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Proximal fixation anterior to the lateral femoral epicondyle optimizes isometry in anterolateral ligament reconstruction

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Abstract

Purpose Concomitant anterolateral ligament (ALL) injury is often observed in patients with an anterior cruciate ligament injury leading some to recommend concurrent ALL reconstruction. In ligament reconstruction, it is imperative to restore desirable ligament length changes to prevent stress on the graft. The purpose of this investigation is to identify the optimal femoral and tibial locations for fixation in ALL reconstruction.

Methods 3D computerized tomography (CT) knee models were obtained from six fresh-frozen, unpaired, cadaveric human knees at 0°, 10°, 20°, 30°, 40°, 90°, 110°, and 125°of knee flexion. Planar grids were projected onto the lateral knee. Isometry between each tibial and femoral grid point was calculated at each angle of flexion by the length change in reference to the length at 0° of knee flexion. The mean normalized length change over the range of motion was calculated for each combination of points at all angles of flexion were calculated.

Results Fixation of the ALL to the lateral femoral epicondyle or 5 mm anterior to the epicondyle with tibial fixation on the posteroinferior aspect of the tibial condyle (14–21 mm posterior to Gerdy's tubercle and 13–20 mm below the joint line) provided the lowest average length change for all possible ALL tibial insertion points. Minimal length change for all femoral fixation locations occurred from 20° to 40° of flexion, which identifies the angle of flexion where graft tensioning should occur intraoperatively.

Conclusion With the use of 3D reconstructed models of knee-CT scans, we observed that there was no ALL fixation point that was truly isometric throughout range of motion. Fixation of the anterolateral ligament on the lateral femoral epicondyle or anterior to the lateral femoral epicondyle and on the inferoposterior aspect of the tibial condyle restores isometry. Additionally, minimal length change was observed between 20° and 40° of flexion, which is the most appropriate range of knee flexion to tension the graft. Reproducing isometry reduces stress on the graft, which minimizes the risk of graft failure.

Keywords Anterolateral ligament · Isometry · Anterior cruciate ligament · Anterolateral ligament reconstruction · 3-Dimensional knee model

Introduction

Concomitant anterolateral ligament (ALL) injury has been observed in 33–90% of patients with an anterior cruciate ligament (ACL) injury [3, 9, 14]. The ALL functions as an internal rotation stabilizer, especially at knee flexion angles greater than 35°, where the contribution of the ALL exceeds that of the anterior cruciate ligament [4, 27, 29]. Intra-articular ACL reconstruction restores anterior–posterior kinematics; however, internal laxity may remain, most likely due to the deficiency of the anterolateral ligament [18, 26]. Concomitant anatomical anterolateral ligament reconstruction during ACL reconstruction reduces internal laxity, and has recently shown to provide satisfactory patient outcomes [38]. Given the association between ALL injury with a positive pivot-shift examination following ACL reconstruction, this has led some to recommend concurrent ALL reconstruction [26, 35].

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Several investigations have described the anatomical insertion points of the ALL with great heterogeneity, specifically the femoral insertion site. The tibial insertion site has consistently been described as posterior to Gerdy's tubercle approximately 10 mm below the joint line [4, 8, 19]. The femoral insertion site has been described to be posterior-proximal [8, 19, 24], anterior [30], anterior-distal [28], or directly on the lateral femoral epicondyle [4, 5]. It has previously been argued that the anterolateral ligament is isometric only during a portion of range of motion or is completely anisometric [8, 13, 16, 39], thus making identification of locations that optimize length change properties increasingly important.. With ligament reconstruction, it is imperative to restore desirable ligament length changes. Ligaments that stretch by more than 10% are subjected to increased forces throughout range of motion, which elevates the strain and deformation placed on the graft as well as the risk of failure [23, 32].

The purpose of this investigation is to identify the most isometric femoral and tibial locations for fixation in ALL reconstruction. The aims of this investigation are to (1) identify the optimal combination of tibial and femoral insertion sites that allow for isometric anterolateral ligament reconstruction, and (2) determine if altering the position of femoral and tibial fixation significantly affects anterolateral ligament isometry. The hypothesis of this investigation is that the most isometric point of fixation in ALL reconstruction will be located on the lateral femoral epicondyle with tibial fixation on the posterior aspect of the tibial plateau.

Materials and methods

3D CT knee models at various flexion angles

Six fresh-frozen, unpaired, cadaveric human knees meeting our inclusion criteria (obtained from Science Care, Lombard, IL, paid for by internal institutional funding) were included in the investigation. This investigation received exemption from institution board review. Specimens with no prior history of trauma, arthritis, cancer, surgery, congenital defects, or any ligamentous knee injury were included in this study. Prior to computerized tomography (CT) scanning, each specimen was examined with a manual Lachman and pivot-shift test to ensure that the ACL was intact. The mean age of the donors for the collected knees was 47 years (26–59). Each knee was preserved at −20 °C and thawed for 24 h prior to undergoing CT imaging (BrightSpeed, GE Healthcare, Chicago, IL) in the coronal, axial, and sagittal planes by use of 0.625-mm contiguous slices (20-cm field of view, 512×512 matrices) at 0°, 10°, 20°, 30°, 40°, 90°, 110°, and 125°of knee flexion as measured by a goniometer. An external fixation device was used to ensure consistent and neutral knee flexion. The knees were scanned at 10° increments from 0° to 40° of flexion as most techniques of ALL reconstruction are conducted at less than 40° of flexion [6, 24]. Flexion angles of 90°, 110°, and 125° were assessed to examine the behavior of the anterolateral ligament at higher degrees of flexion. Utilizing smaller increments of knee flexion allow for identification of the optimal angle of knee flexion that allows for isometric fixation of the ALL. CT images were converted to a DICOM format and underwent segmentation using three-dimensional (3D) reconstruction software (Mimics, Materialise, Leuven, Belgium) to generate the 3D knee models.

Grid placement for the tibia

Twenty-four virtual tibial insertion sites (4×6 grid) were placed on the proximal lateral tibia at 0° flexion (Fig. 1). Anatomical markers such as Gerdy's tubercle, the fibular head, and lateral tibial plateau were identified as boundaries for placement of a grid. The 7 mm × 7 mm planar grid was appropriately sized and placed to provide analytic points on the lateral tibial condyle and Gerdy's tubercle while providing adequate spacing for several fixation sites posterior to Gerdy's tubercle and anterior to the fibular head [4, 8, 19]. The grid was oriented such that osseous landmarks

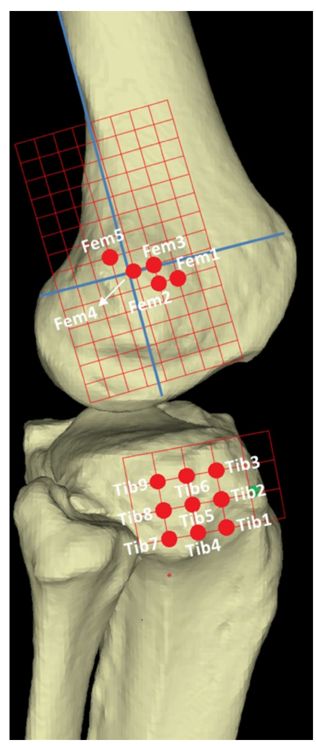

Fig. 1 3D CT models illustrating grid placement and matrix transformation. All analyzed points are highlighted. 3D–3D registration allows for the position of these points to be maintained throughout ROM

corresponded to the same grid coordinates between samples. The planar grid was then projected onto the 3D model of the proximal lateral tibia such that the grid was no longer flat and was contoured to the surface of the tibia.

Tibial insertion sites and relative coordinates

Nine tibial sites located posterior to Gerdy's tubercle, anterior to the fibular head, and below the tibial plateau to the points were identified (Fig. 1): anteroinferior (Tib1), anteromedial (Tib2), anterosuperior (Tib3), inferior (Tib4), central (Tib5), superior (Tib6), posteroinferior (Tib7), posteromedial (Tib8), and posterosuperior (Tib9). After identifying the coordinates of each insertion site, a 3D–3D registration technique was used to transform the matrices from the tibial model at 0° to the tibial models in each angle of flexion. 3D–3D registration is a mechanism of transforming data or a function onto itself in a different spatial orientation that allows for alignment of data sets into a consistent model. This procedure created identical femoral and tibial insertion points on each 3D model at every angle of knee flexion.

Grid placement for the femur

Similar to determination of ALL insertion sites on the tibia, an 8 × 14 (112-point grid) was virtually placed on the lateral wall of the lateral femoral condyle at 0° flexion by utilizing the lateral femoral epicondyle and Blumensaat's line as anatomical boundaries (Fig. 1). The 5 mm × 5 mm planar grid was appropriately sized and placed to provide analytic points on the lateral femoral epicondyle while providing adequate spacing for several fixations sites of the anterolateral ligament on and around the lateral femoral epicondyle [5, 6] The 112-point grid was aligned parallel to the inferior aspect of the lateral femoral condyle with a point fixated on the midpoint of the epicondyle. The grid was placed to ensure complete coverage of anatomical and surgical fixation points of the anterolateral ligament. The grid was oriented such that anatomical landmarks corresponded to the same grid coordinates between samples.

Femoral insertion sites and relative coordinates

Five femoral fixation points were used for isometry analysis. These points were systematically chosen based upon previously described anatomical descriptions and reconstruction techniques of the anterolateral ligament. Femoral points chosen for isometric analysis included the lateral femoral epicondyle (Fem5) [1, 30], proximal-posterior to lateral femoral epicondyle (Fem4) [2], anterior to the lateral femoral epicondyle (Fem3) [33], anterior-distal to the lateral femoral epicondyle (Fem2) [40], and 5 mm below the midpoint of Blumensaat's line (Fem1) [6, 10] (Fig. 1). The grid was projected on the 3D lateral femoral condyle model such that the grid is no longer flat and is contoured to the surface of the femur. Points serving as femoral insertion sites of the ALL were chosen relative to the morphologic osseous landmarks on each individual specimen. A total of 42–51 insertion points was determined to lie on the lateral wall of the lateral femoral condyle for each specimen and 3D coordinates of each insertion point on the femur were obtained. The range of points on the lateral femoral condyle was observed due to anatomical differences in the size of the condyle between cadaveric samples. The insertion points in the flexed conditions were calculated by the same procedure described above for the proximal lateral tibia.

ALL model

Since a reconstructed ALL must wrap around the femur and tibia and contour to osseous landmarks of these structures, a 3D wrap-around algorithm has been introduced to calculate the length of the ligament. This wrap-around technique, unlike the straight-line method, is able to conform to the osseous landmarks, allowing for a better depiction of physiologic motion (Fig. 2). Measurement accuracy of this simulation was given to one decimal place. Repeated simulations yielded identical results. The following steps were used for the wrap-around algorithm;

1. A line between the tibial origin at point j and the femoral insertion at point k at the knee flexion angle i was created and 100 control points were set on the line with an equal distance.
2. If a control point was located in the bone (Fig. 2a), this point was moved laterally until the point was located on the bone surface or outside of the bone (Fig. 2b).
3. The control points outside of the bone were re-aligned so that the ligament outside of the bone became straight (Fig. 2c).
4. The ligament length was calculated by summating the lengths between all control points

Mapping of ligament length changes

Using the nine examined tibial insertion points, the length of the ALL was measured to each point on the lateral wall of the lateral femoral condyle at all angles of knee flexion. The length of the ALL at 0° of knee flexion served as the reference length and is illustrated in length change maps utilizing the following color scale: blue representing ligament shortening, white indicating isometry, and red representing ligament lengthening.

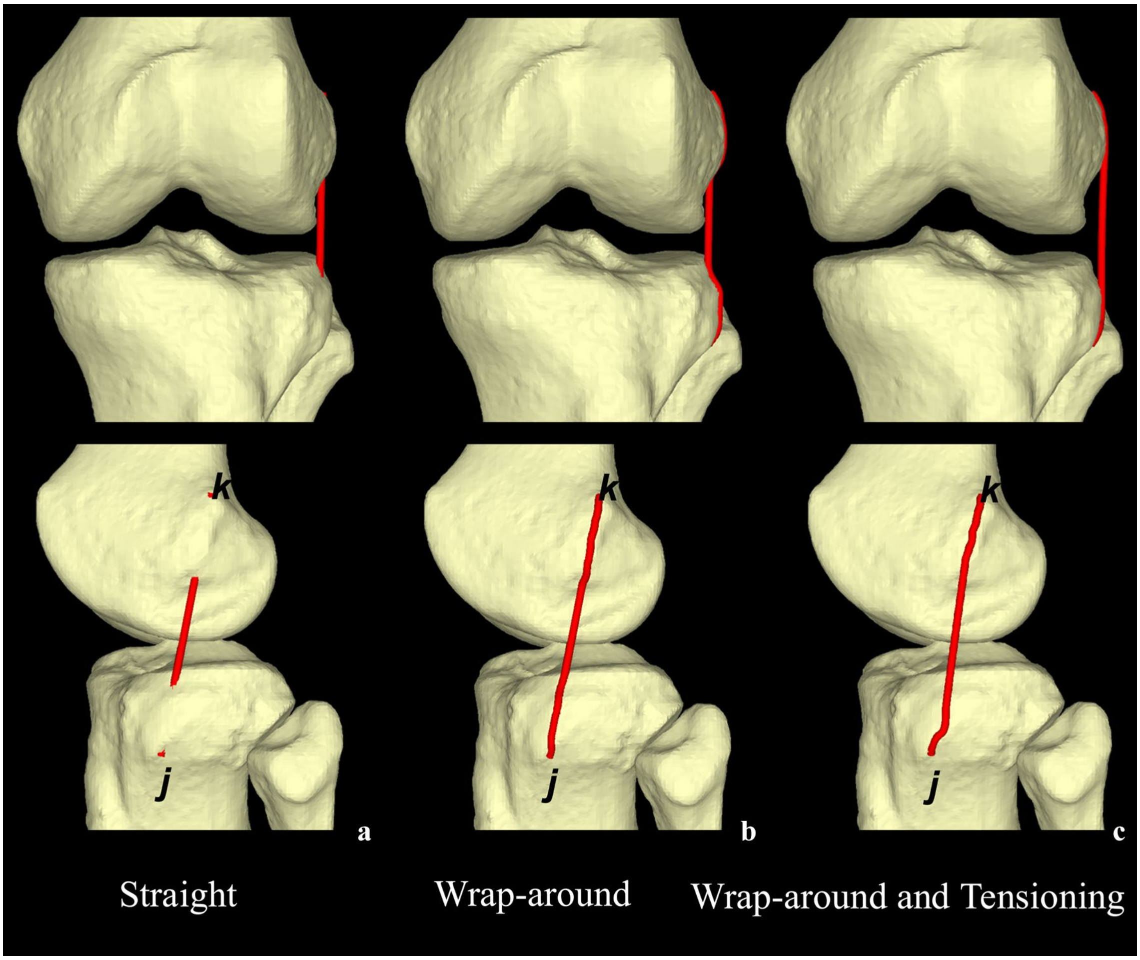

Fig. 2 3D CT models demonstrating the wrap-around algorithm utilized for improved depiction of in vivo length of a reconstructed ligament

ALL length calculation

Isometry between the tibial and femoral insertion sites at a given knee flexion angle was calculated by the length change, Δ, in reference to the length at 0° of knee flexion. It has previously been described that a ligament length change greater than 10% subjects the graft to increased strain, deformation, and risk of failure [23, 32]. A value of zero indicates isometry, a positive value indicates elongation of the anterolateral ligament, and a negative value indicates shortening of the anterolateral ligament during knee flexion.

The maximum and minimum ligament lengths throughout range of motion was defined for each combination of femoral and tibial points. Ligament lengths at each flexion angle were then normalized to the maximum length to allow for more direct comparisons between specimens. Although there was some variability, maximum ALL length was observed between 110° and 125° of flexion in all specimens. The rate of change in ligament length over the entire range of motion was calculated for each combination of points.

Statistical analysis

Statistical analyses were performed with Stata 14 (StataCorp, College Station, TX) and Excel (Microsoft Corporation, Redmond, WA). A three-way ANOVA test with Bonferroni correction was then performed with femoral fixation position, tibial fixation position, and knee flexion angle as independent variables and the normalized ligament length serving as the dependent variable. A one-way ANOVA test with Bonferroni correction was calculated with knee flexion angle as the independent variable and the normalized length as the dependent variable. Finally, an ANOVA with Tukey post-hoc adjustment was performed to evaluate for any differences between normalized ligament length at the most isometric fixation combinations for all flexion angles during range of motion. Significance for these tests was defined as $p < 0.05$. A post-hoc ANOVA power analysis using Rstudio software version 1.0.143 (R Foundation for Statistical Computing, Vienna, Austria)

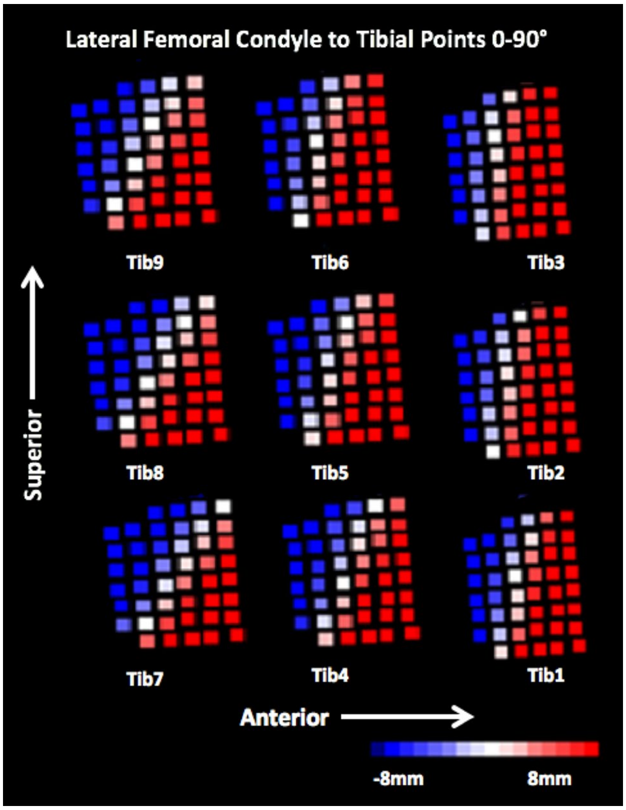

Fig. 3 ALL Length change to all points on the lateral femoral epicondyle for all examined tibial points at 90° of knee flexion

was performed to determine if there was sufficient size to detect a statistical difference on ligament length.

Results

Mapping of ligament length changes

The length change from analyzed points on the lateral femoral condyle of a single specimen from 0° to 90° of flexion for each tibial point is illustrated in Fig. 3. From 0° to 90° of flexion, there are few points that correspond to isometric behavior of the ALL from various tibial fixation sites. A length-change map of the same specimen for points on the lateral femoral condyle from a single point on the tibia (Tib9) throughout range of motion is demonstrated in Fig. 4. The ALL exhibits relative isometry to all femoral points on the lateral wall of the lateral femoral condyle from 0° to 30° of flexion. All examined tibial insertion sites demonstrated relative isometry or a minimal amount of lengthening or shortening from 0° to 30° of flexion.

ALL length change

There was no combination of ALL fixation sites that was truly isometric throughout range of motion. Fixation at Fem3 and Fem4 demonstrated the smallest average normalized percent change for all tibial positions (13.9% and 11.2%, respectively), while fixation at Tib7 and Tib8 demonstrated the smallest average normalized percent change

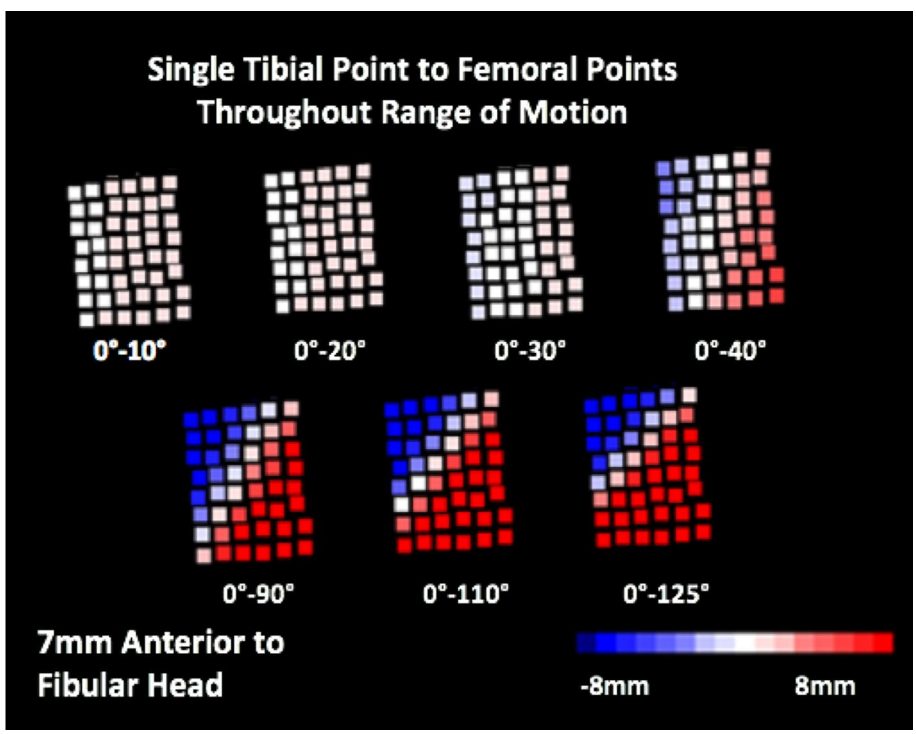

Fig. 4 Length change of the ALL from a single tibial point (Tib9) to all points on the lateral femoral epicondyle throughout range of motion

Table 1 Mean range of normalized lengths throughout range of motion

Mean range of normalized lengths (%)					
Tibial points	Fem1	Fem2	Fem3	Fem4	Fem5
Tib1	23.7	20.5	14.8	10.3	13.7
Tib2	27.8	24.6	18.5	12.7	13.9
Tib3	32.5	29.3	23.0	16.7	15.4
Tib4	19.1	16.2	10.5	**8.4**	17.3
Tib5	22.6	19.9	13.4	10.3	16.7
Tib6	27.3	24.9	17.8	13.2	16.0
Tib7	13.4	11.1	**7.4**	**9.8**	22.1
Tib8	16.1	13.5	**8.7**	**9.2**	21.7
Tib9	19.9	17.5	11.0	10.4	21.2

Mean change less than 10% are bolded

for all femoral positions on the femur (12.8% and 13.8%, respectively). Fem1 exhibited the greatest percent change in mean normalized length with an average length change of 22.5%, while Tib3 exhibited the greatest average percent change in normalized length with an average change of 23.4%. The range of normalized percent length change for each combination of points throughout the entire range of motion is illustrated in Table 1. Combinations that demonstrated the least amount of length change (Fem3–Tib7, Fem3–Tib8, Fem4–Tib4, Fem4–Tib7, Fem4–Tib8) correspond to fixation on the lateral femoral epicondyle and fixation 5 mm anterior to the lateral femoral epicondyle with tibial fixation inferoposterior on the tibial condyle (14–21 mm posterior to Gerdy's tubercle and 13–20 mm below the joint line) (Fig. 5).

One-way ANOVA between the average range in normalized length throughout ROM for every femoral and tibial fixation combination revealed statistically significant differences between several combinations (i.e. Fem5–Tib6 and Fem1–Tib3, $P<0.005$), while there were no statistically significant differences in ligament length for other combinations of fixation points (i.e. Fem5–Tib6 and Fem3–Tib4, P = n.s.).

Results from a one-way ANOVA analysis demonstrated a statistically significant difference in anterolateral ligament length at 40° of flexion in comparison to the length of the ALL at 0° ($P=0.006$) and at 125° of flexion ($P=0.001$). One-way ANOVA for all point combinations that illustrated length change less than 10% demonstrated no statistical difference in average normalized length change throughout range of motion (P = n.s.).

Fem3–Tib7, Fem3–Tib8, Fem4–Tib4, Fem4–Tib7, and Fem4–Tib8 exhibited a length change less than 10% throughout range of motion and also exhibited minimal length change between 20° and 40° of knee flexion (Fig. 6). The length of the ALL at 125° for Fem4–Tib7 was statistically significantly shorter than the length of the ligament at 20° of flexion ($P=0.05$), 30° ($P=0.02$), and 40° of flexion ($P=0.007$).

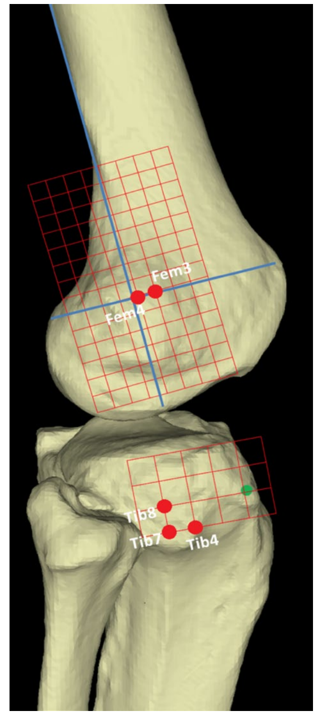

Fig. 5 Fixation of the ALL at a combination of these femoral and tibial points provides the most isometric behavior of the ligament throughout range of motion

Discussion

In this investigation, the femoral and tibial insertion points of the anterolateral ligament that displayed the most isometric behavior throughout full range of motion were identified. Fixation of the ALL to the lateral femoral epicondyle or 5 mm anterior to the lateral femoral epicondyle (LFEC) with tibial fixation on the posteroinferior aspect of the tibial condyle (14–21 mm posterior to Gerdy's tubercle and 13–20 mm below the joint line) provided the lowest average length change. For the isometric combinations of femoral and tibial fixation, minimal length change was observed from 20° to 40° of flexion, which identifies the angle of flexion where graft tensioning should occur. Lastly, the length of the anterolateral ligament was longest at 40° of flexion and exhibited shortening as the knee approached maximal extension and flexion.

Previous studies have investigated the isometric properties of the anterolateral ligament; however, previously described fixation points do not replicate ideal knee kinematic properties. Claes et al. were the first to describe length

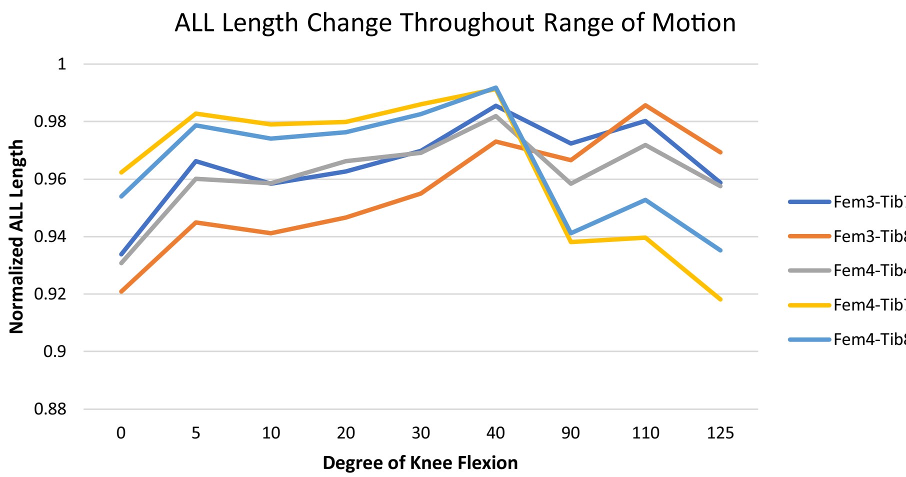

Fig. 6 Normalized ALL length change throughout range of motion for all fixation combinations that illustrate minimal length change

changes of the native anterolateral ligament, and noted that the length of the ALL at its native anatomical origin and insertion sites increased from full flexion to full extension [4]. More recent investigations have identified anatomic fixation of the ALL, posterior and proximal to the lateral femoral epicondyle, to be the most isometric [16, 21, 24, 41]. The corresponding isometric tibial fixation point was located 37% of the anterior–posterior length of the tibial plateau, and 10 mm below the joint line [41]. However, other investigations demonstrate that the anterolateral ligament in its native fixation site is non-isometric [8, 12, 20]. While fixation at these sites may maximize isometry, ideal biomechanical behavior of the knee may not be restored. Biomechanical studies have demonstrated that anatomic ALL reconstruction in the setting of anterior cruciate ligament reconstruction caused significant reduction in rotational laxity; however, it also resulted in overconstraint of normal joint kinematics [31]. Joint overconstraint from combined anterolateral ligament reconstruction and ACL reconstruction can potentially cause long-term discomfort, as abnormal joint loading has been shown to cause osteoarthritis, stiffness, and decreased physiological motion [7, 31]. Several investigations have demonstrated equivalent or improved clinical outcomes and low graft re-rupture rate in patients undergoing concomitant ALL reconstruction with ACL reconstruction at intermediate follow-up [11, 15, 36]. These investigations implemented an anatomic reconstruction, and while patients demonstrated adequate functional outcomes, long-term outcomes of these techniques are needed.

Although the primary purpose of anterolateral ligament reconstruction is to restore the biomechanics of the native anterolateral ligament [34], re-establishing isometry can optimize outcomes from ALL reconstruction. A ligament that stretches by more than 10% is subjected to increased forces throughout a range of motion which increases graft strain, permanent deformation and subsequent risk of failure due to stretching [23, 32]. In our present investigation, of the 45 examined fixation combinations, only 5 fixation combinations demonstrate a change in length less than 10%. Although there was not a statistically significant difference between the most isometric fixation points and all other examined combinations, all non-statistically significant point combinations demonstrated a length change greater than 10%. Thus, supporting that the most isometric position is located on the lateral femoral epicondyle or anterior to the lateral femoral epicondyle. Fixation at these locations not only reconstitutes isometry, but fixation on the LFEC does not cause overconstraint of the knee [37]. However, further investigations are needed to elucidate the biomechanical behavior of anterolateral ligament fixation anterior to the LFEC as well as clinical outcomes.

In this investigation, the change in ALL length in 10° increments from 0° to 40° of knee flexion was measured. The optimal knee flexion angle to tension the ALL graft is from 20° to 40° of flexion as there was minimal length change at these angles of flexion. Neri et al. concluded that graft tensioning should occur between 0° and 30° of knee flexion during reconstruction [24]. However, the limitation of that previous investigation was that the length of the anterolateral ligament was measured only at 0°, 30°, 60°, and 90° of knee flexion. Our findings are an important modification to the findings of Neri et al., as they had insufficient length change data at lower flexion angles to draw a definitive conclusion regarding optimal tensioning angles. More recent investigations have demonstrated conflicting evidence on the optimal angle of graft tensioning in anatomic ALL reconstruction. Graft tensioning at full extension has been shown to restore knee kinemetics [17], while graft tensioning at any angle of flexion restores knee kinematics; however, it causes joint overconstraint [31]. While graft fixation from 20° to 40° of flexion resulted in the most isometric behavior, further investigations are needed to characterize the biomechanical behavior of the graft fixed anterior to the LFEC.

The positions on the femur and tibia that we identified as most isometric differs from the most recent investigation of ALL isometry by Wieser et al [41], who determined the most isometric sites of ALL fixation to be superior to the lateral femoral epicondyle and a tibial fixation site more proximal to the joint line than described in the present study. Wieser et al. utilized a singular tibial point to assess isometry on the lateral femur and then used that femoral point to identify isometry to three previously described anatomical tibial insertion sites. By utilizing previously described anatomical fixation sites on the tibia, this study does not truly assess the most isometric ALL reconstruction technique. Rather, it assesses the most isometric femoral fixation site from the native tibial insertion site. Additionally, Wieser et al. implemented a model that did not account for the path of the ALL over osseous landmarks, which may affect the findings of the investigation. Our results also differ from Helito et al. who described that fixation of the anterolateral ligament anterior to the LFEC resulted in an increase in length throughout range of motion [13]. The authors conducted that investigation by placing a marker at the insertion sites of the ALL and measured the distance of these markers on computer tomography (CT) scans at several angles of knee flexion. Unlike previous investigations which used a straight-line method to calculate the length of the anterolateral ligament, the present study developed and implemented a wrap-around technique that takes into account the path that the ligament traverses around the native bony anatomy of the femur and tibia throughout range of motion. This technique was developed due to a limitation that the authors believe was present in previous investigations of anterolateral ligament isometry as these studies were unable to account for the path of the ALL around osseous landmarks. Additionally, femoral fixation sites of previously described ALL reconstruction techniques were assessed through 24 tibial fixation sites and 7 different angles of flexion to identify the most isometric ALL fixation combination. Thus, the results of the present investigation might be more applicable towards ALL reconstruction versus previous investigations which examined the isometric behavior of native ALL anatomy.

Despite the findings of this investigation, there are limitations. The first limitation was the sample size as only 6 knees fit inclusion criteria with a mean age of 46 years old, which is higher than the average age of a patient undergoing ACL reconstruction [25]. Post-hoc power analysis demonstrated that this investigation was underpowered to accurately perform statistical comparisons. The results of this investigation can be used as a basis to further investigate anterolateral ligament isometry. Although osseous landmarks were used to systematically place the grids, there could be some variability in its placement. In this investigation, we did not assess the isometry of the anterolateral ligament with an applied internal rotation load. This investigation assessed isometry at low angles of knee flexion (0°–40°) in 10° increments since this represents the range of knee flexion angles where many of the ALL reconstruction techniques have been described [6]. However, several techniques have been described to fixate the anterolateral ligament at 60° of flexion, which was not assessed in this investigation [6]. The results of this study would benefit from assessment of ALL isometry at 60° of flexion. Since the major function of the ALL is to resist internal rotation, this is an important variable to consider with isometry [4, 27, 29]. However, the natural internal rotation that occurs throughout knee flexion (screw-home mechanism [22]) was accounted for in this investigation. This study uses advanced modeling methodology to test multiple different points and combinations of points that would not be possible with standard cadaveric or clinical studies. Thus, the results should be evaluated both biomechanically and in the clinical setting to determine the true performance of ALL reconstruction with the findings of this study. Although the methodology of this investigation implemented a novel wrap-around technique to account for osseous landmarks, it remains un-validated. Lastly, as the knees were cycled through the range of motion, there was no additional rotational torque applied to the knees to maintain neutrality. As such, a rotational component for anterolateral ligament isometry could not be evaluated for this investigation. However, there was some degree of inherent internal or external rotation throughout range of motion for all specimens.

Conclusion

With the use of 3D-reconstructed models of knee-CT scans, we observed that there was no ALL fixation point that was truly isometric throughout range of motion. Fixation of the anterolateral ligament on the lateral femoral epicondyle or anterior to the lateral femoral epicondyle and on the inferoposterior aspect of the tibial condyle restores the biomechanical properties of the ligament while exhibiting isometric behavior. Additionally, minimal length change was observed between 20° and 40° of flexion, which is the most appropriate range of knee flexion to tension the graft.

Funding No external funding was used for this investigation.

Compliance with ethical standards

Conflict of interest Dr. Verma is a board member for American Orthopaedic Society for Sports Medicine, American Shoulder and Elbow Society, Arthroscopy Association of North America, and is on the editorial board for Arthroscopy, Journal of Knee Surgery, SLACK Incorporated. Dr. Verma receives research support from Arthrex Inc, Arthrosurface, DJ Orthopaedics, Ossur, Athletic, CONMED Linvatec, Miomed, Smith and Nephew, and Mitek. Dr. Verma has stock options in Cymedica, Minivasive, Omeros. Dr. Verma receives publishing royalties from Arthroscopy, Vindico Medical Orthopedics Hyperguide. Dr. Cole receives research support from Aseculap, Arthrex Inc, Geistlich, National Institute of Health, Sanofi-Aventis, and Zimmer, Dr. Cole is on the editorial board for the American Journal of Orthopaedics, American Journal of Sports Medicine, Arthroscopy, Cartillage, Journal of Bone and Joint Surgery, Journal of Shoulder and Elbow Surgery, and Journal of the American Academy of Orthopaedic Surgeons. Dr. Cole has stock options in Aqua Boom, Biometrix, Giteliscope, Ossio, and Regintis, as well as receives material support from Tournier. Dr. Cole is a board member for Arthroscopy Association of North America, and International Cartilage Repair Society. Dr. Cole receives IP royalties from Elsevier and DJ Orthopaedics, and Dr. Cole is a paid consultant for Flexion, Regentis, and Smith and Nephew. Dr. Bach has received publishing royalties from SLACK Incorporated as well as research support from Arthrex Inc, CONMED Linvatech, DJ Orthopaedics, Ossur, Smith and Nephew and Tornier. Dr. Forsythe receives paid royalties from Elsevier, research support from Arthrex Inc, Stryker, fellowship support from Ossur and Smith and Nephew, and has stock options in Jace Medical. Dr. Inoue receives research support from the National Institute of Health.

Ethical approval This investigation was exempt from approval from our Institutional Review Board.

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