Mapping isometry and length changes in ligament reconstructions of the knee

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Chapter 6

An in vivo simulation of isometry of the anterolateral aspect of the healthy knee

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ABSTRACT

Background: To assess the isometry of theoretical lateral extra-articular reconstruction (LER), we evaluated theoretical grafts attached to various points on the lateral femoral condylar area and to either Gerdy's tubercle or the anatomic attachment site of the anterolateral ligament to the tibia.

Methods: In 18 subjects, healthy knees with no history of either injury or surgery involving the lower extremity were studied. The subjects performed a sit-to-stand motion (from approximately 90° of flexion to full extension), and each knee was studied using magnetic resonance and dual fluoroscopic imaging techniques. The 3-dimensional wrapping paths of each theoretical LER graft were measured. Grafts showing the least change in length during the sit-to-stand motion were considered to be the most isometric.

Results: The most isometric attachment site on the lateral femoral epicondyle to either of the studied tibial attachment sites was posterior-distal to the femoral attachment site of the fibular collateral ligament. The LER graft had a mean change in length of approximately 3%. Moving the femoral attachment site anteriorly resulted in increased length of the graft with increasing flexion; more posterior attachment sites resulted in decreased length with increasing flexion. Moving the attachment site in the proximal-distal direction had a less profound effect. Moving the tibial attachment site from Gerdy's tubercle to the tibial attachment site of the anterolateral ligament affected the overall isometric distribution on the lateral femoral epicondyle.

Conclusions: The most isometric attachment site on the femur for an LER would be posterior-distal to the femoral attachment site of the fibular collateral ligament. Different length changes for LER grafts were identified with respect to different femoral attachment sites. Desirable graft fixation locations for treating anterolateral rotatory instability were found posterior-proximal to the femoral fibular collateral ligament attachment.

Clinical Relevance: The present data could be used both in biomechanical studies and in clinical studies as guidelines for planning LER surgical procedures.

INTRODUCTION

Recent anatomic studies on the anterolateral aspect of the knee have created renewed interest in lateral extraarticular reconstruction (LER) of knees that have a torn anterior cruciate ligament (ACL).[13, 19, 28, 32, 35] Historically, the LER procedures were tried but were abandoned because of clinical failures.[30] However, an LER theoretically has appeal, as it is peripheral to the center of rotation of the knee and therefore has a lever arm to constrain excess rotatory laxity. The combined LER and intra-articular ACL reconstruction might therefore be able to better control excessive internal rotation of knees and reduce intra-articular forces on ACL grafts. However, there are few data on the biomechanical behavior of these extra-articular reconstructions, especially with respect to isometry.[8, 13, 16, 19, 21 22, 34] Information on this behavior is clinically relevant, enabling proper placement of the graft.

In the in vitro setting, different femoral attachment sites were believed to result in isometric or desirable patterns in length changes.[8, 13, 16, 21, 22, 34] These different results in the cadaveric experiments may be explained by the variety of methods used. Tibiofemoral biomechanics are highly dependent on the muscle-loading conditions of the knee. Length changes between points are highly sensitive to minor shifts in position around the rotational axis of the femur.[29] Even the most advanced in vitro experiments are limited by the difficulty in simulating the complex physiological loading conditions that occur during weight-bearing flexion of the knee.[39] Therefore, care should be taken when translating the in vitro biomechanical measurements during variable loading conditions to the results that would be seen in the knee during in vivo weight-bearing motion. Previously, we measured the theoretical length changes of the anterolateral ligament and 2 nonanatomic LERs during in vivo weight-bearing flexion.[18, 40] The anterolateral ligament was a nonisometric structure that showed a consistent length increase, up to 50%, from 0º to 90º of knee flexion. The nonanatomic LER showed length changes up to 15%. These results are promising and demonstrate the potential benefits of adding an LER to the intra-articular ACL reconstruction to better restore knee laxity and intra-articular graft forces. However, the most isometric point in vivo and most desirable length changes in vivo remain unknown and could improve current surgical techniques.

Therefore, the purpose of this study was to determine the in vivo isometry between various femoral attachment sites and 2 tibial attachment sites: Gerdy's tubercle and the anterolateral ligament attachment. This isometry was determined in healthy subjects during a dynamic sit-to-stand weight-bearing motion.

METHODOLOGY

Patient Selection

This study was approved by our institutional review board. Written consent was obtained from all subjects prior to participation in this study. In 18 subjects, healthy knees with no history of injury or surgery involving the lower extremity (12 male and 6 female subjects; mean age [and standard deviation], 35.4 ± 10.9 years; mean height, 175 ± 9 cm; mean weight, 83.3 ± 18.0 kg; and mean body mass index [BMI], 27 ± 3.5 kg/m2) were analyzed in the study. These subjects were included in our previous study on changes in the length of the anterolateral ligament.[18]

Imaging Procedures

The magnetic resonance imaging (MRI) and dual fluoroscopic imaging techniques for the measurement of ligament kinematics have been described in detail previously.[20, 38] MRI scans of the knee joints were performed in the sagittal plane using a 3-T MRI scanner (MAGNETOM Trio; Siemens Healthcare) with a double-echo water-excitation sequence (thickness, 1 mm; resolution, 512 × 512 pixels).[6] The images were then imported into solid-modeling software (Rhinoceros; RobertMcNeel & Associates) to construct 3-dimensional (3D) surface-mesh models of the tibia, fibula, and femur. The attachment sites of the fibular collateral ligament were identified as previously described and were included in the 3D model.[38]

After the MRI-based computer models were constructed, the knee of each subject was simultaneously imaged using 2 fluoroscopes (BV Pulsera; Philips) as the patient performed a sit-to-stand motion (from approximately 90° of flexion to full extension). Next, the fluoroscopic images were imported into solid-modeling software and placed in the imaging planes based on the projection geometry of the fluoroscopes during imaging of the patient. Finally, the 3D MRI-based knee model of each subject was imported into the software, viewed from the directions corresponding to the source of fluoroscopic radiation used to acquire the images, and independently manipulated in 6 degrees of freedom in the software until the projections of the model matched the outlines of the fluoroscopic images. When the projections best matched the outlines of the images taken during in vivo knee motion, the positions of the models were considered to be reproductions of the in vivo 3D positions of the knees. This system has errors of <0.1 mm and 0.3° in measuring tibiofemoral joint translations and rotations, respectively.[6, 23, 24]

Tibial and Femoral Attachment Sites

To determine the in vivo lengths of theoretical LERs during motion, various femoral attachment sites and 2 tibial attachment sites—the center of Gerdy's tubercle and the anterolateral ligament attachment (midway between Gerdy's tubercle and the anterior margin of the fibular head)—were used.[4, 17] To account for the geometric variations between knees, all 3D knee models were scaled using the anteroposterior borders of the lateral femoral condyle to the mean anteroposterior length (66.1 mm). Next, the right femoral models were mirrored to the left models with respect to the sagittal plane. Thereafter, the scaled and mirrored 3D models were aligned to find the best-fit position with respect to the lateral femoral condyle using a surface-to-surface registration method.[37] This process resulted in a mean average error of 0.9 ± 0.3 mm between models. An average femoral model was constructed from the scaled, mirrored, and aligned 3D models. The average model was then used to construct a transepicondylar axis (connecting the medial and lateral femoral epicondyles).[27] The direction of the transepicondylar axis of the average 3D femoral model was used to project 156 femoral attachment points to the individual scaled, mirrored, and aligned 3D models. The region of interest for the femoral points was determined by the data from previously published in vitro studies.[8, 19, 21, 34] Approximately the posterior half of the lateral femoral epicondyle was used to project the points to the 3D model with 2.5mm of spacing (Fig. 1). Once the femoral attachment points were determined on each femoral model, the scaled and mirrored 3D models with the projected attachment points were restored to the original coordinates for the measurement of individual graft lengths.

Length-Change Measurements

The length changes for each theoretical graft were measured as a function of knee flexion. The direct line connecting the femoral and tibial attachment points was projected on the osseous surfaces to create a curved line to avoid penetration of the connecting line through bone (a wrapping path). An optimization procedure was implemented to determine the projection angle to find the shortest 3D wrapping path at each flexion angle of the knee. This technique has been described in previous studies for measurement of ligament kinematics.[20, 29, 38] The length of the projected line (curved around the osseous surfaces) was measured as the length of the ligament. For each subject, the length-change data were normalized to percentage change by using the reference length of each tibiofemoral graft from the relaxed, non-weight-bearing MRI position (MR): (length – length MR)/length MR × 100%. A heat map was created to provide visual representation of the isometry distribution over the lateral femoral epicondyle by using the mean maximum percentage length change minus the mean minimum percentage length change of each theoretical tibiofemoral graft during the sit-to-stand motion.

Quadrant Method

A true lateral view of the femur was established at 90º of flexion. A 4 × 4 grid was applied to the lateral femoral epicondyle using a line extended along the posterior cortex of the distal femoral shaft and the posterior condylar offset line (PCOL). This technique has been used in other studies and was found to have intraobserver and interobserver reliabilities of 0.899 and 0.882, respectively.[14] Next, lines perpendicular to the PCOL were drawn to the proximal condylar cartilage border and the osseous femoral joint line, and 3 lines were drawn in between to create an evenly distributed grid (Fig. 2). Similar to the intraarticular quadrant method developed by Bernard et al.,[3] the current method used 4 distances, including condylar width perpendicular to the PCOL with the extended posterior cortex line as border (distance x), sagittal diameter along the PCOL (distance y), distance from the femoral attachment site to the anterior border along line x (distance Δx), and distance from the femoral attachment site to the proximal border along line y (distance Δy). Distances Δx and Δy were expressed as percentages of x and y.

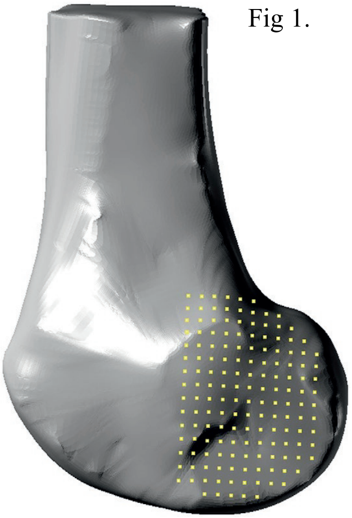

Fig 1.

Fig. 2

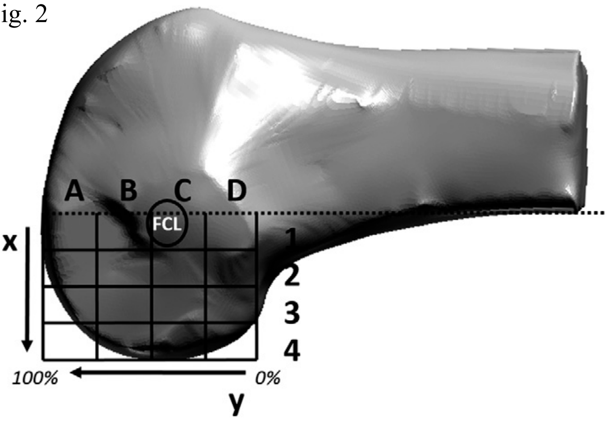

Fig. 1 Lateral view of a 3D femoral model showing the distribution of the femoral attachment sites (dots). Various femoral attachment sites were connected to either Gerdy's tubercle or the tibial attachment site of the anterolateral ligament (midway between Gerdy's tubercle and the fibular head). **Fig. 2** Lateral view of a 3D femoral model in 90º of flexion. A 4 × 4 grid was applied to the lateral femoral epicondyle. A line extended along the posterior cortex of the distal femoral shaft was used as a landmark for the anterior border of the grid, and the PCOL formed the posterior border. The proximal and distal borders were formed by the proximal condylar cartilage border and the osseous femoral joint line, respectively. Distal to proximal: A to D. Anterior to posterior: 1 to 4. Line x: maximum distance perpendicular to the PCOL to the posterior edge of the lateral condyle. Line y: maximum distance from the proximal condylar cartilage border to the osseous femoral joint line. FCL = fibular collateral ligament.

RESULTS

Isometric Point

The mean maximum observed flexion angle during the dynamic sit-to-stand motion was 88º ± 10º.

The most isometric femoral attachment site of the theoretical LER grafts that connected to Gerdy's tubercle was found to be posterior-distal to the femoral fibular collateral ligament attachment site; on average, it was 57% distal and 39% posterior, with a mean length change of 2.2% (95% confidence interval [CI], 1.8% to 2.6%).

When the LER was connected to the anterolateral ligament attachment, the most isometric femoral attachment site was found to be slightly more proximal-anterior to the point described above; on average, it was 50% distal and 31% posterior, with a mean length change of 3.3% (95% CI, 2.9% to 3.7%) (Fig. 3).

Posterior to the femoral fibular collateral ligament attachment site, a zone in the proximal-distal direction (the blue area on the femoral condyle in Fig. 3) demonstrated the lowest percentage change in length during the sit-to-stand motion when connected to Gerdy's tubercle. When connected to the anterolateral ligament attachment, the most isometric zone had a slightly oblique direction from posterior-distal to proximal-anterior.

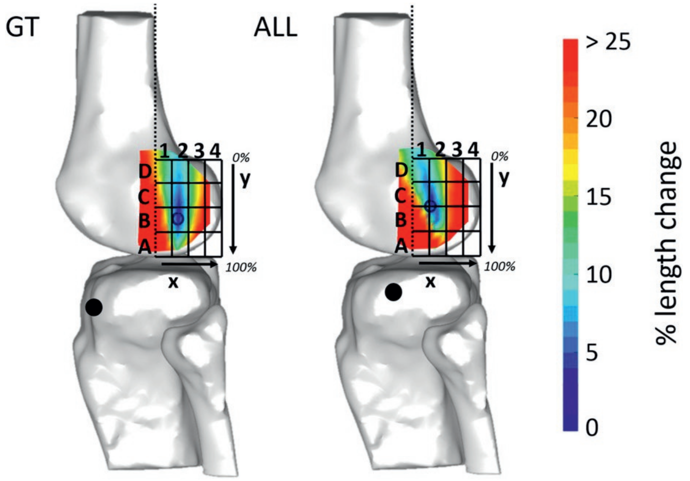

Fig. 3 Heat map illustrating the isometry distribution (mean maximum percentage length change – minimum percentage length change) over the lateral femoral epicondyle for single point-to-point curves when connected to Gerdy's tubercle (GT) or the tibial attachment site of the anterolateral ligament (ALL) during the dynamic sit-to-stand motion. The circle on the femur represents the most isometric attachment site (a 2.2% length change for Gerdy's tubercle and a 3.3% length change for the tibial attachment site of the ALL).

Femoral and Tibial Attachment Sites

Altering the femoral attachment site in the anterior-posterior direction affected the length changes, irrespective of the tibial attachment site (Fig. 4). The areas located anterior to the most isometric zone resulted in increased graft lengths with increased flexion angles; more posteriorly located areas resulted in decreased length with increased flexion. Moving the femoral attachment site in the proximal-distal direction had a less profound effect on the length changes (Fig. 5). Moving the tibial attachment site from Gerdy's tubercle to the anterolateral ligament attachment changed the overall isometric distribution on the lateral femoral epicondyle (Fig. 3). Comparable length changes could be found with respect to the most isometric zone (Fig. 6).

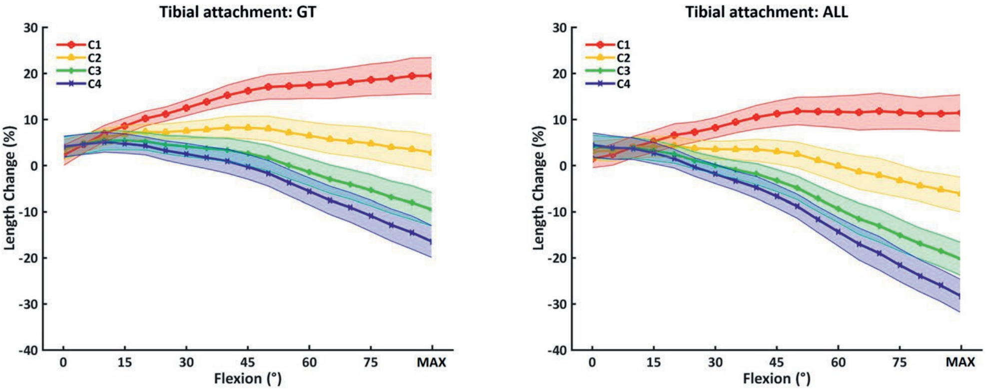

Fig. 4 Normalized length changes in percentage of area (C1 [anterior], C2 [middle anterior], C3 [middle posterior], and C4 [posterior]) during the dynamic sit-to-stand motion when connected to Gerdy's tubercle (GT; left) or the tibial attachment site of the anterolateral ligament (ALL; right). The mean maximum flexion angle (MAX) was 88° ± 10°. Mean values are shown, with the shaded area indicating the 95% CI.

Graft Length Changes

LER grafts that exhibited the least change and a tight (long) graft during early knee flexion (from full extension to 45º) and a slack (short) state during deep knee flexion (from 45º to approximately 90º) were found in the posterior-proximal area: C3-4 and D3-4 for Gerdy's tubercle, and C2-3 and D3-4 (using the quadrant method) for the anterolateral ligament attachment (Fig. 6).

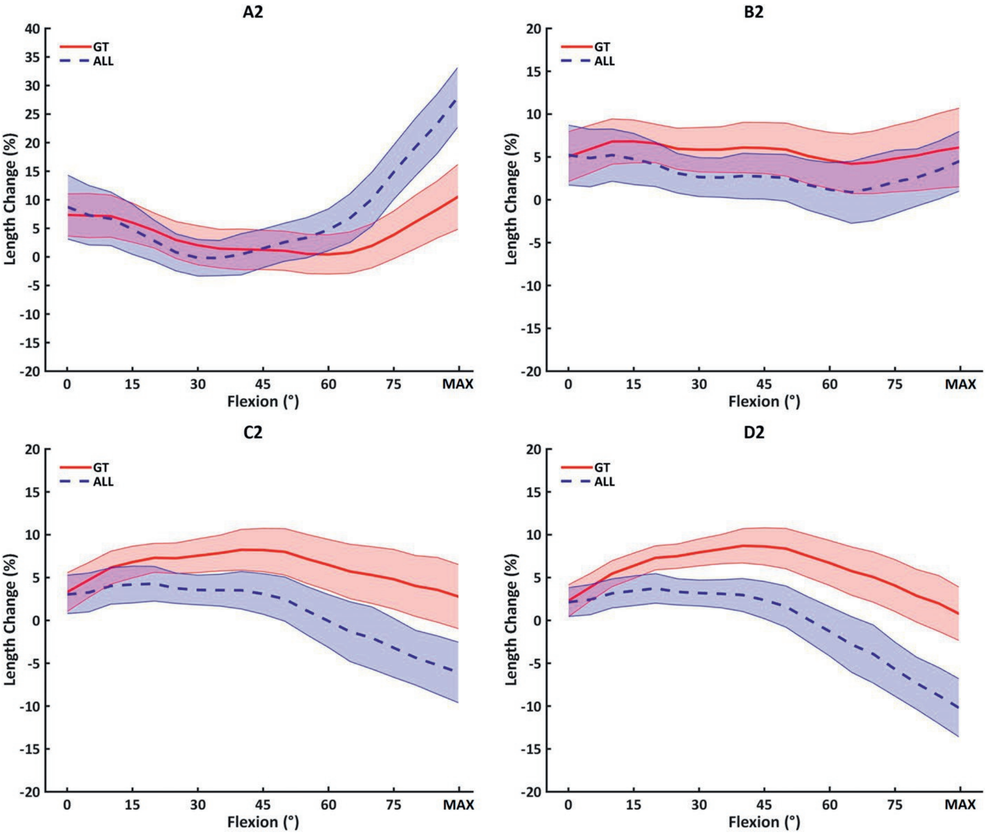

Fig. 5 Normalized length changes in percentage for healthy knees in the proximal-distal direction (A2 to D2) during the dynamic sit-to-stand motion. The mean maximum flexion angle (MAX) was 88º ± 10º. The dashed and solid lines represent the theoretical tibiofemoral grafts connected to Gerdy's tubercle (GT) and the tibial attachment site of the anterolateral ligament (ALL), respectively. Mean values are shown, with the shaded area indicating the 95% CI.

DISCUSSION

The most important finding in this study was that the most isometric location for a theoretical LER graft on the lateral femoral epicondyle was posterior-distal to the femoral fibular collateral ligament attachment site. This was true for both of the tibial attachment sites studied, Gerdy's tubercle and the attachment site of the anterolateral ligament. A graft in this position underwent a length change of approximately 3% during approximately 90º of active knee flexion. A zone, mainly in the proximal-distal direction, was found to show the lowest percentage length change during motion from full extension to approximately 90º of flexion. On the basis of Fig. 3, one might conclude that the most isometric femoral attachment site is in the region of the popliteus sulcus, and thus, an LER at this point might interfere with the popliteus tendon. Desirable length changes for LER, in which a tight graft in early knee flexion and a slackened graft in deep flexion were observed, were located in the posterior-proximal area of the lateral femoral epicondyle. Moving the tibial attachment site changed the overall isometry distribution on the lateral femoral epicondyle.

Several cadaveric studies have been published on the isometry of extra-articular reconstructions attached to the lateral femoral condyle.[9, 13, 16, 19, 21, 22, 34] The findings of the current study are most consistent with those of the cadaveric studies by Draganich et al.[8] and Ankri et al.,[2] in which the most isometric point was posterior-distal with a mean length change of 2% to 6% and 4.3%, respectively. Similar to the authors of previous cadaveric studies,[2, 8] we found that the most isometric zone (demonstrating the least overall length change) was posterior to the fibular collateral ligament attachment site and ran mainly in

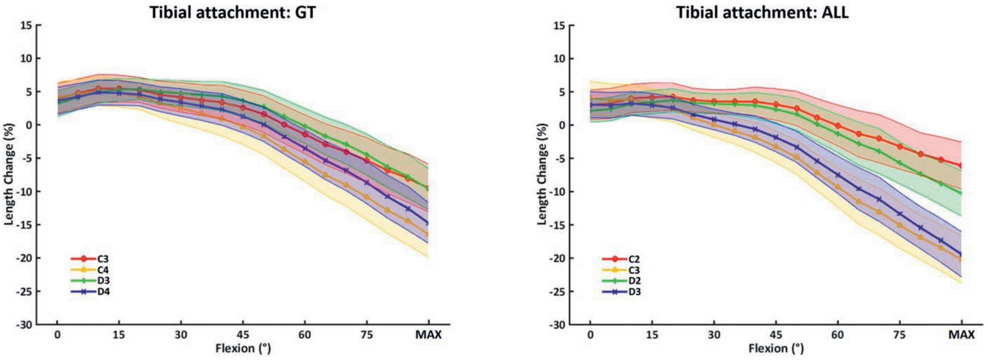

Fig. 6 Desirable changes in graft length (tightness in extension and lower flexion angles, and not limiting the range of motion in deeper flexion) could be found in the posterior-proximal area of the lateral femoral epicondyle. Similar patterns in graft-length change were found with respect to the most isometric zone (areas C3-4 and D3-4 when connected to Gerdy's tubercle [GT; left] as well as C2-3 and D2-3 for the tibial attachment site of the anterolateral ligament [ALL; right]). The mean maximum flexion angle (MAX) was 88º ± 10º. Mean values are shown, with the shaded area indicating the 95% CI.

the proximal-distal direction. Sidles et al.[34] found the most isometric attachment site to be directly posterior to the fibular collateral ligament and the most isometric zone to be more posterior. These differences may be explained not only by the kinematic difference between in vitro and in vivo loading of the knee but also by the different way that their data were normalized ([maximum length – minimum length]/[maximum length + minimum length]); also, the wrapping effect of the tibiofemoral curves was not considered in their study. In the present study, moving the femoral attachment sites in the anterior direction caused changes in which increased flexion resulted in increased length, whereas more posteriorly located points resulted in decreased length with increased flexion. This phenomenon is in agreement with findings of the most recent cadaveric studies by Imbert et al.[13] and Katakura et al.,[16] which measured the isometric characteristics and graft tension, respectively, of 3 different anterolateral ligament locations on the femur.

The rate of injury to the extra-articular structures of the knee at the time of the primary ACL tear has been found to be as high as 90%.[11, 36] It is thought that the combination of an intra-articular ACL tear with injury to anterolateral extraarticular structures might be responsible for the severe rotatory instabilities that can be seen in the clinic.[11, 26, 36] Unaddressed injury to secondary stabilizers may put the knee at risk for persistent postoperative rotatory instability[15] and consequently secondary injuries such as meniscal and chondral lesions, increased failure rates, and early cartilage degenerative changes. The combined LER and ACL reconstruction might be able to better restore anterolateral rotatory instability to normal in some patients,[41] and improve the tensile strength of the reconstruction, decreasing excessive loads through the ACL graft,[9, 10] potentially protecting the ACL graft during the healing phase[35] and subsequently reducing graft failure and recurrence rates.[12, 25]

A minimum degree of isometry reduces the likelihood of unwanted graft behavior, such as graft stretching, failure, and overconstraint of the lateral compartment.[1] In the normal knee, with increased knee flexion angles, internal tibial rotation also increases.[31] Thus, a certain degree of isometry is necessary to reduce undesirable graft behavior, but a true isometric reconstruction technique might overconstrain the knee during deeper flexion angles. Therefore, the ideal LER would provide internal rotatory constraint in lower flexion angles, extension, and slacken at increased flexion angles. Hence, the nonisometric behavior of the anterolateral ligament, with its increased length at increased flexion angles makes it unsuitable for reconstruction. This unsuitability was recently confirmed in the study by Schon et al.,[33] in which anterolateral ligament reconstruction overconstrained knee joint kinematics compared with the native knee at all fixation angles.

Functional length of the graft (determined by its proximal and distal fixation) is an important variable in any reconstruction. Stress-strain curves are characterized by a nonlinear toe region and a linear region. Long grafts have a greater elongation under the same load compared with short grafts for both nonlinear and linear regions; decreasing the length of a graft linearly increases its stiffness.[5] The fixation sites of the graft in LER determine the effective lengths of the graft and thus play an important role in the kinematic response of the knee.

The femoral attachment site directly affects the effective graft length and length changes that occur during knee motion. Moving the femoral attachment site in the anterior-posterior direction results in considerable length changes during motion, whereas alteration in proximal-distal direction has a less profound effect (Fig. 5). If one wanted to achieve a tight (long) graft in extension and a slack (short) graft in flexion, a femoral location posterior-proximal to the fibular collateral ligament attachment would be chosen; to achieve a tight graft in increased flexion, a more anterior location would be chosen (Fig. 4). Moving the tibial attachment site changes the effective graft length and changes the isometry distribution. In addition, the tibial attachment site affects the angle of the graft vector. A more anterior tibial attachment site (e.g., Gerdy's tubercle) holds a mechanical advantage over a posterior site (e.g., the anterolateral ligament attachment) for limiting internal rotation.

Limitations

There are several limitations to this study. Only data from healthy knees during 1 functional activity were used. Future research should also consider knees with a torn ACL and more demanding in vivo functional activities, such as lunging, walking, and running. No pivoting motion was performed in this study and, thus, the effect of rotational moments could not be assessed. Caution should be taken when translating the length changes as observed in this study to actual LER. No reconstruction was performed in the current study. Therefore, no actual restraint due to LER was present. Kinematics, and consequently length changes, could be altered if an LER had been performed. Finally, tunneling grafts deep to the fibular collateral ligament was not considered in this study.

Nevertheless, we believe that the findings of this study offer data that can be used to optimize LER techniques. Future studies should focus on the biomechanical effects of combining LER with ACL reconstruction and should investigate whether the most isometric graft, or a graft that is tight in extension and slack in flexion, would best restore laxity in a knee with a torn ACL.

Conclusions

In summary, the most isometric attachment site on the femur for an LER would be posterior-distal to the femoral attachment site of the fibular collateral ligament. Moving the femoral attachment site anteriorly resulted in increased length of theoretical LERs with increased flexion, whereas more posteriorly attachments resulted in decreased length with increased flexion angles. Desirable graft-fixation locations, stabilizing the knee at low flexion angles but not overconstraining the knee at high flexion, were found posterior-proximal to the femoral fibular collateral ligament attachment.

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