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In vivo biomechanics of cruciate ligament injuries

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CHAPTER

In vivo length changes of the anterolateral ligament and related extra-articular reconstructions

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Background: Based on little in vitro biomechanical data with considerable variability, both anatomic anterolateral ligament (ALL) and non-anatomic anterolateral reconstructions are performed to improve the stability of anterior cruciate ligament (ACL)-deficient patients. However, no in vivo biomechanical data are available, which is essential for safe and effective reconstruction techniques.

Purpose: To measure the theoretical length change patterns of the ALL and various anterolateral extra-articular reconstructions in healthy and ACL-deficient knees during in vivo weight-bearing flexion.

Study Design: Descriptive In Vivo Laboratory Study

Methods: Ten patients with an ACL injury in one knee and the contralateral side intact were included. Using MR and dual fluoroscopic imaging techniques, the changes in length of the ALL, **modelled** with its femoral attachment either anterior or posterior-proximal to the fibular collateral ligament (FCL) attachment, and non-anatomic extra-articular reconstructions were measured as a function of knee flexion, and compared between the intact and ACL-deficient knees.

Results: The ALL, with its femoral attachment anterior to the FCL attachment, showed a consistent length increase of approximately 50% from 0° to 90° of knee flexion. The length change of the ALL was 20% when its femoral attachment was placed posterior-proximal to the FCL. ACL deficiency did not affect ALL length.

An extra-articular reconstruction with the femoral attachment proximal to the lateral epicondyle and the tibial attachment on Gerdy's tubercle increased 15% in length from 0° to 60° and shortened at 90° of flexion. When the tibial fixation of the anatomical ALL with its femoral attachment posterior to the FCL was moved to Gerdy's tubercle, a 30% length increase over 90 degrees occurred, without the drop in length at 90°. A significant length increase of both theoretical reconstruction grafts was seen at 0° in ACL-deficient knees.

Conclusion: An anatomic ALL reconstruction as modelled based on recent anatomical studies was not isometric during in vivo knee flexion, and was not affected by ACL deficiency. The non-anatomic extra-articular reconstructions demonstrated more biomechanically favorable length change patterns with the smallest percent increase in elongation during knee flexion.

Clinical Relevance: This study presents the first in vivo biomechanical data on the ALL, both in healthy and ACL-deficient knees, and provides surgical information for restoring normal anterolateral stability.

INTRODUCTION

Several studies have documented the anterolateral ligament (ALL) in cadaveric knees and its possible role in controlling rotational stability, together with the anterior cruciate ligament (ACL). Most researchers agree, based on the anatomic location and some exploratory cadaveric testing, that the ALL might be an important stabilizer of internal tibial rotation.^{2, 4, 11, 16, 19, 22, 23, 27, 30} However, the actual length change pattern of the ALL, and thus the flexion angle at which the ALL might perform its stabilizing function, remain unclear. According to the measurements by Dodds et al., the ALL was close to isometric between 0° and 60° of flexion, and shortened from 60° to 90° of flexion.⁴ In contrast, Zens et al. described the ALL as a non-isometric structure which increased in length with increasing knee flexion.³⁰ In the study by Parsons et al., the ALL was an important stabilizer of internal rotation at flexion angles greater than 35°.¹⁹ This is in conflict with the study by Saiegh et al., in which adding an ALL lesion in ACL-deficient cadaveric knees did not increase tibiofemoral instability in any of the testing conditions.²⁰

Given the considerable discrepancy between these *in vitro* measurements, it is not surprising that the recommendations for surgical restoration of anterolateral knee stability vary widely as well. Some groups have advised securing the ALL tenodesis in extension,²¹ others argued for tensioning and fixation of the ALL graft at 90° of flexion,³⁰ yet others have reasoned against performing an anatomic ALL reconstruction altogether.^{10, 12, 22} Based on possible unacceptable graft strains at higher knee flexion¹² and overconstraining the lateral compartment,¹⁰ the traditional, non-anatomic lateral extra-articular reconstructions might actually be biomechanically more favorable and more effective at controlling anterolateral laxity than an anatomic ALL reconstruction.^{12, 22}

A possible explanation for the above-mentioned contradictory biomechanical results and recommendations for anterolateral reconstruction might be the variability in the anatomic landmarks used for ALL measurement in the cadaveric studies – more specifically the femoral attachment of the ALL. Some investigators reported that the femoral attachment of the ALL was anterior-distal with respect to the attachment of the fibular collateral ligament (FCL),^{2, 8, 28} while others described the femoral ALL attachment as more posterior and proximal of the FCL origin.^{4, 11, 16} Even minor shifts in position around the rotational axis of the femur would result in contrary ligament kinematic patterns.¹⁸ Another explanation might be that ligament kinematics are highly dependent on the loading conditions, and subsequent tibiofemoral biomechanics, of the knee during 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.²⁴ It is therefore difficult to extrapolate the biomechanical behavior of the ALL and related anterolateral reconstructions that were measured during variable loading conditions in cadaveric studies to the length change patterns that would be seen in the knees of either healthy or ACL-deficient patients during *in vivo* weight-bearing knee flexion.

The purpose of the present study was to measure the theoretical length change pattern of the ALL and various anterolateral extra-articular reconstructions in healthy knees and ACL-deficient knees during in vivo weight-bearing flexion of the knee using magnetic resonance (MR) and dual fluoroscopic imaging techniques.

MATERIAL AND METHODS

Patient Selection

Ten patients (six men and four women; age range 19-38 years old; active on a moderate athletic level before injury and with no previous abnormal condition of the knee or lower limb) with complaints of knee instability were included in the study. The patients had a diagnosis of an acute ACL rupture, as documented by clinical examination findings (8-mm Lachman test with weak end point and a grade 2 pivot-shift test) and findings of an isolated ACL tear on MR imaging. All patients had healthy contralateral knees. Patients had been injured within a mean $\pm$ SD of 4.5 ± 3 months of testing. Patients with injury to other ligaments, noticeable cartilage lesions, and injury to the underlying bone were excluded from the study. Six patients had no significant damage to the menisci, one patient had a partial-thickness tear of the lateral meniscus, and the remaining three patients had injuries requiring up to 30% removal of the lateral meniscus at time of ACL reconstruction. Five of these 10 patients were included in our previous studies of the 6 degrees-of-freedom tibiofemoral kinematics,³ elongation of the collateral ligaments,²⁶ and tibiofemoral cartilage contact deformation²⁵ in ACL deficiency.

Each patient signed a consent form that had been approved by our Institutional Review Board.

Imaging Procedure

The MR and dual fluoroscopic imaging techniques for the measurement of ligament kinematics have been described in detail previously.^{14,18, 26} Briefly, both the left and right knees were imaged with a MR scanner to create 3-dimensional (3-D) meshed models of the knees, using a protocol established in our laboratory.³ Patients were asked to lie supine, with the knee in a relaxed, extended position while sagittal plane images were acquired with a 1.5T MRI scanner (Siemens, Malvern, PA). The MR scanner was equipped with a surface coil and used a 3-D double-echo water excitation sequence (field of view 16 X 16 X 12 cm, voxel resolution 0.31 X 0.31 X 1.00 mm, repetition time [TR] 24 msec, echo time [TE] 6.5 msec, and flip angle 25°). Each scan lasted for approximately 12 minutes. The images were then imported into solid modeling software (Rhinoceros; Robert McNeel and Associates, Seattle, WA) to construct 3-D surface mesh models of the tibia, fibula and femur. The meshes were assembled using a point density of 80 vertices/cm² and triangular facets, with an average aspect ratio of 2. The attachment sites of the FCL were identified as

previously described and included in the 3-D knee model.²⁶ On these anatomical knee models the attachment sites of the anatomic ALL and theoretical extra-articular reconstructions were presented as points. The femoral attachment sites of the ALL were positioned based both on the description by Claes et al. (i.e. slightly anterior-distal with respect to the attachment of the FCL)² and the description by Kennedy et al. (posterior and proximal of the FCL origin).¹¹ 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.^{2, 11} A more proximal over-the-top (OTT) extra-articular reconstruction position was chosen based on the descriptions by Zarins and Rowe²⁹ and Kittle et al.¹² To minimize intra-subject variability in positioning the attachment sites for the ALL and extra-articular reconstructions, the 3-D model of the right knee was mirrored to create a "left" knee model. The mirrored right knee was then overlapped with the 3-D model of the left knee so that the attachment sites could be created on both knees simultaneously.²⁶

After the MRI-based computer models were constructed, both knees of each patient were simultaneously imaged using 2 orthogonally placed fluoroscopes (OEC 9800; GE Healthcare, Salt Lake City, UT) as the patient performed a single-leg quasistatic lunge at 0°, 15°, 30°, 60°, and 90° of flexion. At each flexion angle, the patient paused for 5 seconds while simultaneous fluoroscopic images were obtained. Throughout the experiment, the leg being tested supported the patient's body weight, while the other leg provided stability.

Next, the fluoroscopic images were imported into solid modeling software and placed in the orthogonal planes based on the position of the fluoroscopes during imaging of the patient. Finally, the 3-D MRI-based knee model of each patient was imported into the same software, viewed from the 2 orthogonal directions corresponding to the orthogonal 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 a reported error of <0.1 mm and 0.3° in measuring tibiofemoral joint translations and rotations, respectively.^{3, 15}

Measurement of Length Change of the ALL and Extra-Articular Reconstructions

The changes in length of the ALL and extra-articular reconstructions were measured as a function of knee flexion with several combinations of the tibiofemoral attachment points (Figure 1). The length of the ALL and theoretical grafts was defined as the shortest distance between the attachment site points. Because the structures wrap around the femoral condyles and the tibial plateau, a 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.^{14, 26} The length of this projected curve was measured as length of the ligament or theoretical graft. For the analysis of anatomic ALL length change, the tibial

point midway between the center of Gerdy's tubercle and the anterior margin of the fibular head was connected with either (1) the femoral point slightly anterior-distal with respect to the attachment of the FCL (Claes et al.)², or (2) the femoral point posterior and proximal to the FCL origin (Kennedy et al.)¹¹. For the analysis of theoretical non-anatomic extra-articular reconstruction grafts, the tibial point on Gerdy's tubercle was connected with

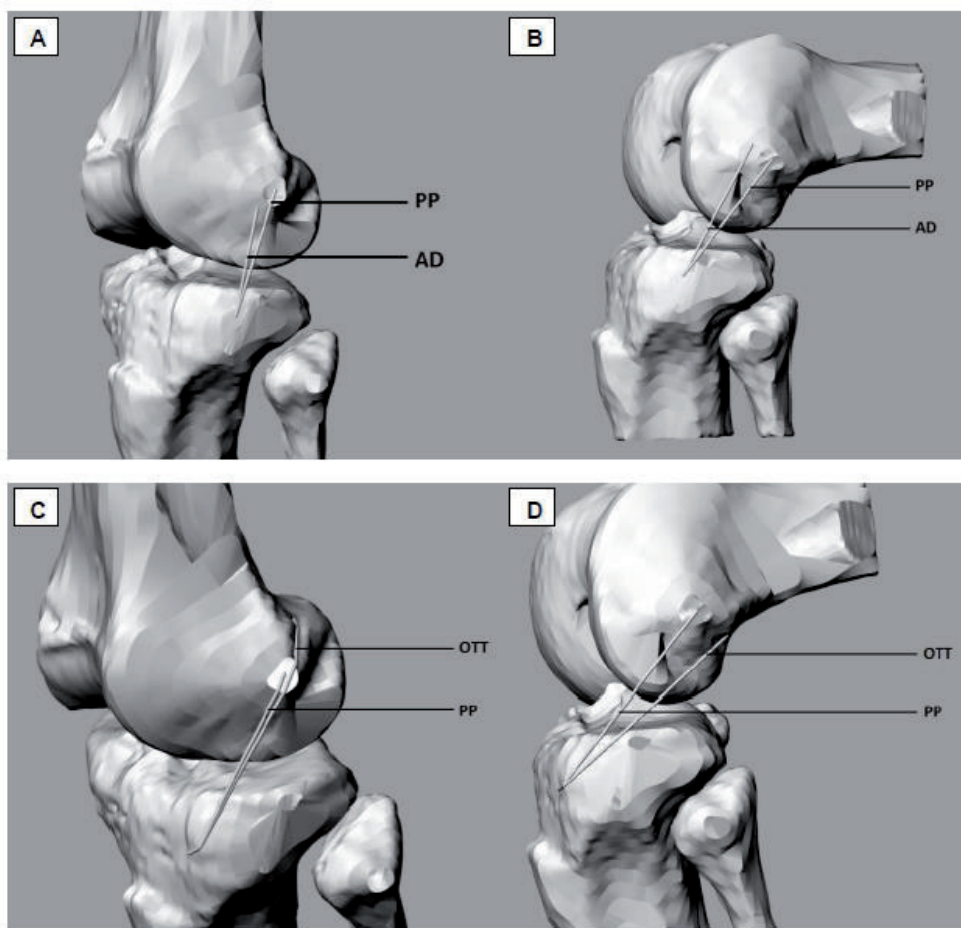


Figure 1. 3-D MR knee models illustrating the anatomic anterolateral ligament (ALL) with the femoral attachment anterior-distal (AD) and posterior-proximal (PP) with respect to the attachment of the fibular collateral ligament (FCL) at 0° (A) and 90° (B) of knee flexion; non-anatomic extra-articular grafts with the tibial attachment at Gerdy tubercle and with the femoral attachment over-the-top (OTT) and posterior-proximal (PP) with respect to the attachment of the FCL at 0° (C) and 90° (D) of knee flexion.

either (1) the more proximal OTT extra-articular reconstruction position on the lateral femur with the connecting curve always projected so that the theoretical graft intersected with the FCL, or (2) the femoral point of the ALL posterior and proximal to the FCL origin.

Statistical Analysis

Changes in the length of the anatomic ALL, based on the descriptions by both Claes et al.² and Kennedy et al.¹¹, and the theoretical extra-articular reconstruction grafts caused by flexion of the knee were examined using one-way analysis of variance with pairwise comparisons, having the Newman-Keuls procedure for multiple comparisons. A two-way repeated-measures analysis of variance and the Newman-Keuls post hoc test were used to determine statistically significant differences in length between the intact contralateral knees and the ACL-deficient knees at each flexion angle. *P*-values less than 0.05 were considered significant.

RESULTS

Anatomic ALL length change (Figure 2).

The ALL as described by Claes et al.² demonstrated a consistent, significant increase in length with increasing flexion, from 32.8 ± 2.5 mm at 0° to 48.5 ± 4.6 mm at 90° ($P < 0.001$). This increase was approximately a 50% increase over 90° of flexion. The ALL as described by Kennedy et al.¹¹ also showed a consistent increase with flexion, but with only a 20 % increase during knee flexion from 0° to 90° , from 40.0 ± 2.4 mm at 0° to 48 ± 3.6 mm at 90° of flexion ($P < 0.001$). ACL deficiency did not significantly affect the **length** in either group at any of the flexion angles.

Non-anatomic anterolateral reconstructions (Figure 3).

The OTT position on the femur, tunneled under the FCL, and attached to Gerdy's tubercle, resulted in only a 15% increase in length from 0° to 60° but then decreased again at 90° of flexion. In the OTT measurements, ACL deficiency did cause a significant length increase of the reconstruction around 0° (68.5 ± 2.9 mm versus 70.5 ± 2.4 mm in intact and ACL deficient knees, respectively, $P = 0.019$). When the anatomical ALL as described by Kennedy et al.¹¹ was modified by leaving the femoral point identical, but moving the tibia fixation to Gerdy's tubercle, a similar significant graft elongation effect of ACL deficiency was noticed at 0° of flexion (51 ± 2.1 mm versus 53.8 ± 2.2 mm in intact and ACL deficient knees, respectively, $P = 0.037$). A 30% increase in length over 90 degrees was seen, without the drop in length at 90° .

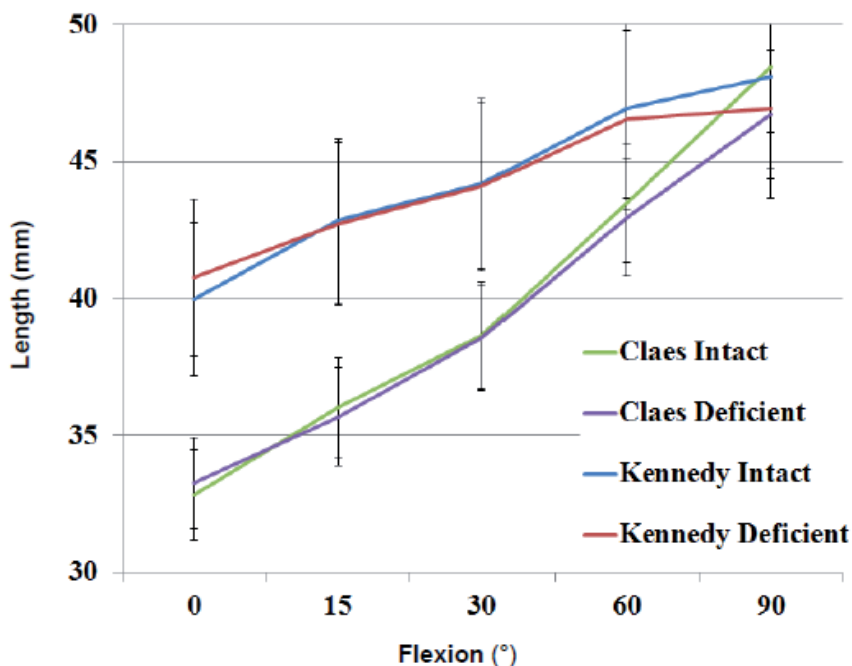


Figure 2. Anterolateral ligament (ALL) length (mm) in intact and anterior cruciate ligament (ACL)-deficient knees (femoral attachment of the ALL based on Claes et al.,² bottom lines; femoral attachment of the ALL based on Kennedy et al.,¹¹ top lines) as function of flexion (°) in 10 patients with acute, isolated rupture of the ACL. Values are mean $\pm$ SD.

DISCUSSION

The most important findings of this study were that the ALL was not isometric between any of the flexion angles and was not affected by ACL deficiency, and that the non-anatomic extra-articular reconstructions demonstrated more biomechanically favorable length change patterns with the smallest percent length increase during knee flexion. There are several recent studies that have elucidated the anatomy and biomechanical role of the ALL in cadaveric knees. Based on these *in vitro* data, reconstruction techniques are proposed to improve anterolateral stability in ACL-deficient knees. However, there is an ongoing debate on what might be the most optimal reconstruction, due to the variability in the results of these cadaveric studies. The present study is the first *in vivo* biomechanical analysis of the ALL and related anterolateral reconstructions. We described the length change patterns of the anatomic ALL and various non-anatomic anterolateral extra-articular reconstructions in

healthy and ACL-deficient knees during in vivo weight-bearing flexion, using combined MR and dual fluoroscopic imaging techniques.

In the present study, the ALL as described by the Claes et al.² was not isometric between any of the flexion angles, as was believed based on some cadaveric work.⁴ This finding is consistent with the in vitro study by Kittl et al., which measured a similar length increase of the ALL from full extension to 90° of flexion of 19%.¹² However, in the present study, the length increase of the ALL during in vivo weight bearing was actually closer to 50% at 90° of flexion. Such increase during knee flexion suggests that an anatomic reconstruction of this structure as described at this femoral attachment might likely be biomechanically unfavorable. Specifically, an anatomic ALL graft with its femoral fixation slightly anterior and distal to the attachment of the FCL would be either slack in extension, where it is intended to correct rotational instability,^{1, 5} or too tight in flexion, potentially causing

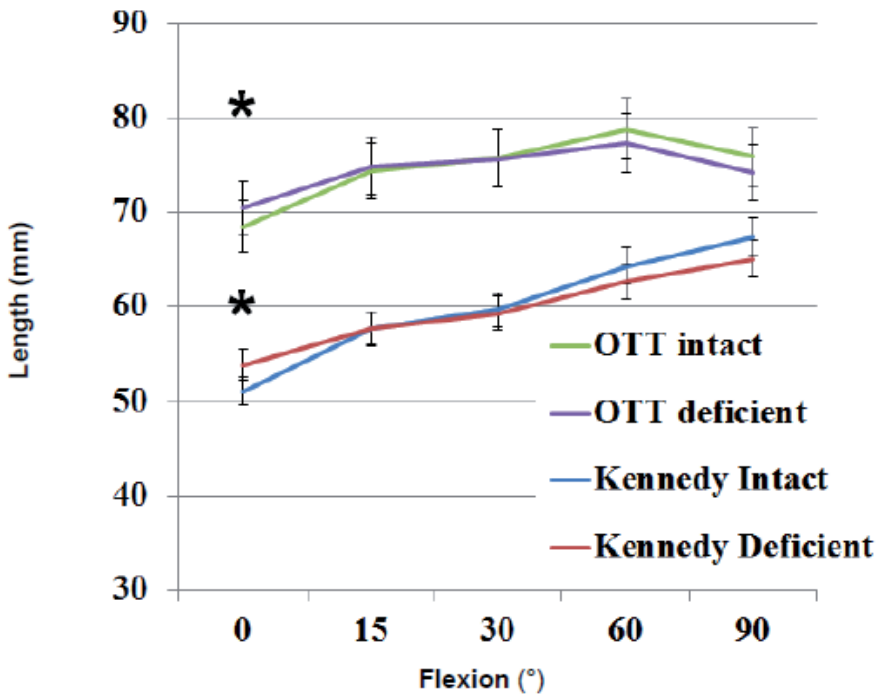


Figure 3. Length of non-anatomic extra-articular reconstructions (mm) in intact and anterior cruciate ligament (ACL)-deficient knees with the tibial attachment on Gerdy tubercle and the femoral attachment over-the-top proximal to the lateral epicondyle (OTT, top lines) and femoral attachment posterior to the FCL (modified Kennedy, bottom lines) as a function of flexion (°) in 10 patients with acute, isolated rupture of the ACL. Values are mean $\pm$ SD. * = $P < 0.05$

overconstraint of the lateral compartment. Interestingly, when the femoral attachment of the anatomic ALL was moved only a few mm posterior and proximal to the FCL attachment, as described in the anatomic study by Kennedy et al,¹¹ the same length change pattern persisted, but with only a 20 % increase during knee flexion from 0° to 90°.

The length change patterns of the non-anatomic extra-articular reconstructions that were modelled on the 3-D models of healthy knees in the present study demonstrated more biomechanically favorable behavior, analogous to the in vitro biomechanical benefits of the traditional extra-articular reconstructions described several decades ago.^{6, 7, 17} Particularly, the theoretical graft attached to Gerdy's tubercle, tunneled under the FCL and attached proximally to an OTT position showed only a 15% length increase from 0° to 90° of flexion. This finding corroborates the conclusion of the recent biomechanical study by Spencer et al. in which it was not an anatomic ALL reconstruction, but rather a non-anatomic lateral extra-articular tenodesis which was able to control both anterior and rotational laxity.²² However, this graft reconstruction would be simultaneously the longest reconstruction, therefore possibly resulting in a less stiff reconstruction. In addition, there might be concern about interference of the OTT graft tenodesis with the femoral tunnel of the ACL reconstruction. An alternative to the OTT reconstruction, based on the present findings, would be to modify the anatomic ALL reconstruction based on the description by Kennedy et al,¹¹ by leaving the femoral point identical but moving the tibia fixation anteriorly to Gerdy's tubercle. This reconstruction was slightly less isometric than the OTT reconstruction, but could be performed with a shorter, hence stiffer, graft and would evade the possible interference with the femoral tunnel of the ACL reconstruction.

Because anatomic ALL and non-anatomic extra-articular reconstructions are intended to control the anterolateral subluxation of the tibia seen in some ACL-deficient patients, we determined which of the length change patterns of the various reconstruction options were affected by ACL deficiency, thereby indirectly indicating which reconstruction option would have the capability at offering the most efficient control of the kinematic changes seen in ACL deficiency. In the present study, ACL deficiency did not affect the anatomic ALL length at any of the flexion angles. It should be noted that an effect of ACL deficiency might have been noticed if forced internal rotation or during pivot maneuvers were tested rather than knee flexion in neutral rotation.^{16, 19} Interestingly though, ACL deficiency did cause a significant increase in graft length at 0° of flexion in the non-anatomic theoretical reconstruction grafts during the loading condition used in the present study. This finding could be explained by the altered angle of the graft on the tibia, hereby exacerbating the effect of the minor increase in internal rotation that is seen in ACL deficient knees during weight-bearing flexion.

We acknowledge some limitations to this study. We acquired data during only one functional activity, a single leg lunge. Other in vivo activities such as walking and stair climbing should be considered in future studies. In the present study, we measured the

length of the ALL and related extra-articular reconstructions as the shortest distance between the attachment site points on the 3-D models projected to the bony surfaces. These data cannot be directly related to ligament strains because the reference lengths of the ligaments (zero-load length) are unknown. On the available 1.5T MR images, we could not identify the ALL, and by no means its precise attachment anatomy, with the same certainty as described by others.^{9, 13} We therefore used the meticulously performed anatomic descriptions by Claes et al.² and Kennedy et al.¹¹ instead to position the ALL attachment sites on the 3-D knee models. In addition, no actual non-anatomic reconstructions were performed in this study. Rather, the length measurements for these reconstructions were performed between theoretical points as proposed in previous studies.¹² As mentioned above, weight bearing flexion of the knee was performed with the foot in neutral position. We could therefore not assess what the effect of forced internal rotation would be on the elongation behavior of the ALL.

As the presented data were obtained during only one functional *in vivo* activity—namely, the single leg lunge—we advise caution when extrapolating the data to other functional activities. Nevertheless, we believe that these findings might be useful for the design of improved treatment protocols for anterolateral instability in ACL deficient patients. On the basis of our data, it could be theorized in future studies that for optimal anterolateral reconstructions one could choose either an OTT to Gerdy's tubercle reconstruction fixed at 60° of flexion (i.e., the smallest percent length increase, but longer graft hence less stiff reconstruction, with a drop at 90° of flexion, and possible interference with ACL tunnel), or a modified ALL reconstruction (i.e., femur attachment proximal and posterior to the FLC attachment and tibia attachment at Gerdy's, fixed at 90°) with slightly less isometry, but without the drop in length at 90°, no risk of interference with the ACL tunnel, and a shorter graft.

In conclusion, this study presents the first *in vivo* data on the ALL and related anterolateral reconstructions, both in healthy knees and ACL-deficient knees. The anatomic ALL reconstruction was not isometric between any of the flexion angles, and was not affected by ACL deficiency. The non-anatomic extra-articular reconstructions showed more biomechanically favorable length change patterns with the smallest percent increase in length during knee flexion.

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