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Biomechanical Role of Lateral Structures in Controlling Anterolateral Rotatory Laxity: The Anterolateral Ligament

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Recent renewed interest in the anatomy of the anterolateral complex of the knee, combined with concern regarding persistent instability after anterior cruciate ligament reconstruction, has led to an expansion of the literature on the biomechanics of many structures of the anterolateral complex of the knee. A review of the clinical significance and the key biomechanical principles concerning this region is performed. The primary and secondary roles of key anatomical structures, with a specific emphasis on the anterolateral ligament, along with length change patterns and implications on anterolateral complex-based reconstruction are reviewed.

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KEYWORDS anterolateral ligament, knee, anterior cruciate ligament, rotational instability, anterolateral corner

Introduction

Re-establishment of anteroposterior (AP) stability after an anterior cruciate ligament (ACL) reconstruction has been reported to be foreseeable with traditional endoscopic reconstruction techniques. Nonetheless, persistent rotatory laxity constitutes a challenge in a subset of patients after the ACL reconstruction (ACLR), even with appropriate anatomical reconstruction techniques. It has been reported that up to 25% of patients who underwent an ACLR may experience residual rotatory instability.[1] In this regard, several techniques have been described in an attempt to address the rotatory laxity and their biomechanical consequences by augmenting or reconstructing the anterolateral structures of the knee.

These structures have been described and studied by numerous authors throughout the years that have attributed different anatomical and functional descriptions (and consequently a diverse nomenclature) with great unanimity. Segond[2] first described an avulsion fracture pattern of the proximal aspect of the lateral tibia in 1879, which was reported to have an association with ACL injuries over 100 years later.[3,4] Further, he described this structure as a pearly band, which coincides with a capsular thickening of what Hughston[5-8] called the mid-third lateral capsular ligament and the anterior oblique band of the lateral collateral ligament described by Johnson.[9] Descriptions of a distinct anatomical structure with well-defined anatomical attachments began to emerge in the early 21st century, changing the denomination to "the anterolateral ligament (ALL) of the knee".[10] Additional studies have subsequently determined that the ALL plays a role in anterior and rotatory stability of the knee.[11]

Early attempts to address rotatory instability, with lateral extra-articular tenodesis (LET) procedures,[12] created great controversy because they did not replicate the native anatomy, and long-term studies reported less than optimal results because of residual instability, overconstraint of the lateral compartment, and graft failure.[13-16] Thus, the ALL was redefined as a potential source of supplemental rotatory control in the setting of an ACL injury that can potentially improve outcomes compared with nonanatomical LET procedures.[10,17]

Recent biomechanical studies have demonstrated that the ALL has a role in stabilizing the knee; restraining internal

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rotation at 35° or more of knee flexion, with a minimal primary or secondary stabilizing role in the AP direction.[11] As with other anatomical-based ligament reconstructions that yielded excellent clinical and objective results,[18] an ALL reconstruction can provide increased knee stability and allow for improved knee function. This synergistic relationship between the anterolateral structures and ACL has led to renewed research and debate. The purpose of this narrative review was to describe the clinical significance and key biomechanical principles concerning the anterolateral structures of the knee. Primary and secondary roles of key anatomical structures along with length change patterns and implications on reconstruction are reviewed.

Anatomical Overview

In 2013, Claes et al[10] described the anatomical location and function of the ALL and invigorated the lay press' attention to a so-called "new ligament of the knee." Several descriptions followed the original report, although inconsistencies in the femoral origin of the ALL have been reported. Essentially, the following 2 femoral attachment locations have been described: (1) between the fibular collateral ligament (FCL) origin and the insertion of the popliteus tendon on the lateral femoral condyle[10,19-21]; (2) posterior and proximal to the FCL attachment.[17,20,22] Moreover, other authors support that there might be an anatomical variance between specimens, which could potentially explain the differing findings.[20] Thus, this anatomical disagreement could potentially lead to an altered biomechanical understanding and differing anatomy-based reconstruction procedures.

Our group has previously performed an anatomical, radiographical, and biomechanical analysis of the structural properties of the ALL.[17] In this study, the femoral origin was located 4.7 mm posterior and proximal to the FCL, then coursed distally to attach on the anterolateral tibia, midway between Gerdy tubercle and the anterior margin of the fibular head[17] (Fig. 1).

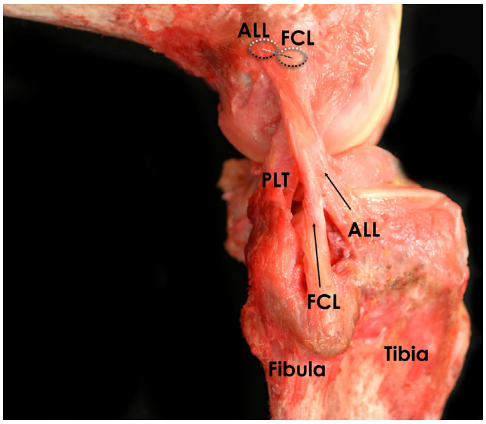

Figure 1 Cadaveric picture demonstrating the course of the ALL in a right knee. Note that the proximal femoral attachment is located posterior and proximal to the FCL. The ALL crosses the FCL superficially and inserts distally into the tibia approximately midway between the center of Gerdy tubercle and the anterior margin of the fibular head. PLT, popliteus tendon. (Color version of figure is available online.)

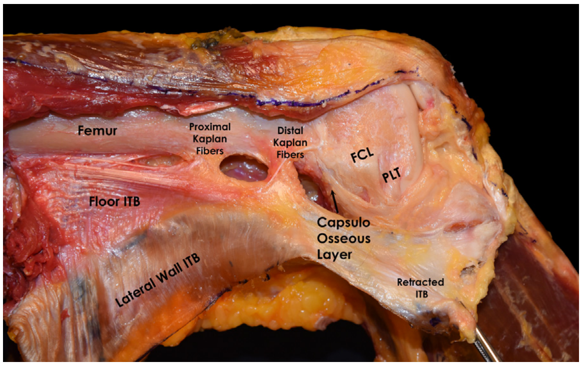

Figure 2 Anatomical dissection demonstrating the proximal and distal insertion of the Kaplan fibers on the lateral aspect of the femur. Note that the iliotibial band (ITB) is posteriorly reflected and the "floor" of the ITB inserting on the lateral aspect of the line aspera is visualized. PLT, popliteus tendon. (Color version of figure is available online.)

On AP radiographs, the ALL originated on the femur 22.3 mm proximal to the joint line, and inserted on the tibial 13.1 mm distal to the lateral tibial plateau.[17] On the lateral view, the femoral attachment was 8.4 mm posterior and proximal to the lateral epicondyle, whereas the tibial attachment was 19.0 mm posterior and superior to the center of Gerdy tubercle. Importantly, there are several lateral knee structures that contribute to restraining internal tibial rotation. These structures can be identified as the anterolateral corner of the knee and include the ALL, the superficial layer of the iliotibial band (ITB) and its Kaplan fibers, the capsulo-osseous layer of the ITB and the mid-third lateral capsular ligament (Figs. 2 and 3).

Biomechanical Role of Key Anterolateral Structures

The anterolateral structures of the knee are reported to be frequently injured concurrently with ACL tears, potentially

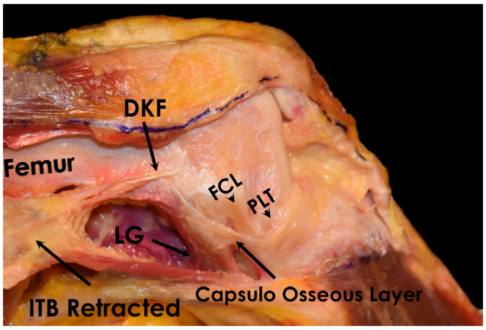

Figure 3 Anatomical dissection with the iliotibial band (ITB) retracted showing the deep structures of the anterolateral corner. The distal Kaplan fibers and the capsule osseous layer with its anatomical soft tissue landmarks are demonstrated. LG, lateral gastrocnemius; PLT, popliteus tendon. (Color version of figure is available online.)

increasing the instability and resulting in a high-grade pivot shift, which is the hallmark of anterolateral rotatory instability. Hughston et al[8] reported in 1976, the important role of the anterolateral structures in anterolateral instability of the knee.

In a dissection study by Terry and LaPrade, the muscular part of the short head of the biceps was reported to terminate into the capsulo-osseous layer of the ITB forming what they called the biceps-capsulo-osseous iliotibial tract confluence. Anteriorly, the anterior arm of the short head of the biceps inserted overlapping the capsulo-osseous layer, both attaching to the tibia, between Gerdy tubercle and the fibular head.[23] When the same authors examined 82 consecutive acute injured knees with clinical anterolateral-anteromedial rotatory instability, injuries to individual components of the biceps muscle were reported in 72% and 35% had injuries to multiple components of the muscle, with most injuries to the short head of the biceps femoris. There was a significant correlation between anterior tibial translation at 25° of knee flexion and injury to the biceps-capsulo-osseous iliotibial tract confluence. This study demonstrated the intricate anatomical proximity and interplay between the biceps femoris and the ITB.[23] Wroble et al[24] performed a sectioning study where they reported a significant increase in internal tibial rotation at angles $\geq 30°$ after sectioning the anterolateral complex. In their study, the anterolateral complex constituted the ITB and midlateral capsule. The role of each component was not delineated, and therefore the contribution of each of the components of the anterolateral complex could not be determined.

In recent years, there has been more interest in the anterolateral structures, and the contribution of each component to rotatory knee stability. Kaplan's fibers have been reported to act as a stabilizing ligament, holding the distal portion of the ITB against the lateral femoral condyle and increasing in tension during internal tibial rotation.[25]

In separate studies, Terry et al and Yamamoto et al reported that the ITB and not the ACL was the key structure in controlling the pivot shift. In an evaluation of 82 patients with acute knee injuries, tears of the ACL were found in 98%; however, there was no correlation between ACL tears and abnormal motion demonstrated by the Lachman and pivot shift test. Injuries to the ITB were found in 93% of the patients, and there was a correlation between these injuries and a positive pivot shift test, anterior translation at 90° and the Lachman test.[7] In a biomechanical study on cadaveric knees, Yamamoto et al[26] reported on the important role of the ITB in controlling coupled anterior tibial translation during a simulated pivot shift test at high flexion angles.

The role of the ALL in controlling internal tibial rotation has gained much interest in recent years. Several biomechanical studies have reported that the ALL is important in controlling internal tibial rotation in ACL-deficient knees.[11,27,28] However, Kittl et al[29] reported that the ALL had only a minor role in controlling internal rotation in ACL-deficient knees. The role of the ALL seems to be most important at knee flexion angles $\geq 30°\text{-}35°$. The ALL seem to be acting at the same angles as the ITB in providing a restraint to internal tibial rotation. Both structures, together with the lateral capsule, appear to act synergistically in controlling internal tibial rotation at higher flexion angles.

In an effort to determine the role of each of the anterolateral structures and the ACL in restraining simulated clinical laxity, the ITB was reported to be the main contributor in restraining anterior tibial translation of the lateral tibia plateau and internal tibial rotation. In a recent biomechanical study by Sonnery-Cottet et al,[27] both the ITB and the ALL were reported to play an important role in controlling internal tibial rotation at 20° and 90° of knee flexion, and coupled axial rotation during a pivot shift test, with the ITB contributing more to restrain internal tibial rotation. Rahnemai-Azar et al recently investigated the structural properties of the ITB and the anterolateral capsule, and found significantly reduced structural properties of the anterolateral capsule as compared with the ITB, but comparable to the posteromedial capsule. In addition, a thickening of the anterolateral capsule was found in only 2 of the 9 specimens, casting doubt on the importance of the role of the ALL.[30]

Based on the biomechanical properties of the native ALL, it has been reported that an average minimum load of 175 N should be achieved by the chosen graft for reconstruction.[17] Therefore, single-looped semitendinosus tendon (1216 N) and gracilis tendon (838 N) grafts outweigh the native properties of

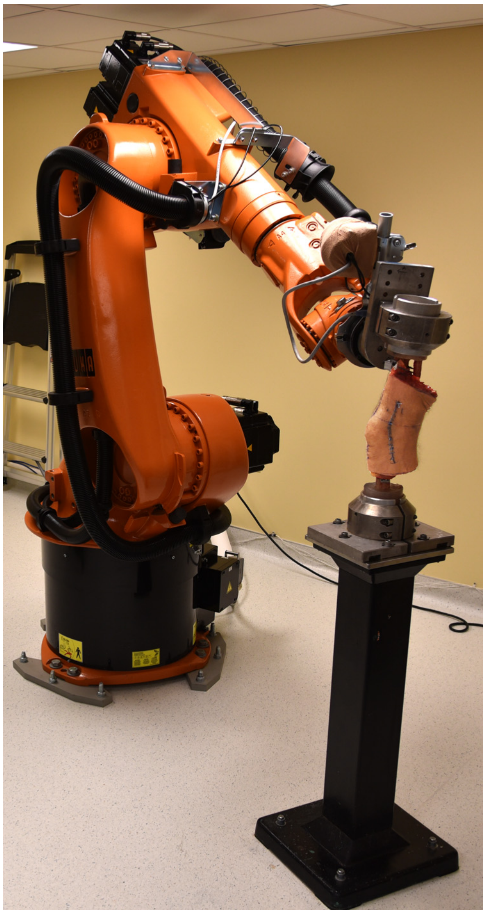

Figure 4 Photograph of a right knee inverted and mounted into the pedestal of a 6° of freedom robotic system for anterolateral ligament reconstruction biomechanical testing. (Color version of figure is available online.)

the ALL. However, a gracilis tendon autograft is the preferred graft for most authors as reported in the literature[1,10] (Fig. 4).

Role of the ALL in ACL Intact and ACL-Deficient Knees

It has been widely reported that the ALL is a primary stabilizer to tibial rotatory stability and contributes significantly to internal tibial rotation as the knee flexes past 30°.[11,17,31,32] Clinically, residual rotatory instability after ACLR in symptomatic patients is found near extension and up to 30° of knee flexion. On clinical examination, patients usually present with a positive pivot shift test, which reproduces their symptoms. However, biomechanical studies reported that these are the angles at which the ALL was not the main stabilizer to rotatory stability of the knee and also, that its function increases with higher flexion angles.[33] Biomechanical studies have reported that the contribution of the ALL during internal tibial rotation (primary stabilizer) increases significantly with increasing flexion (above 35°), whereas that of the ACL decreased significantly.[11] Of note, a pivot shift could be reproduced only in the presence of a combined ALL and ACL deficiency.[11]

Rasmussen et al[28] demonstrated in a biomechanical study that the presence of a combined ACL and ALL lesion caused the knee to have a significantly higher internal rotatory instability and axial plane translation during the pivot shift test when compared with an isolated ACL tear. Although a deficient ALL knee has a 1.7°-1.8° additional increase in internal rotatory laxity, a recent cadaveric study suggested that a concurrent ACL- and ALL-reconstruction further reduces rotatory laxity compared with an isolated ACLR with the presence of a combined ACL and ALL deficiency.[34] Isolated ACLR resulted in significant residual internal tibial rotation compared with an intact knee during applied internal rotation torques and a simulated pivot shift in an ALL-deficient knee. By adding an ALL reconstruction, internal tibial rotation was significantly reduced and therefore comparable with the intact state.[34]

Length Change Patterns of the ALL

The distance between 2 anatomical attachment points on the femur and tibia has been used as a surrogate for length change patterns of soft tissue structures of the anterolateral complex of the knee. Two trends, which are perhaps anatomically intuitive, were observed. When the femoral attachment point is located anterior or distal to the lateral femoral epicondyle, the distance increases with greater knee flexion; when the attachment point is located posterior or proximal to the lateral femoral epicondyle, the distance decreases (ie, the anterolateral structures slacken) with greater knee flexion.

Dodds et al[22] described the anatomy and length change patterns of an extra-capsular ligamentous structure that they termed the ALL in fresh-frozen cadavers. This was distinct from the capsule, deep to the ITB, and superficial to the FCL. They defined the femoral attachment as 8 mm proximal and 4.3 mm posterior to the lateral femoral epicondyle and the tibial attachment was midway between Gerdy tubercle and the fibular head. These anatomical locations were used when evaluating the length change patterns of this structure. They reported a nearly isometric behavior between 0° and 60° of knee flexion and a shortening by 4.1 mm between 60° and 90° of knee flexion.

Kittl et al[35] evaluated the isometry of several lateral extra-articular reconstruction techniques for the anterolateral complex. In an elegant series of tests, they evaluated several tibial and femoral attachment sites, and the influence of graft placement deep to the FCL. The 2 tibial attachment sites evaluated were Gerdy tubercle and the ALL attachment site reported by Dodds et al.[22] Several femoral attachment sites were evaluated, all referenced relative to the lateral femoral epicondyle. They reported that the femoral and tibial attachment sites reported by Dodds et al had the optimal isometric properties. They also reported that improved isometric properties were identified for LET procedures with femoral attachments proximal to the lateral epicondyle when the graft was routed deep to the FCL. Kittl et al[35] observed a remarkable variability in length change for the grafts running superficial to the FCL with a tendency to lengthen during early knee flexion, whereas those running deep to the FCL tended to decrease in length. The epicondyle acted as a barrier for grafts running superficial, and the graft remained anterior for low flexion angles and moved posteriorly at high flexion angles.

Lutz et al[25] evaluated the anatomy and length change properties of the anterolateral structures. Similar to Dodds et al,[22] they reported a change of length of approximately 1 cm when the knee was placed at 30° of flexion with internal tibial rotation compared with a neutral position. Zens et al[36] evaluated the length change properties of the ALL as defined by Claes et al[10] with the origin of the ALL anterior to the lateral femoral epicondyle. They reported lengthening from full extension to 90° of flexion in a fairly uniform fashion. In addition, external rotation shortened the ALL, whereas internal rotation lengthened the ALL. Kittl et al[35] also reported lengthening, approximately 20%, with increasing flexion (from 10°-90°) when the anatomical locations reported by Claes et al were used.

Helito et al[37] performed a lateral knee dissection and applied 2 mm metal spheres to the femoral and tibial attachment sites of the ALL; computed tomography was used to image the knee at 0°, 30°, 60°, and 90° of flexion. The distance between the 2 attachment points increased from 0°-90° by approximately 17% on average. The greatest length change increase occurred between 60° and 90°.

Conclusions

In conclusion, a comprehensive knowledge of the anterolateral knee anatomy is a key to understand its biomechanics and ultimately, better diagnose different instability patterns to be able to precisely reconstruct the damaged structures causing instability. The anterolateral corner of the knee comprises several structures that work in conjunction to provide rotatory stability to the knee. The ALL has been found to be an important stabilizer of the anterolateral complex, but its overall role in providing anterolateral or internal rotatory stability, especially compared with the ITB, is still being investigated. Further studies are required to precisely determine the role of each structure on unstable knees and clinical data to determine the real effect of the injury or reconstruction natural history.

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