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Mapping isometry and length changes in ligament reconstructions of the knee

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Chapter 5

In vivo anterolateral ligament length change in the healthy knee during functional activities – A combined magnetic resonance and dual fluoroscopic imaging analysis

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ABSTRACT

Purpose: To measure the in vivo anterolateral ligament (ALL) length change in healthy knees during step-up and sit-to-stand motions.

Methods: Eighteen healthy knees were imaged using magnetic resonance and dual fluoroscopic imaging techniques during a step-up and sit-to-stand motion. The ALL length change was measured using the shortest three-dimensional wrapping path, with its femoral attachment located slightly anterior-distal (ALL-Claes) or posterior-proximal (ALL-Kennedy) to the fibular collateral ligament attachment. The ALL length measured from the extended knee position of the none-weight-bearing magnetic resonance scan was used as a reference to normalize the length change.

Results: During the step-up motion (approximately 55º flexion to full extension), both the ALL-Claes and ALL-Kennedy showed a significant decrease in length of 21.2% (95% confidence interval 18.0-24.4, $P < .001$) and 24.3% (20.6-28.1, $P < .001$), respectively. During the sit-to-stand motion (approximately 90º flexion to full extension), both the ALL-Claes and ALL-Kennedy showed a consistent, significant decrease in length of 35.2% (28.8-42.2, $P < .001$) and 39.2% (32.4-46.0, $P < .001$), respectively. From approximately 90º to 70º of flexion, a decrease in length of approximately 6% was seen; 70º of flexion to full extension resulted in an approximately 30% decrease in length.

Conclusions: The ALL was found to be a nonisometric structure during the step-up and sit-to-stand motion. The length of the ALL was approximately 35% longer at approximately 90º of knee flexion when compared with full extension and showed decreasing length at lower flexion angles. Similar ALL length change patterns were found with its femoral attachment located slightly anterior-distal or posterior-proximal to the fibular collateral ligament attachment.

Clinical relevance: These data suggest that, if performing anatomic ALL reconstruction, graft fixation may be performed beyond 70º flexion to reduce the chance of lateral compartment overconstraint. Anatomic ALL reconstruction may affect the knee kinematics more in high flexion than at low flexion angles.

INTRODUCTION

In recent cadaveric studies, discrepancy exists in the description of length change patterns of the anterolateral ligament (ALL) during knee flexion. This information is important when considering optimal graft fixation during ALL reconstruction.[1] Some researchers have found the ALL to be close to isometric between 0º and 60º of knee flexion angles and decrease in length from 60º to 90º of flexion.[14] These findings are directly at odds with findings by others who found the ALL to be nonisometric and gradually increase in length during 0º to 90º of flexion; its greatest length increase was noticed from 60º to 90º of flexion.[3] Similar nonisometric behavior was found in another independent study group.[32]

Possible explanations for the aforementioned differences in length change patterns might be the variability of the femoral attachment of the ALL used for ALL measurement in the cadaveric studies. The femoral insertion of the ALL has been described either together with the fibular collateral ligament (FCL),[2, 24] anterior-distal to the FCL,[1, 8, 32] posterior[6] or more posterior-proximal to the FCL.[4, 13, 19] Minor shifts in position around the rotational axis of the femur would result in contrary ligament kinematic patterns.[22] Another explanation might be the high dependence of the tibiofemoral biomechanics on the muscle loading conditions and subsequent length change patterns of the knee during in vitro testing. Even the most advanced in vitro experiments are limited by the difficulty in simulating the complex physiological loading conditions that occur during weight-bearing knee flexion.[29] Therefore, care should be taken when extrapolating the biomechanical behavior of the ALL that were measured during variable loading conditions in the in vitro setting to the length change patterns that would be seen in the healthy knee during in vivo weight-bearing flexion.

Therefore, in this study, we aimed to quantify the length change of the ALL in healthy subjects during dynamic in vivo functional activities, namely step-up and sit-to-stand weight-bearing motions of the knee to evaluate its isometric behavior. We hypothesized that during the dynamic functional activities, the ALL of the healthy knee would show nonisometric behavior with greater length at higher flexion angles.

METHODOLOGY

Patient Selection

This study was approved by our institutional review board. All subjects meeting the inclusion and exclusion criteria were enrolled from our institutional broadcast e-mail announcements. The inclusion criteria for this study were an age of 18 to 60 years, and the ability to perform daily activities independently without any assistance device and without taking pain medication. The exclusion criteria were knee pain, previous knee injury, and previous surgery to the lower limb. The magnetic resonance (MR) imaging scan of the knee of each subject was assessed for potential meniscal tears, chondral defects, and ligamentous injuries; if present, the subject was excluded for further analyses. Written consent was obtained from each subject. All subjects were tested between November 2008 and April 2010 to study the normal in vivo knee kinematics during dynamic functional activities. To address the research aim of the current study, the knees were analyzed to investigate the change in length of the anatomic ALL.

Imaging Procedure

The MR and dual fluoroscopic imaging techniques for the measurement of ligament kinematics have been described in detail previously.[15,18] The healthy knee was imaged with an MR scanner to create 3-dimensional (3D) meshed models of the knees, using a protocol established in our laboratory.[3] MR imaging was used to scan the knee joint in the sagittal plane using a 3-Tesla MR imaging scanner (MAGNETOM Trio; Siemens, Malvern, PA) with a double-echo water-excitation sequence (thickness 1 mm; resolution of 512 × 512 pixels). The images were then imported into solid modeling software (Rhinoceros; Robert McNeel and Associates, Seattle, WA) to construct 3D surface mesh models of the tibia, fibula, and femur. The attachment sites of the FCL were identified as previously described and included in the 3D knee model.[28] On these anatomical knee models the attachment sites of the ALL were presented as points. The femoral attachment sites of the ALL were positioned based on both the description by (1) Claes et al.,[1] that is, slightly anterior-distal with respect to the attachment of the FCL (ALL-Claes), and the description by (2) Kennedy et al.,[13] that is, posterior-proximal of the FCL origin (ALL-Kennedy). The tibial attachment site of the ALL was positioned midway between the center of Gerdy's tubercle and the anterior margin of the fibular head.[1, 13]

After the MR imaging-based computer models were constructed, the knee of each subject was simultaneously imaged using 2 fluoroscopes (BV Pulsera, Philips, the Netherlands) as the patient performed 2 dynamic motions: step-up and sit-to-stand motion. The motions were practiced multiple times before recording the finale motion that was used for analyses. Next, the fluoroscopic images were imported into solid modeling software and placed in planes based on the position of the fluoroscopes during imaging of the patient. Finally, the 3D MR imaging-based knee model of each subject was imported into the same software, viewed from the directions corresponding to the fluoroscopic setup used to acquire the images, and independently manipulated in 6 degrees of freedom inside the software until the projections of the model matched the outlines of the fluoroscopic images. When the projections matched the outlines of the images taken during in vivo knee flexion, the model reproduced the in vivo position of the knee. This system has an error of <0.1 mm and 0.3° in measuring tibiofemoral joint translations and rotations, respectively.[3, 17, 18]

Length Change Measurement of the ALL

The ALL length was measured as a function of knee flexion with several combinations of the tibiofemoral attachment points (Fig. 1). The direct line connecting the attachment sites was projected on the bony surfaces to create a curved ligament path to avoid penetration of the connecting line through bone. An optimization procedure was implemented for determination of the line projection angle to find the shortest 3D wrapping path of the ALL around the femoral condyles and the tibial plateau at each flexion angle of the knee. This technique has been described in previous studies for measurements of ligament kinematics.[15, 16, 22, 28] The length of this projected curve was measured as the length of the ligament. For each subject, the length change data were normalized to percentage length change by using the relaxed, non-weight-bearing MR imaging scan as a reference ([length – MR length]/MR length × 100%). The ALL is likely to be unloaded at this position and the length change is not representative of true ligament strain (i.e., change in length due to an applied force divided by the original length) but rather an increase in the distance between 2 anatomical sites.

Statistical Analysis

Changes in the length of the ALL (dependent variable), based on the descriptions by both Claes et al.[1] and Kennedy et al.,[13] caused by independent variables flexion of the knee and functional activities (step-up and sit-to-stand) were examined using a one-way analysis of variance with pairwise comparisons, having the Newman-Keuls post hoc procedure for multiple comparisons. Values are described as the mean percentage length change and 95% confidence intervals (CIs) (lower limit to upper limit). P values less than .05 were considered significant.

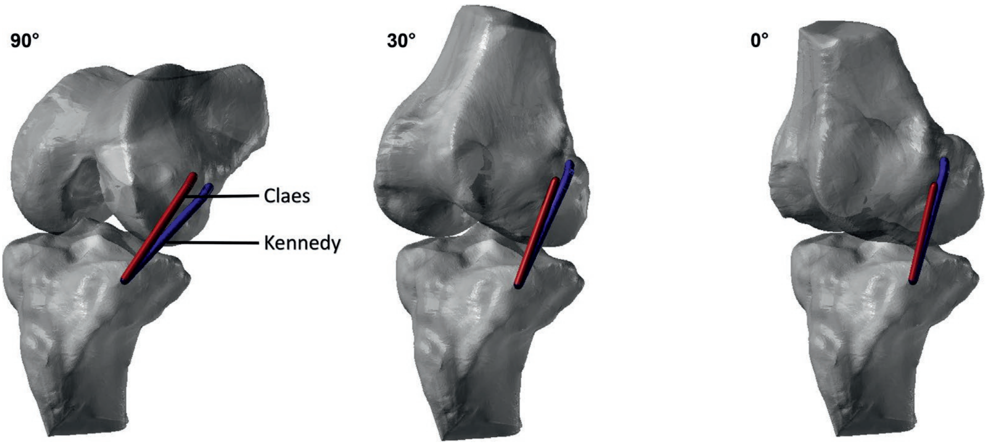

Fig. 1 Lateral view of a 3-dimensional knee model illustrating the anatomic anterolateral ligament with the femoral attachment anterior-distal (Claes et al.[1]) and posterior-proximal (Kennedy et al.[13]) with respect to the attachment of the fibular collateral ligament at 90º, 30º of knee flexion, and full extension during the sit-to-stand motion. The tibial insertion is midway between Gerdy's tubercle and the anterior margin of the fibula.

RESULTS

Eighteen healthy knees were included in this study (12 male, 6 female; age 35.4 years ± 10.9 years [mean ± standard deviation]; body height 175 ± 9 cm; body weight 83.3 ± 18.0 kg; body mass index 27 ± 3.5).

Reference Length

The mean length of the ALL-Claes (i.e., slightly anterior-distally to the FCL) as based on the non-weight-bearing MR imaging scan was 33.9 mm (95% confidence interval [CI], 32.5-35.4), and that of the ALL-Kennedy (i.e., posterior-proximal to the FCL) was 44.0 mm (95% CI, 41.8-46.2). The knees of the healthy subjects were slightly flexed during MR imaging, on average 2 ± 3.5º.

Step-Up Motion

The mean maximum flexion angle was 55 ± 4º (Fig. 2, Table 1). The ALL-Claes showed a consistent, significant decrease in length of 21.2% with decreasing flexion (95% CI, 18.0-24.4) over approximately 55º of flexion ($P < .001$) as compared with the non-weight-bearing MR reference length. The ALL-Kennedy also showed a consistent, significant decrease in length of 24.3% with decreasing flexion (95% CI, 20.6-28.1) over approximately 55º of flexion ($P < .001$) as compared with the MR reference length.

Sit-to-Stand Motion

The mean maximum observed flexion angle was 88 ± 10º (Fig. 3, Table 2). Both the ALL-Claes and ALL-Kennedy showed a consistent, significant decrease in length of 35.2% (95% CI, 28.2-42.2, $P < .001$) and 39.2% (95% CI, 32.4-46.0, $P < .001$), respectively, over approximately 90º of flexion as compared with the MR reference length. Length change from approximately 90º to 70º of flexion accounted for 5.0% (95% CI, 3.3-6.8, $P < .001$) and 6.0% (95% CI, 4.5-7.6, $P < .001$), respectively, whereas 70º of flexion to full extension resulted in 30.1% (95% CI, 23.6-36.6, $P < .001$) and 31.5% (95% CI, 25.4-37.7, $P < .001$). Likewise, from approximately 90º to 45º of flexion, the ALL showed a decrease in length of 13.1% (95% CI, 9.0- 17.2, $P < .001$) and 14.5% (95% CI, 11.0-17.9, $P < .001$); 45º of flexion to full extension resulted in an additional 22.0% (95% CI, 17.2-26.8, $P < .001$) and 23.1% (95% CI, 18.1-28.1, $P < .001$) decrease in length for the ALL-Claes and ALL-Kennedy, respectively.

Fig. 2

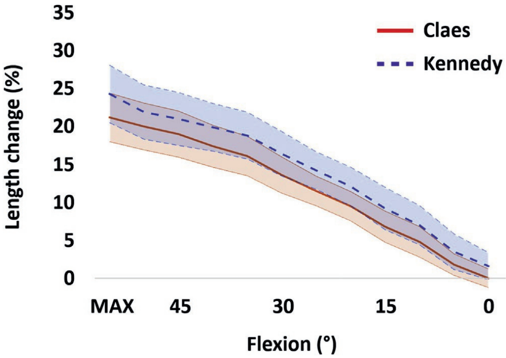

Fig. 3

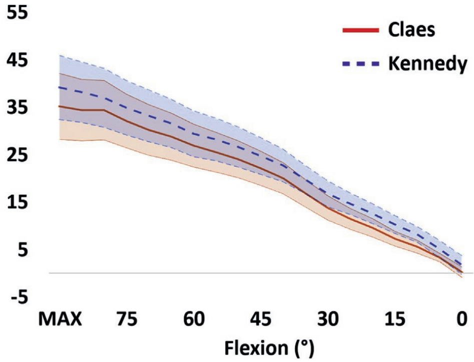

Fig. 2 and Fig. 3 The anterolateral ligament (ALL) length change (%) of intact knees as a function of the flexion (º) in 18 healthy subjects during the step-up (left) and sit-to-stand motion (right), the mean maximum flexion angle was (MAX) was 55 ± 4º and 88 ± 10º respectively. The red solid line depicts the femoral attachment of ALL-Claes, and the blue dashed line depicts the femoral attachment of the ALL-Kennedy. Values are mean and 95% confidence interval.

Table 1. Step-up motion

Knee flexion angle	ALL-Claes length change (%)	P-value†	Accumulated length change (%)	ALL-Kennedy length change (%)	P-value†	Accumulated length change (%)
Max - 50°	1.2 (0.3 to 2.2)	0.386	1.2	2.5 (1.6 to 3.4)	0.283	2.5
50° - 40°	2.6 (1.5 to 3.7)	<0.001	3.8	1.9 (2.9 to 1.0)	<0.001	4.4
40° - 30°	3.8 (2.8 to 4.9)	<0.001	7.7	3.5 (2.7 to 4.4)	<0.001	7.9
30° - 20°	4.1 (2.8 to 5.4)	<0.001	11.7	4.3 (3.0 to 5.7)	<0.001	12.3
20° - 10°	4.7 (3.6 to 5.8)	<0.001	16.5	5.1 (3.9 to 6.2)	<0.001	17.3
10° - 0°	4.7 (3.5 to 6.0)	<0.001	21.2	5.4 (3.9 to 6.9)	<0.001	22.7
0° - MRI	0.0 (-1.2 to 1.3)	0.987	21.2	1.6 (-0.1 to 3.4)	0.280	24.3

NOTE. Values are expressed as a percentage of the length as measured from non-weight-bearing MR reference length. Values are presented as mean (95% confidence interval), positive values indicate lengthening of the distance between attachment points, negative values indicate shortening.
† *P*-value: shows the statistical difference between each knee flexion angle range (e.g. MAX° - 50°).

Table 2. Sit-to-stand motion

Knee flexion angle	ALL-Claes length change (%)	P-value†	Accumulated length change (%)	ALL-Kennedy length change (%)	P-value†	Accumulated length change (%)
MAX – 80°	0.8 (-0.3 to 2.0)	0.024	0.8	2.2 (1.3 to 3.1)	0.007	2.2
80° – 70°	4.2 (3.0 to 5.4)	<0.001	5.0	3.9 (2.7 to 5.0)	<0.001	6.0
70° – 60°	3.2 (2.0 to 4.5)	<0.001	8.3	3.7 (2.5 to 5.0)	<0.001	9.8
60° – 50°	2.9 (1.8 to 4.1)	<0.001	11.2	2.8 (1.6 to 4.0)	<0.001	12.6
50° – 40°	4.0 (2.9 to 5.1)	<0.001	15.2	3.9 (2.9 to 5.0)	<0.001	16.5
40° – 30°	6.3 (5.1 to 7.5)	<0.001	21.5	6.0 (4.7 to 7.2)	<0.001	22.5
30° – 20°	4.2 (2.5 to 5.8)	<0.001	25.7	4.2 (2.2 to 6.2)	<0.001	26.7
20° – 10°	4.0 (2.4 to 5.7)	<0.001	29.7	4.4 (2.9 to 6.0)	<0.001	31.1
10° – 0°	5.4 (4.5 to 6.2)	<0.001	35.1	6.5 (5.3 to 7.7)	<0.001	37.6
0° – MR scan	0.1 (0.1 to 0.2)	0.826	35.2	1.6 (-0.4 to 3.6)	0.337	39.2
Knee flexion angle						
MAX – 70°	5.0 (3.3 to 6.8)	<0.001	5.0	6.0 (4.5 to 7.6)	<0.001	6.0
70° – 0°	30.1 (23.6 to 36.6)	<0.001	35.1	31.5 (25.4 to 37.7)	<0.001	37.6
MAX – 45°	13.1 (9.0 to 17.2)	<0.001	13.1	14.5 (11.0 to 17.9)	<0.001	14.5
45° – 0°	22.0 (17.2 to 26.8)	<0.001	35.1	23.1 (18.1 to 28.1)	<0.001	37.6

NOTE. Values are expressed as a percentage of the length as measured from non-weight-bearing MR reference length. Values are presented as mean (95% confidence interval), positive values indicate lengthening of the distance between attachment points, negative values indicate shortening.

† *P*-value: shows the statistical difference between each knee flexion angle range (e.g. MAX° - 80°).

DISCUSSION

The principal findings of this study show that both the ALL-Claes and ALL-Kennedy consistently and significantly decreased in length from approximately 90º of flexion to full extension, as is in agreement with our hypothesis. Similar nonisometric length change patterns were found during the step-up and sit-to-stand motion. The ALL length decreased approximately 22% during the step-up motion (approximately 55º of flexion to full extension) and 35% for the sit-to-stand motion (approximately 90º of flexion to full extension). An approximately 6% decrease in length was seen between 90º and 70º of flexion, and a 30% decrease in length was seen between 70º of flexion and full extension.

The nonisometric pattern of the ALL is in agreement with previous in vitro studies,[7, 14, 32] and a comparable length change of the ALL to our previous measurements during a quasi-static lunge was observed.[30] Helito et al.[7] found that the ALL increased in length from full extension to 90º, with a greater length increase from 60º to 90º than from 0º to 60º. These findings are in agreement with the study by Zens et al.,[32] who found the ALL to be a nonisometric structure that increased in length with increasing knee flexion. However, these results are in contrast with the findings described by Dodds et al.[4] In their study, they found the ALL to be near isometric between 0º and 60º of flexion, and the ALL to decrease in length between 60º and approximately 90º of flexion. These differences in length change may be explained due to the different techniques for measurement of the ALL length change that have been used in the cadaveric setting, for example, forced neutral tibial flexion,[3] unconstrained passive flexion,[7] fixed knee flexion angle at 30º,[19] with[4, 14] or without muscle loading conditions and with[4, 19] or without the use of forced internal rotation. Various ways to calculate the ALL length were used, such as a linear variable displacement transducer technique,[4, 14] and measurement based on a highly elastic capacitive polydimethylsiloxane strain gauge technique.[33] In the study by Helito et al.,[7] the ALL insertion sites were marked with metallic spheres and the distance between the 2 spheres was measured; no muscle tensioning was used and tibial rotation was controlled during flexion. Hereby, no native knee joint motion was simulated and the wrapping effect of the ALL was unaddressed.

Most recently, Imbert et al.[10] reported on the length change of 3 different ALL descriptions. The attachment sites anterior-distal to, and at the center of the lateral femoral epicondyle showed increasing length with increasing flexion, similar to the current study findings. The posterior-proximal point in their study was found to decrease in length with increasing flexion; no such length decrease was found in the current study. However, this may be explained due to the apparent difference in posterior-proximal descriptions: 7-7 mm (Imbert et al.[10]) versus approximately 3-3 mm (Kennedy et al.[13]). This could suggest that a more posterior-proximal location changes the length change pattern drastically.

Previous studies have shown that anterolateral extraarticular injuries accompanying anterior cruciate ligament (ACL) tears are frequently seen, and can attribute to the different instability patterns seen after ACL injury.[9, 27] Failure to recognize and manage concomitant injuries at the time of primary ACL reconstruction might result in persistent postoperative instability[11, 12] and put the knee joint at risk of secondary damage.[5, 26] Persistent postoperative instability as revealed by a residual pivot-shift test has been reported in 25% of the patients.[25] Monaco et al.[20] found that extraarticular reconstruction improved axial tibial rotation and stability during the pivot-shift test. Sonnery-Cottet et al.[25] found that combined ACL and extra-articular reconstruction can be an effective procedure in restoring knee stability without specific complications at a minimum follow-up of 2 years. Most recently, it was found that in the presence of anterolateral extraarticular injury, isolated ACL reconstruction was unable to restore internal rotation instability, whereas concomitant ALL reconstruction to the ACL reconstruction was able to significantly reduce internal rotation.[21] These results are promising and show the possible benefits of adding an extra-articular reconstruction to the ACL reconstruction to better restore knee stability.

In our recent pilot study,[31] we found that nonanatomic extra-articular reconstructions showed more biomechanically favorable length change patterns (i.e., smaller length change percentage) compared with the ALL reconstruction, therefore reducing the likelihood of graft stretch. However, only 1 functional activity a single quasi-static leg lunge was performed at discrete flexion angles. It is important to note that the anatomic ALL showed nonisometric behavior with increased length in deeper flexion angles. This means that more isometric, nonanatomic reconstructions potentially overconstrain the lateral compartment of the knee. In the present study, the considerable length change of the ALL as was previously measured during the quasi-static lunge was also seen during 2 fully dynamic activities. This finding further substantiates the probability that an anatomic ALL reconstruction might not be biomechanically favorable. It has been suggested that an increase of 6% in separation distance between insertion points could lead to permanent graft stretching.[23] The ALL changed approximately 6% in length between approximately 90º and 70º of flexion. These data therefore suggest that anatomic ALL reconstruction might have to be performed beyond 70º of knee flexion. Graft tensioning at lower flexion angles potentially results in excessive stretch of the graft and overconstraint of the lateral compartment of the knee. We believe that the findings of this study can contribute to the design of improved treatment protocols for anterolateral rotatory instability. Future studies should focus on the biomechanical changes of adding the anatomical ALL reconstruction to the ACL reconstruction and investigate possible nonanatomic extraarticular attachment points with similar length change patterns to the native biomechanics.

Limitations

The ALL length was measured as the shortest distance between the attachment sites on the 3D models projected to the bony surfaces. Baseline measure of the ALL length was defined as the relaxed, non-weight-bearing knee state as was seen in the MR imaging scan to which the percentage length change was calculated. Therefore, the ALL is likely to be unloaded at this position and the length change is not representative of true ligament strain (i.e., change in length due to an applied force divided by the original length) but rather an increase in the distance between 2 anatomical sites. We could not identify the ALL on the available 3-Tesla MR images; instead the detailed anatomic descriptions by Claes et al.[1] and Kennedy et al.[13] were used to determine the ALL attachment sites. No pivoting motion was performed, and thus, the effect of internal rotation demanding movements on the ALL length change could not be assessed.

Conclusions

The ALL was found to be a nonisometric structure during the step-up and sit-to-stand motion. The length of the ALL was approximately 35% longer at approximately 90º of knee flexion when compared with full extension and showed decreasing length at lower flexion angles. Similar ALL length change patterns were found with its femoral attachment located slightly anterior-distal or posterior-proximal to the FCL attachment.

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