Mapping isometry and length changes in ligament reconstructions of the knee

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Chapter 7

The medial patellofemoral ligament is a dynamic and anisometric structure – An in vivo study on length changes and isometry

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ABSTRACT

Background: Medial patellofemoral ligament (MPFL) reconstruction is associated with a high rate of complications, including recurrent instability and persistent knee pain. Technical errors are among the primary causes of these complications. Understanding the effect of adjusting patellofemoral attachments on length change patterns may help surgeons to optimize graft placement during MPFL reconstruction and to reduce graft failure rates.

Purpose: To determine the in vivo length changes of the MPFL during dynamic, weightbearing motion and to map the isometry of the 3-dimensional wrapping paths from various attachments on the medial femoral epicondyle to the patella.

Study Design: Descriptive laboratory study.

Methods: Fifteen healthy participants were studied with a combined computed tomography and biplane fluoroscopic imaging technique during a lunge motion (full extension to ~110° of flexion). On the medial femoral epicondyle, 185 attachments were projected, including the anatomic MPFL footprint, which was divided into 5 attachments (central, proximal, distal, posterior, and anterior). The patellar MPFL area was divided into 3 possible attachments (proximal, central, and distal). The length changes of the shortest 3-dimensional wrapping paths of the various patellofemoral combinations were subsequently measured and mapped.

Results: For the 3 patellar attachments, the most isometric attachment, with an approximate 4% length change, was located posterior and proximal to the anatomic femoral MPFL attachment, close to the adductor tubercle. Attachments proximal and anterior to the isometric area resulted in increasing lengths with increasing knee flexion, whereas distal and posterior attachments caused decreasing lengths with increasing knee flexion. The anatomic MPFL was tightest in extension, decreased in length until approximately 30° of flexion, and then stayed near isometric for the remainder of the motion. Changing both the femoral and patellar attachments significantly affected the length changes of the anatomic MPFL ($P < .001$ for both).

Conclusions: The most isometric location for MPFL reconstruction was posterior and proximal to the anatomic femoral MPFL attachment. The anatomic MPFL is a dynamic, anisometric structure that was tight in extension and early flexion and near isometric beyond 30° of flexion.

Clinical Relevance: Proximal and anterior MPFL tunnel positioning should be avoided, and the importance of anatomic MPFL reconstruction is underscored with the results found in this study.

INTRODUCTION

The medial patellofemoral ligament (MPFL) is the primary restraint to lateral patellar translation, contributing 50% to 60% of the total restraining force.[16,25,41,45] The MPFL is almost always ruptured during a lateral patellar dislocation.[24,38] Primary patellar dislocations may be treated nonoperatively; however, a redislocation is seen in up to 35% to 50% of patients,[5,9,12,14,15,36,79] which has been related to increased cartilage damage and the early onset of osteoarthritis.[75] Therefore, surgical reconstruction of the MPFL is indicated in patients with recurrent patellar dislocations.[47,77] Moreover, recently, some authors have described that in specific cases, MPFL reconstruction may be beneficial after primary patellar dislocations.[42,50] Although several studies have shown significant improvements in patient outcomes after MPFL reconstruction,[54,66,72] others have described high complication rates, in particular recurrent instability and persistent knee pain.[3-5,13,37,43,58,68] One of the primary causes of these complications is technical surgical errors, of which femoral tunnel malpositioning has been found to be one of the most common.[10,43,51,52,68]

Knowledge about the native anatomy and understanding its function are paramount in ligament reconstruction. The anatomy of the MPFL has been heavily debated, and recent publications have shown variability of its femoral attachment.[1,6,67] It has been shown that nonanatomic graft positioning can lead to decreased range of motion, knee pain, graft failure, tunnel widening, recurrent dislocations, and increased medial patellofemoral joint contact pressure, which has been postulated to cause early degenerative changes of the patellofemoral joint.[10, 13, 18, 19, 52, 56, 63, 64, 68, 71] Few studies have investigated the effects of patellofemoral attachment locations on graft length changes.[22,27,40,59,60,65,78] It has been found that modifying the femoral graft position, mainly in the proximal-distal direction, is more sensitive for graft length changes than altering the patellar position.[65] However, most of these studies were limited by using only a few patellofemoral attachments and the nature of their cadaveric, nonphysiological muscle-loading conditions.[30] Moreover, Kaiser et al.[29] recently underscored the importance of muscle-loading conditions on both tibiofemoral and patellofemoral joint kinematics. Therefore, it is difficult to extrapolate the biomechanical behavior of the MPFL that was measured in these studies to the length change patterns that would be seen during in vivo weightbearing knee flexion.

The purpose of this study was to assess the in vivo isometry and length change patterns of the MPFL in the healthy knee using various patellofemoral attachments. The hypothesis was that attachments outside the anatomic footprint would yield nonphysiological graft length changes (i.e., cannot replicate ‘‘normal’’ MPFL behavior).

METHODS

Participants

This study was approved by the Shanghai Jiao Tong University Institutional Review Board, and written consent was obtained from each participant before taking part in this study project. All participants were examined between June and July 2018. The inclusion criteria consisted of participants aged 18 to 45 years with the ability to perform daily activities independently without any assistance device and without taking pain medication. A standard knee examination was performed on the knee, and participants with increased laxity (as described by Brighton[23]) were excluded. Other exclusion criteria were a positive lateral patellar apprehension test finding, retropatellar tenderness or crepitation, joint effusion, recurrent or chronic knee pain, and either a history of injuries or surgery involving the lower limb. Fifteen healthy participants were included in this study (9 men, 6 women; mean age, 25.1 ± 5.2 years; mean height, 170 ± 10 cm; mean weight, 63.9 ± 11.9 kg; mean body mass index, 22.1 ± 2.7 kg/m2). The mean tibial tuberosity–trochlear groove distance was 13.3 ± 3.0 mm (range, 8.1-17.4 mm).

Imaging

The computed tomography (CT) and dual fluoroscopic imaging techniques for the measurement of ligament kinematics have been described in detail previously.[34,35] CT scans (SOMATOM Definition AS+; Siemens) of the knee joints ranging from approximately 30 cm proximal and distal to the joint line (thickness, 0.6 mm; resolution, 512 × 512 pixels) were obtained. The images were then imported into solid modeling software (3D Slicer, www.slicer.org[21]) to construct 3-dimensional (3D) surface models of the femur, patella, tibia, and fibula. Then, the knee of each participant was simultaneously imaged using 2 fluoroscopes (BV Pulsera; Philips) as the participant performed a lunge motion (full extension to ~110° of flexion). In addition to the lunge motion, the knee was imaged in its relaxed full extension position. Next, the fluoroscopic images were imported into MATLAB (R2018a; Math-Works) and placed in the imaging planes based on the projection geometry of the fluoroscopes during imaging of the participant. Finally, the CT-based knee model of each participant was imported into the software, viewed from the directions corresponding to the fluoroscopic X-ray source used to acquire the images, and independently manipulated in 6 degrees of freedom inside the software until the projections of the model matched with 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.

Patellofemoral Attachments

To determine in vivo the shortest 3D wrapping paths (i.e., theoretical grafts) during motion, various patellofemoral attachments were used. First, a true medial-lateral view of the femur was established. Second, to account for geometric variations between knees, the quadrant method, as described by Stephen et al.,[65] was applied to the femoral 3D models. The anterior and posterior borders of the quadrant were formed by lines parallel to the posterior femoral cortex at the anterior and posterior bony aspects of the medial femoral condyle (line t). The proximal and distal borders were formed by lines perpendicular to line t, proximally to the tip of line t, and distally at the bony cortex of the medial condyle (line h). The medial-lateral view was used to project 185 femoral attachment points to the medial aspect of the medial femoral condyle (Fig. 1). Based on the recent systematic review by Aframian et al.,[1] an area of interest was created, to which the 185 points were placed on the medial femoral epicondyle, including 5 attachments for the anatomic MPFL (proximal, central, distal, posterior, and anterior), which were placed within the dimple between the adductor tubercle and the medial femoral epicondyle, as described by the meticulous anatomic study of Kruckeberg et al.[32] Three patellar attachments (proximal, central, and distal) were selected to describe the anatomic MPFL length changes (Fig. 1).

Length Change Measurements

The length changes for each theoretical graft were measured as a function of knee flexion using in vivo 6 degrees of freedom knee joint kinematics. To create the path of a true graft, a direct line connecting the patellofemoral attachments (i.e., direct end-to-end distance) was projected on the bony surfaces using the convex hull algorithm to create a curved line, avoiding penetration of the connecting line through bone, that is, a ''wrapping path'' (Fig. 2). An optimization procedure was implemented to find the shortest 3D wrapping path at each flexion angle of the knee. This technique has been described in previous studies for measurements of ligament lengths.[73] The length of the 3D wrapping path (i.e., the line curved around the bony surfaces) was measured as the length of the theoretical graft. The MPFL length change data were calculated as follows: $L_n = L - L_0 / L_0 \times 100\%$; where Ln is the normalized length change, L is the graft length, and L0 is the reference length (defined as the length of the MPFL with the lower limb in full extension). Then, the offset at 0° of flexion, caused by the normalization procedure, was zeroed for each participant. The length change measurements had an accuracy of 0.3 ± 0.1 mm based on the systematic error of the registration method (i.e., dual fluoroscopic imaging technique). A heat map was created to provide visual representation of the isometry distribution over the medial femoral epicondyle by using the mean maximum percentage length change – mean minimum percentage length change of each theoretical patellofemoral graft during the lunge motion.

The patellofemoral attachment combination yielding the least length change was considered to be the most isometric graft.

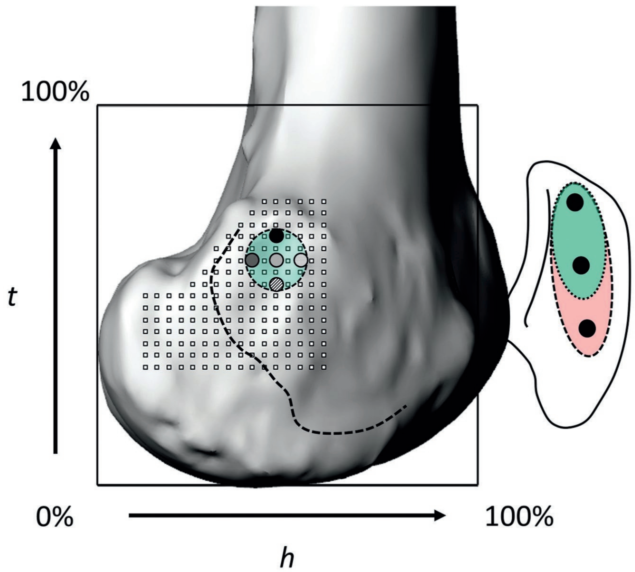

Fig. 1 True medial-lateral view of the knee in extension. The grid, as described by Stephen et al.[65], was applied to the medial femoral condyle. Line t was formed parallel to the posterior femoral cortex line, and line h was formed by the anterior-posterior distance of the medial femoral condyle; lines t and h were identical in length. Line t was connected with the anterior and posterior cortices of the medial femoral condyle. Line h was connected proximally to the tip of line t and distally with the femoral cortex. On the medial femoral epicondyle, 185 points were placed, and 3 patellar attachments (proximal, central, and distal attachments) were selected to describe the anatomic medial patellofemoral ligament (MPFL) length changes. The dashed line on the medial condyle lines shows the true Blumensaat line; the green filled circle on the medial condyle shows the anatomic MPFL attachment within the dimple between the adductor tubercle and the medial femoral epicondyle with its proximal, central, distal, posterior, and anterior attachments.

Statistical Analysis

We analyzed the changes in the length of the anatomic MPFL caused by flexion of the knee using repeated measures 2-way analysis with Tukey honest significant difference post hoc analysis, examining the 5 femoral attachments (i.e., proximal, central, distal, posterior, and anterior) connected to the 3 patellar attachments (i.e., proximal, central, and distal). Analyses were performed in MATLAB. P values 0.05 were considered significant.

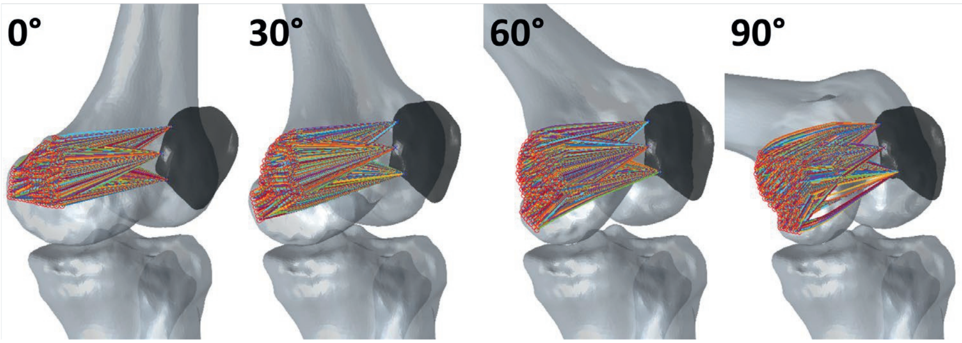

Fig. 2 Illustration of the knee with the 3-dimensional (3D) wrapping paths over the bony geometry of the femur and patella, that is, at 0°, 30°, 60°, and 90° of knee flexion. At each flexion angle, an optimization procedure was implemented to determine the shortest 3D wrapping path of each graft, creating a path of least resistance for the medial patellofemoral ligament.

RESULTS

Isometry

The most isometric femoral attachment was located posterior and proximal to the anatomic MPFL attachment area, that is, near the adductor tubercle (Fig. 3, Video 1 available on the journal's website). This was true for the proximal, central, and distal patellar attachments. The 3D wrapping paths of the femoral attachments proximal and anterior to the isometric zone increased with increasing flexion angles, whereas attachments distal and posterior to the isometric zone decreased with increasing flexion angles (Fig. 4). Moving the patellar attachment proximally caused the most isometric area to move proximally; conversely, the most isometric area moved distally with a distal patellar attachment.

Length Changes of the Anatomic MPFL

In the relaxed full extension position, for the central-to-central patellofemoral attachment, the anatomic MPFL had a mean length of 60.7 mm (95% CI, 58.0-63.4 mm). The central-to-central attachment of the MPFL was longest at full extension and rapidly decreased in length (i.e., slackened) between full extension to 35° of flexion, decreasing in length by 8.5%, and remained near isometric through the remainder of the flexion cycle (Fig. 5). The proximal and anterior femoral attachments tended to increase in length with deeper flexion angles, best seen for the central and distal patellar attachments. The length changes of the other patellofemoral attachment combinations are shown in Fig. 5. Moving the patellar and femoral attachments resulted in significantly different length changes ($P < .001$ for both) (Table 1). Post hoc analyses showed that moving the patellar attachment from central to proximal, central to distal, and proximal to distal caused significant different length changes ($P < .001$ for all). Moving the patellar attachment distally caused the 3D wrapping paths to increase in length at >30° to 110° of flexion (Fig. 5). Moving the femoral attachment from the central to proximal position caused a significant increase in length with knee flexion ($P < .001$). Moving the femoral attachment from central to distal caused a significant decrease in length with knee flexion ($P < .001$). For the proximal patellar attachment, no significant differences were found when moving in the anterior-posterior direction; however, for the central and distal patellar attachments, the length change patterns did alter when moving in the anterior-posterior direction. Detailed information is found in Table 1.

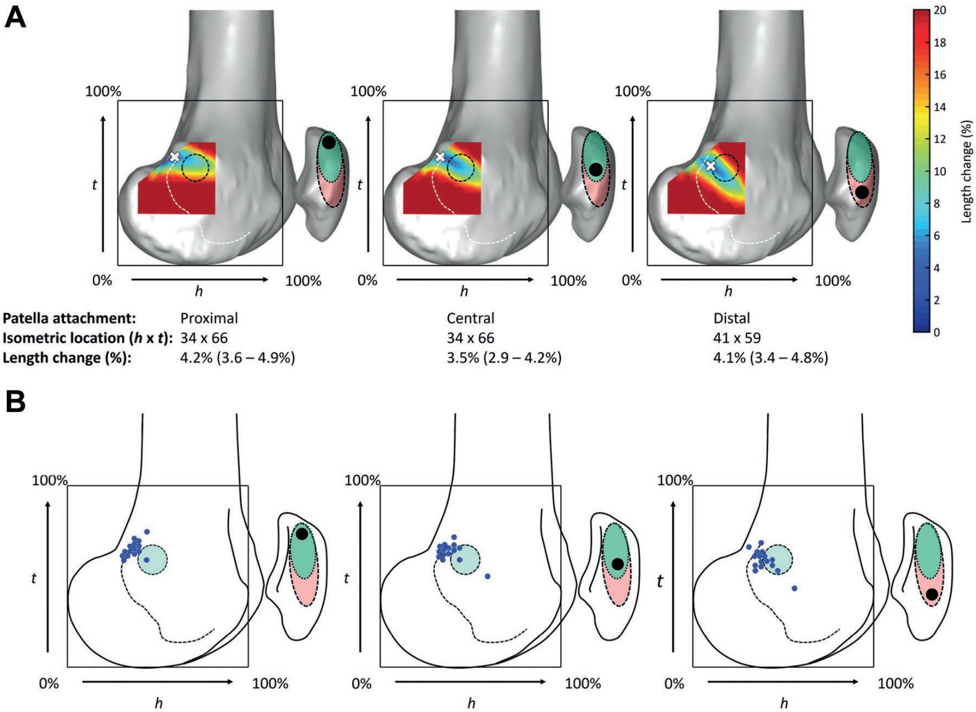

Fig. 3 (**A**) Heat map illustrating the isometry distribution (mean maximum % length change – mean minimum % length change) over the medial aspect of the medial femoral epicondyle for the 3-dimensional wrapping paths around the bony contours when connected to the proximal, central, and distal patellar attachments during the lunge motion. The darkest blue area on the femur shows a near isometric attachment area, while red areas highlight areas with a high degree of anisometry. The white cross represents the most isometric attachment. Values are shown as mean (95% CI). The dashed line (white) on the medial condyle lines shows the true Blumensaat line, and the dashed circle (black) on the medial condyle shows the anatomic medial patellofemoral ligament attachment area. (**B**) The most isometric attachment location per patellar attachment per patient.

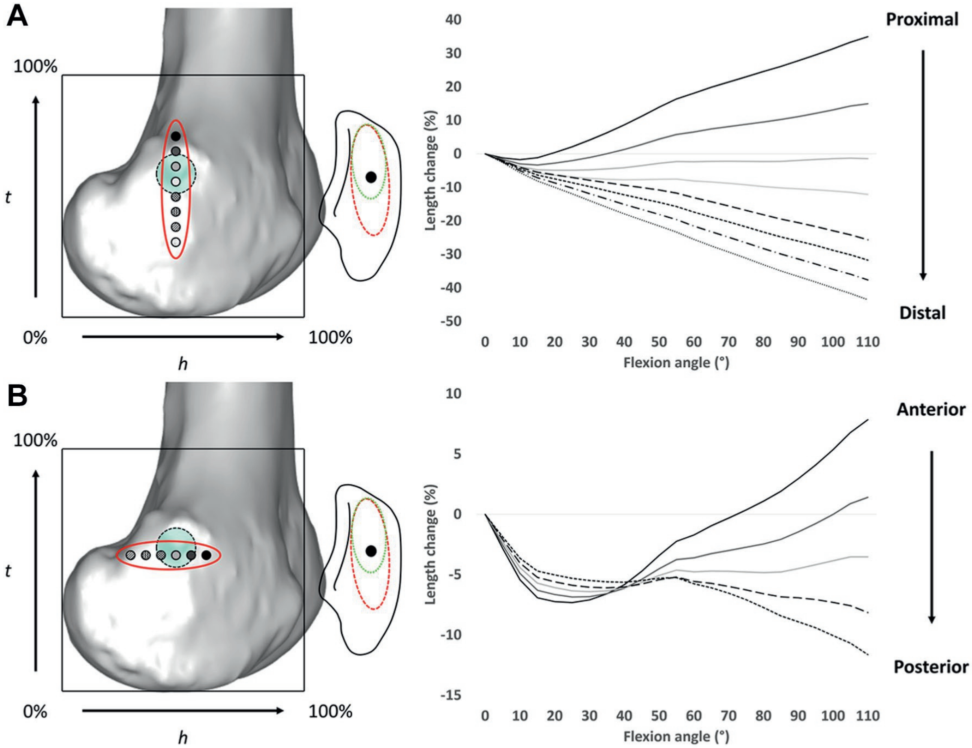

Fig. 4 On the left, a true medial-lateral view of a 3-dimensional femur model with several attachment points illustrated when moving (A) along the proximal-distal direction or (B) along the anterior-posterior direction. The normalized length changes for the attachments, when connected to the central patellar attachment, are shown by the line graphs on the right. Proximal attachments increased in length with increasing flexion angles, whereas distal attachments decreased in length with increasing flexion angles. When moving the attachment along the anterior-posterior direction, posterior attachments would decrease with increasing flexion angles, whereas anterior attachments would increase in length beyond approximately 30° of flexion. The greater the distance of a femoral attachment to the isometric zone, the greater the percentage length change as the knee flexes.

Table 1. Results of the repeated-measures two-way analysis of variance having the Tukey's Honest Significant Difference post hoc analysis for the length changes of the various studied bundles in the lunge motion.

	P-values									
Femur	**Central vs Proximal**	**Central vs Distal**	**Central vs Posterior**	**Central vs Anterior**	**Posterior vs Anterior**	**Posterior vs Proximal**	**Posterior vs Distal**	**Proximal vs Distal**	**Proximal vs Anterior**	**Distal vs Anterior**
Patella										
Proximal	<0.001	<0.001	*N.S. (0.983)*	*N.S. (1.0)*	*N.S. (0.958)*	<0.001	<0.001	<0.001	<0.001	<0.001
Central	<0.001	<0.001	*N.S. (0.357)*	0.031	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Distal	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	*N.S. (1.0)*	<0.001	*N.S. (0.620)*	<0.001

DISCUSSION

The most important finding of this study was that the most isometric femoral MPFL attachment was located posterior and proximal to the anatomic MPFL attachment when connected to the 3 different patellar attachments. In addition, the anatomic MPFL is a dynamic, anisometric structure that was longest (i.e., tightest) in extension; the MPFL decreased in early flexion (i.e., ~30° of flexion) and remained near isometric during deeper flexion angles (i.e., >30° of flexion). Moving the femoral attachments in the proximal-distal direction significantly affected the length changes, whereas moving in the anterior-posterior direction had a much smaller but also significant effect. Similarly, moving the patellar attachments affected the length changes significantly, with more distal attachments causing increasing lengths at >30° of flexion.

Several researchers have attempted to define the isometry and length changes of the MPFL using various methods in both cadaveric[44,59,62,65,74] and in vivo settings.[27,40,52,61,69,78] Previous studies were often limited by using single[27] or only several[11, 22, 28, 44, 59, 61, 62, 65, 74, 78] patellofemoal points within or close to the MPFL attachment and have found different isometric locations. Our approach of analyzing the isometry using various attachments

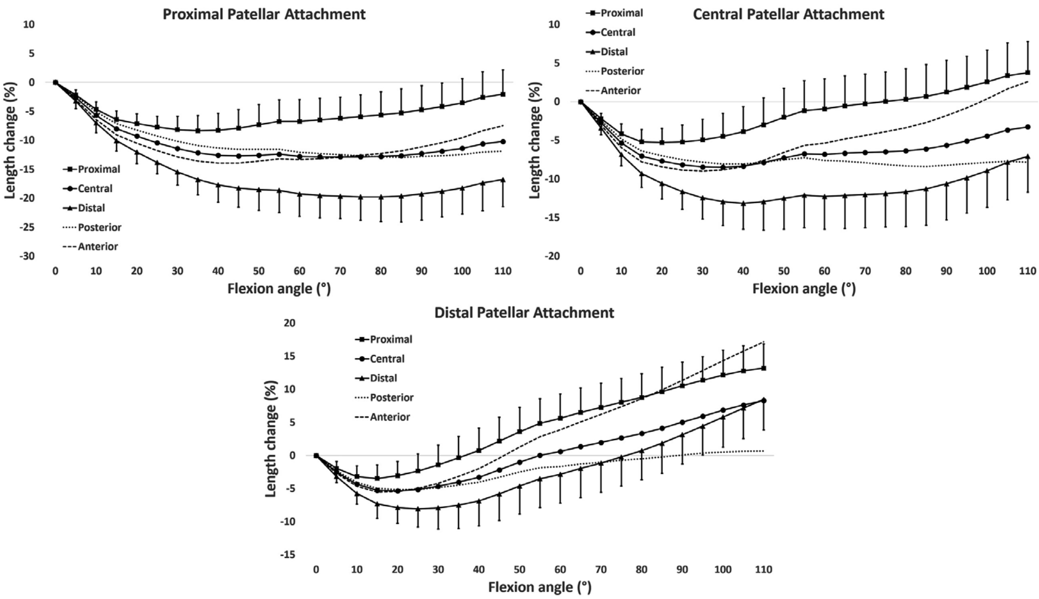

Fig. 5 Normalized length changes as a function of knee flexion for the 5 femoral anatomic medial patellofemoral ligament attachments (proximal, central, distal, posterior, and anterior) when connected to the 3 patellar attachments (proximal, central, and distal) in the lunge motion. Values are shown as mean (95% CI).

within a larger area of interest, including but not limited to the anatomic MPFL footprint on the medial femoral epicondyle, enabled us to find the most isometric area on the medial femoral epicondyle when connected to the 3 patellar attachments. We found the most isometric area to be posterior and proximal to the femoral MPFL attachment, close to/on the adductor tubercle when connected to any of the patellar attachments (see Fig. 3). Thus, the most isometric attachment had a nonanatomic location and yielded non-physiological length changes.

The adductor tubercle has been described as the ''lighthouse of the medial knee'' because when it is found, it allows the surgeon to find all other landmarks.[33,76] Recent anatomic studies have agreed that the MPFL is located in a dimple between the adductor tubercle and the medial femoral epicondyle[6,33,39,46,65,76]; this location cannot be palpated and therefore is hard to find during surgery. Several articles have described radiographic landmarks of the MPFL[7,31,48,55,69,76]; however, others have questioned the accuracy of performing anatomic reconstruction using these radiographic landmarks.[53,80] In this study, the center of the dimple was, on average, 7.2 mm (95% CI, 6.3-8.2 mm) distal and 4.6 mm (95% CI, 4.0-5.2 mm) anterior to the adductor tubercle. We argue that surgeons can use the adductor magnus tendon to routinely locate the adductor tubercle to find the ideal position for MPFL reconstruction.

In agreement with previous studies, we found that the length changes were more sensitive to changes in the proximal-distal direction[11,59,65,78] than in the anterior-posterior direction.[40,59,65] In addition, the effect of moving the patellar attachments distally also showed strong similarities with the patterns found in the cadaveric work by Stephen et al.,[65] leading to greater length changes for the distal patellar attachments, most evident at deeper flexion angles. Therefore, when performing MPFL reconstruction, any errors to be accepted on the femoral side should be made in the anterior-posterior direction (avoiding too anterior positions, which cause increased lengths at deeper flexion angles), not in the proximal-distal direction. On the patellar side, placement should not be more distal than the anatomic MPFL attachment, as this will cause increased length changes at deeper flexion angles.

We confirmed that the anatomic MPFL is a nonisometric structure that was longest (i.e., tightest) in extension, decreased during early flexion, and remained near isometric for the remainder of the flexion cycle. This is in agreement with the cadaveric work by Stephen et al.;[65] however, this was different than others have reported.[11, 22, 27, 28, 44, 59, 61, 62, 74, 78] These differences may be explained by methodological differences inherent to the cadaveric setup, limited selection of analyzed patellofemoral attachments, different loading conditions, and not considering the wrapping effect. The length change patterns of the anatomic MPFL suggest that its role is to prevent dislocations with the knee in extension and early flexion angles (which has been shown to be where the patella luxates most easily[2]) as well as keep the patella medially enough, pulling it toward and enabling its entrance in the trochlea, corroborating the MPFL function descriptions by Bicos et al.[8] At deeper flexion angles, the MPFL slackens, and its stabilization is primarily dependent on the patellofemoral geometry and becomes less important.[26] Perhaps because the patellofemoral geometry takes over the role as primary restraint to lateral patellar displacement at knee flexion angles beyond 30°, it is not necessary for the anatomic MPFL to be an isometric structure, as it is only providing secondary stability at deeper flexion angles.

Another key element for achieving successful MPFL reconstruction is the knee flexion angle for graft fixation.[63] Currently, there is no consensus on graft fixation angles in MPFL reconstruction; fixation angles varying from 0° to 90° have been proposed/used.[17,20,70] As the patellofemoral attachment combination determines its length change pattern, it is important for surgeons to realize that the graft fixation angle recommendations are attachment location specific. For example, graft fixation at 0° of flexion for a graft with a proximal femoral attachment will result in a graft that is slack in extension and early flexion angles and tightens with knee flexion, whereas a graft with a distal femoral attachment would be tight in extension and early flexion and slacken with knee flexion (Fig. 5). Previously, it was shown that minor changes in tunnel positioning and graft tensioning could already cause increased cartilage contact pressure.[63] Therefore, because the anatomic MPFL is longest at 0° of flexion, with a central patellar attachment, this may be the most suitable knee position for graft fixation to prevent overconstraint of the patellofemoral joint as the knee goes into flexion.

High complication rates have been described after MPFL reconstruction.[43,58] However, only few reports have described the potential causes of postoperative complications in the eye of femoral tunnel placement.[10,13,52,56,57] In the case series by Camp et al.,[13] nonanatomic femoral positioning of the MPFL was found to be the only significant risk factor for failure. Sanchis-Alfonso et al.[52] found that failed MPFL reconstruction was significantly anteriorly when compared with clinically successful reconstruction. Bollier et al.[10] found that graft positioning anterior and proximal to the anatomic femoral MPFL attachment caused medial patellofemoral articular overloading, iatrogenic medial subluxation, or recurrent lateral instability. These adverse outcomes may, in part, be explained by the length changes found in this study for such proximal and anterior attachments, which showed an increase in length with increasing flexion angles, causing the MPFL graft to overconstrain the patellofemoral joint and to repetitively elongate, leading to attenuation of the MPFL graft and ultimately failure. However, others were unable to find such strong correlations between femoral tunnel positioning and worse patient outcomes.[57] Future studies should focus on the tunnel location and postoperative outcomes to provide better insight on its clinical importance.

Finally, these data may be used in settings in which the above-suggested ideal femoral and patellar MPFL tunnel placements are impeded, for example, in revision cases with tunnels of the initial surgical procedure present. The heat maps per patellar attachment can serve as a map for surgeons to find the length changes that can most closely replicate the physiological length changes for MPFL reconstruction.

Limitations

There are some limitations to this study. Only healthy participants were studied. Future studies should include groups with patellar instability and patellofemoral abnormalities such as patella alta, trochlear and patellar dysplasia, a laterally positioned tibial tubercle, and the recently described variable short lateral posterior condyle.[49] Data were acquired during a lunge motion. Future studies may analyze different activities with different muscle loading conditions. The length changes were normalized to the MPFL length as measured with the leg in full extension as a reference. The precise reference lengths (zero load length) are unknown because of the in vivo nature of the study; hence, no force or true strain could be measured. Finally, no MPFL reconstruction was performed in the present study, so no definite conclusions could be generated regarding the most optimal graft positions.

Conclusions

The most isometric location for MPFL reconstruction was posterior and proximal to the anatomic femoral MPFL attachment. The anatomic MPFL is a dynamic, anisometric structure that was tight in extension and early flexion and near isometric beyond 30° of flexion.

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