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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 (MR) and dual fluoroscopic imaging techniques during a step-up and sit-to-stand motion. The ALL length change was measured, using the shortest 3-D wrapping path, with its femoral attachment located slightly anterior-distal (ALL-Claes) or posterior-proximal (ALL-Kennedy) to the fibular collateral ligament (FCL) attachment. The ALL length measured from the extended knee position of the non-weight-bearing MR-scan, was used as a reference to normalize the length change.

Results—During the step-up motion (~55° 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 to 24.4, $P<0.001$) and 24.3% (20.6 to 28.1, $P<0.001$) respectively. During the sit-to-stand motion (~90° flexion to full extension), both the ALL-Claes and ALL-Kennedy showed a consistent, significant decrease in length of 35.2% (28.8 to 42.2, $P<0.001$) and 39.2% (32.4 to 46.0, $P<0.001$) respectively. From ~90° to 70° of flexion, a decrease in length of approximately 6% was seen; 70° of flexion to full extension resulted in an approximate 30% decrease in length.

Conclusion—The ALL was found to be a non-isometric structure during the step-up and sit-to-stand motion. The length of the ALL was approximately 35% longer at ~90° of knee flexion when compared to 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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Clinical Relevance—These data suggest that, if performing anatomic ALL reconstruction, graft fixation may be performed beyond 70° 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.

Keywords

Anterolateral Ligament; Anterior Cruciate Ligament; Anterolateral Rotatory Instability; Biomechanics; Fluoroscopy

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 0° to 60° of knee flexion angles and decrease in length from 60° to 90° of flexion.² These findings are directly at odds with findings by others which found the ALL to be non-isometric, and gradually increase in length during 0° to 90° of flexion, its greatest length increase was noticed from 60° to 90° of flexion.³ Similar non-isometric behavior was found in another independent study group.⁴ 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),^{5, 6} anterior-distal to the FCL⁷⁻⁹, posterior¹⁰ or more posterior-proximal to the FCL.^{2, 11, 12} Minor shifts in position around the rotational axis of the femur would result in contrary ligament kinematic patterns.¹³ Another explanation might be the high dependency 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.¹⁴ 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 non-isometric behavior with greater length at higher flexion angles.

METHODS

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, 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, 16} The healthy knee was imaged with an MR scanner to create three-dimensional (3-D) meshed models of the knees, using a protocol established in our laboratory.¹⁷ 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 (Rhinceros; Robert McNeel and Associates, Seattle, WA) to construct 3-D surface mesh models of the tibia, fibula and femur. The attachment sites of the FCL were identified as previously described and included in the 3-D knee model.¹⁶ 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 both on the description by (1) Claes et al,⁷ i.e. slightly anterior-distal with respect to the attachment of the FCL (ALL Claes), and the description by (2) Kennedy et al,¹¹ i.e. posterior-proximal of the FCL origin (ALL-Kennedy). The tibial attachment site of the ALL was positioned midway between the center of Gerdy tubercle and the anterior margin of the fibular head.^{7, 11}

After the MR imaging based computer models were constructed, the knee of each subject was simultaneously imaged using two fluoroscopes (BV Pulsera, Philips, The Netherlands) as the patient performed two dynamic motions: step-up and sit-to-stand motion. The motions were practiced multiple times prior to 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 3-D 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 six-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.¹⁷⁻¹⁹

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 (Figure 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 3-D 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.^{13, 15, 16, 20} 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 ($\text{length-MR length} / \text{MR length} \times 100\%$). 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 original length) but rather an increase in the distance between two anatomical sites.

Statistical Analysis

Changes in the length of the ALL (dependent variable), based on the descriptions by both Claes et al⁷ and Kennedy et al,¹¹ 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 mean percentage length change and 95% confidence intervals (lower limit – upper limit). *P* values less than 0.05 were considered significant.

RESULTS

Eighteen healthy knees were included in this study (12 male, 6 female; age $35.4 \text{ years} \pm 10.9$ years (mean $\pm$ standard deviation); body height $175 \pm 9 \text{ cm}$; body weight $83.3 \pm 18.0 \text{ kg}$; BMI $27 \pm 3.5 \text{ kg/m}^2$). *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% CI, 32.5 to 35.4), and the ALL-Kennedy (i.e. posterior-proximal to the FCL) was 44.0 mm (95% CI, 41.8 to 46.2). The knees of the healthy subjects were slightly flexed during MR imaging, on average $2 \pm 3.5^\circ$.

Step-up motion (Figure 2, table 1)

The mean maximum flexion angle was $55 \pm 4^\circ$. The ALL-Claes showed a consistent, significant decrease in length with decreasing flexion; in total 21.2% (95% CI, 18.0 to 24.4) over $\sim 55^\circ$ of flexion ($P < 0.001$) as compared to the non-weight-bearing MR reference length. The ALL-Kennedy also showed a consistent, significant decrease in length with decreasing flexion; in total 24.3% (95% CI, 20.6 to 28.1) over $\sim 55^\circ$ of flexion ($P < 0.001$) as compared to the MR reference length.

Sit-to-stand motion (Figure 3, table 2)

The mean maximum observed flexion angle was $88 \pm 10^\circ$. Both the ALL-Claes and ALL-Kennedy showed a consistent, significant decrease in length; 35.2% (95% CI, 28.2 to 42.2, $P < 0.001$) and 39.2% (95% CI, 32.4 to 46.0, $P < 0.001$) respectively, over $\sim 90^\circ$ degrees of flexion as compared to the MR reference length. Length change from $\sim 90^\circ$ to 70° of flexion

accounted for 5.0% (95% CI, 3.3 to 6.8, $P<0.001$) and 6.0% (95% CI, 4.5 to 7.6, $P<0.001$) respectively, whereas 70° of flexion to full extension resulted in 30.1% (95% CI, 23.6 to 36.6, $P<0.001$) and 31.5% (95% CI, 25.4 to 37.7, $P<0.001$). Likewise, from ~90° to 45° of flexion, the ALL length decreased with 13.1% (95% CI, 9.0 to 17.2, $P<0.001$) and 14.5% (95% CI, 11.0 to 17.9, $P<0.001$); 45° of flexion to full extension resulted in an additional 22.0% (95% CI, 17.2 to 26.8, $P<0.001$) and 23.1% (95% CI, 18.1 to 28.1, $P<0.001$) decrease in length for the ALL-Claes and ALL-Kennedy respectively.

DISCUSSION

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

The non-isometric pattern of the ALL is in agreement with previous in vitro studies,^{1, 3, 4} and comparable length change of the ALL to our previous measurements during a quasi-static lunge were observed.²¹ Helito et al³, found that the ALL increased in length from full extension to 90°, with greater length increase from 60° to 90° than from 0° to 60°. These findings are in agreement with the study by Zens et al⁴, which found the ALL to be a non-isometric structure that increased in length with increasing knee flexion. However, these results are in contrast with the findings described by Dodds et al². In their study they found the ALL to be near isometric between 0° to 60° of flexion, and the ALL to shorten between 60° to ~90° of flexion. These differences in length change may be explained due to the different techniques for measurement of the ALL length change have been used in the cadaveric setting – e.g. forced neutral tibial flexion,³ unconstrained passive flexion,⁴ fixed knee flexion angle at 30°,¹² with^{1, 2} or without muscle loading conditions and with^{2, 12} 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,^{1, 2} and measurement based on highly elastic capacitive polydimethylsiloxane strain gauges technique.⁴ In the study by Helito et al³, the ALL insertion sites were marked with metallic spheres and the distance between the two spheres were 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 al²² reported on the length change of three 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 al²²) versus approximately 3-3 mm (Kennedy et al¹¹). This could suggest that a more posterior-proximal location changes the length change pattern drastically.

Previous studies have shown that anterolateral extra-articular injuries accompanying ACL tears are frequently seen, and can attribute to the different instability patterns seen after ACL injury.^{23, 24} Failure to recognize and manage concomitant injuries at the time of primary ACL reconstruction might result in persistent postoperative instability^{25, 26} and put the knee joint at risk of secondary damage.^{27,28} Persistent postoperative instability as revealed by a residual pivot-shift test has been reported in 25% of the patients.²⁹ Monaco et al³⁰ found that extra-articular reconstruction improved axial tibial rotation and stability during the pivot-shift test. Sonnery-Cottet et al²⁹ 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 extra-articular 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.³¹ These results are promising and demonstrate the possible benefits of adding an extra-articular reconstruction to the ACL reconstruction in order to better restore knee stability.

In our recent pilot study³² we found that non-anatomic extra-articular reconstructions showed more biomechanically favorable length change patterns (i.e. smaller length change percentage) compared to the ALL reconstruction therefore reducing the likelihood of graft stretch. However, only one functional activity - a single quasi-static leg lunge - was performed at discrete flexion angles. It is important to note that the anatomic ALL showed non-isometric behavior with increased length in deeper flexion angles. This means that more isometric, non-anatomic 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 two 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.³³ The ALL changed approximately 6% in length between ~90° to 70° of flexion. These data therefore suggest that anatomic ALL reconstruction might have to be performed beyond 70° of knee flexion. Graft tensioning at lower flexion angles potentially result 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 non-anatomic extra-articular attachment points with similar length change patterns to the native biomechanics.

Limitations

The ALL length was measured as the shortest distance between the attachments sites on the 3-D 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 original length) but rather an increase in the distance between two anatomical sites. We could not identify the ALL on the available 3-Tesla MR images, instead the detailed anatomic descriptions by Claes et al.⁷ and Kennedy et al.¹¹ 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.

Conclusion

The ALL was found to be a non-isometric structure during the step-up and sit-to-stand motion. The length of the ALL was approximately 35% longer at ~90° of knee flexion when compared to 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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Figure 1.

Lateral view of a 3-D knee model illustrating the anatomic anterolateral ligament (ALL) with the femoral attachment anterior-distal (Claes et al⁷) and posterior-proximal (Kennedy et al¹¹) with respect to the attachment of the fibular collateral ligament (FCL) at 90°, 30° of knee flexion and full extension - during the sit-to-stand motion. The tibial insertion is midway between Gerdy tubercle and the anterior margin of the fibula.

Figure 2.

The anterolateral ligament (ALL) length change (%) of intact knees as function of flexion (°) in eighteen healthy subjects during the step-up motion. The mean maximum flexion angle (MAX) was $55 \pm 4^\circ$. 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.

Figure 3.

The anterolateral ligament (ALL) length change (%) of intact knees as function of flexion (°) in eighteen healthy subjects during the sit-to-stand motion. The mean maximum flexion (MAX) was $88 \pm 10^\circ$. The red/solid line depicts the femoral attachment of the 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 (%)	<i>P</i> -value [†]	Accumulated length change (%)	ALL-Kennedy length change (%)	<i>P</i> -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°).