne in mind when sectioning studies to investigate the role of the ITB are performed. Other authors have not specifically looked at these distal femoral attachments of the ITB. The proximal attachments of the ITB around the hip may also play a role in resisting the pivot shift. The proximal portion of the ITB is also a complex structure, with a thickening of fascia originating from the tensor fascia lata and gluteus maximus and a deep portion attaching to the hip joint. The gluteus maximus and tensor fascia latae can produce tightening of the of the iliotibial tract, and may therefore be involved in an effect on resisting anterolateral instability at the knee. This has not been investigated in the current literature and warrants further study.

7.7 Further work

Other authors have answered some of the questions posed in this thesis, however much work remains to be done. The ITB appears to be a key area, and relatively neglected due to the focus on the ALL. The roles of the Kaplan fibres, in particular the supracondylar and epicondylar bands should be investigated further. Further biomechanical investigation could take place in the form of a sectioning study of this area.
At the moment there is insufficient evidence to support any form of surgical intervention, although further investigation in the form of outcomes following extra-articular techniques such as the Lemaire procedure are warranted via clinical trials before they are adopted into widespread clinical practice. The clinical indication for when the procedure should be undertaken also needs to be more firmly defined.
The anterolateral structures of the knee appear to have a role in resisting anterolateral rotatory instability. Reviewing the work in this thesis together with contemporary literature on this subject, it seems more likely that there are several structures on the anterolateral aspect of the knee acting together that may have a role in resisting the pivot shift of which the ALL has a part. The ITB and its associated structures probably play a key role in resisting the pivot shift. Perhaps the best overall way to think of them would be as forming an anterolateral knee complex. Although some surgeons have already tried to produce an anatomical reconstruction of the ALL, a non-anatomical extra-articular tenodeses based on a similar design to those that were historically used would seem to be the most appropriate for resisting the pivot shift. A reconstruction based on a modified Lemaire procedure would seem a good basis but further work needs to be carried out to evaluate both its function and indications. Despite the vast amount of work on this topic of which this thesis is a part, further work needs to be carried out to determining clinically when these reconstructions may be used and how they relate to longer-term clinical results.
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