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PODCAST In-Depth

In Vivo Length Changes Between the Attachments of the Medial Patellofemoral Complex Fibers in Knees With Anatomic Risk Factors for Patellar Instability

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Background: Medial patellofemoral complex (MPFC) reconstruction plays an important role in the surgical treatment of patellar instability. Anatomic reconstruction is critical in re-creating the native function of the ligament, which includes minimizing length changes that occur in early flexion. Anatomic risk factors for patellar instability such as trochlear dysplasia, patella alta, and increased tibial tuberosity to trochlear groove (TT-TG) distance have been shown to influence the function of the MPFC graft in cadaveric studies, but the native length change patterns of the MPFC fibers in knees with anatomic risk factors have not been described.

Purpose: To describe the in vivo length changes of the MPFC fibers in knees with anatomic risk factors for patellar instability and identify the optimal attachment sites for MPFC reconstruction.

Study Design: Controlled laboratory study.

Methods: Dynamic computed tomography imaging was performed on the asymptomatic knee in patients with contralateral patellar instability. Three-dimensional digital knee models were created to assess knees between 0° and 50° of flexion in 10° increments. MPFC fiber lengths were calculated at each flexion angle between known anatomic attachment points on the extensor mechanism (quadriceps tendon, MPFC midpoint [M], and patella) and femur (1, 2, and 3, representing the proximal to distal femoral footprint). Changes in MPFC fiber length were compared for each condition and assessed for their relationships to morphologic risk factors (trochlear depth, Caton Deschamps Index [CDI], and TT-TG distance).

Results: In 22 knees, native MPFC fibers were found to be longer at 0° than at 20° to 50° of flexion. Length changes observed between 0° and 50° increased with the number of risk factors present. In the central fibers of the MPFC (M-2), 1.7% ± 3.1% length change was noted in knees with no anatomic risk factors, which increased to 5.6% ± 4.6%, 17.0% ± 6.4%, and 26.7% ± 6.8% in the setting of 1, 2, and 3 risk factors, respectively. Nonanatomic patella-based attachments were more likely to demonstrate unfavorable length change patterns, in which length was greater at 50° than 0°. In patellar attachments, an independent relationship was found between increasing length changes and TT-TG distance, while in quadriceps tendon attachments, a trend toward a negative relationship between length changes and CDI was noted. All configurations demonstrated a strong relationship between percentage change in length and number of morphologic risk factors present, with the greatest influence found in patella-based attachments.

Conclusion: The MPFC fibers demonstrated increased length changes in knees when a greater number of morphological risk factors for patellar instability were present, which worsened in the setting of nonanatomic configurations. This suggests that the function of the intact MPFC in patients with anatomic risk factors may not reflect previously described findings in anatomically normal knees. Further studies are needed to understand the pathoanatomy related to these changes, as well as the implications for graft placement and assessment of length changes during MPFC reconstruction techniques.

Clinical Relevance: MPFC length change patterns vary based on the number of morphologic risk factors for patellar instability present and should be considered during reconstructive procedures.

Keywords: knee; ligaments; patella; biomechanics; patellofemoral; medial patellofemoral complex; medial patellofemoral ligament; TT-TG distance; patella alta

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Patellar dislocation occurs at a reported rate of 5.8 to 29 per 100,000 individuals, and reconstruction of the ligamentous stabilizers can be indicated for patients who have

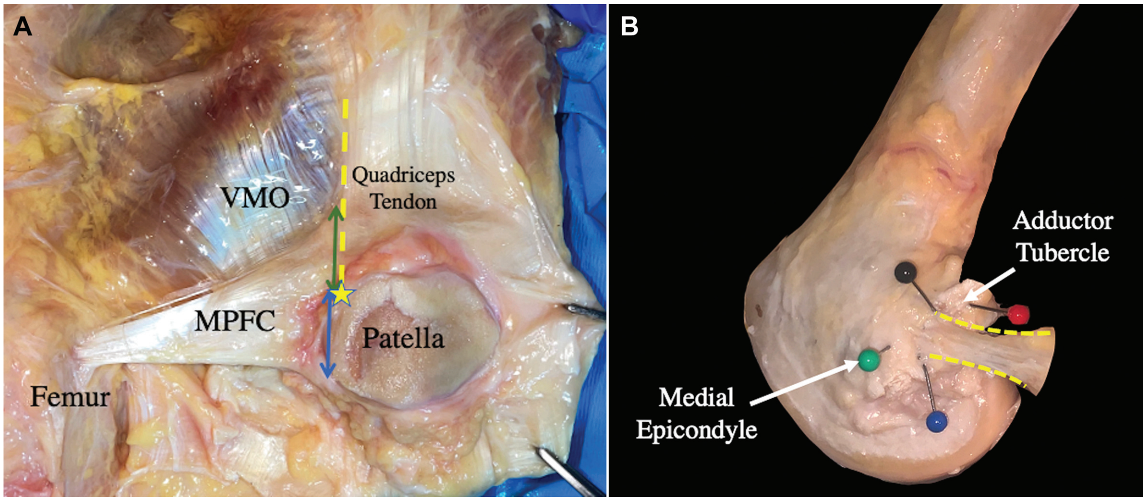

Figure 1. (A) Articular-sided view of a right knee demonstrates the medial patellofemoral complex (MPFC) attachment to the patella (blue line) and quadriceps tendon (green line). The midpoint (yellow star) of the MPFC can be identified at the junction of the medial border of the quadriceps tendon (dashed yellow line) and articular surface of the patella. (B) Medial view of right knee dissection demonstrates the elongated attachment of the MPFC (dashed lines) to the femur, posterior to the medial epicondyle and distal to the adductor tubercle. VMO, vastus medialis obliquus.

recurrent dislocations or are at high risk of redislocation.[6,14,19,20,24,36,41,57] "Medial patellofemoral complex" (MPFC) is the term used to describe the primary static stabilizer to lateral patellar translation.[49,52,53] Originally described as the medial patellofemoral ligament (MPFL), studies over the past 10 years have highlighted the variable attachment of this ligament to both the patella (MPFL) and the quadriceps tendon (medial quadriceps tendon femoral ligament [MQTFL])[17,27,33,42,47,53] (Figure 1).

MPFC reconstruction has been shown to restore patellar stability and improve knee function and quality of life in patients with patellar dislocations, with low rates of redislocation or persistent symptoms.[10,26,45] However, knees with morphologic risk factors, including patella alta, coronal malalignment, and trochlear dysplasia, have been associated with a greater rate of revision surgeries, redislocations, and persistent instability than knees with normal morphology.[26] In the setting of severe morphologic risk factors, concurrent procedures such as tibial tuberosity osteotomy to address bony malalignment or patella alta, or trochleoplasty in the setting of severe trochlear dysplasia, have been described in conjunction with MPFC reconstruction, yet the exact indications for each additional procedure, particularly in combination, have not been defined.[11,16,18,21,29,37,50]

One of the important goals of MPFC reconstruction surgery is re-creating the proper function of the ligament by minimizing length changes during range of motion.[32,40,48,55] Abnormal length change patterns of the graft can occur because of inappropriate graft positioning and have been associated with abnormal patellar kinematics and contact pressures, increased graft strain, and increased risk of graft failure.[8,9,15,31] Because of this, surgical techniques during MPFC reconstruction have emphasized the importance of assessing and minimizing graft length changes intraoperatively to properly re-create the function of the native MPFC.[12]

The native MPFC has been reported to be longest in extension while remaining relatively constant in length from 0° to 60°.[35,42] Less is known about the intact function of the MPFC in morphologically abnormal knees. Cadaveric studies have simulated the presence of morphologic risk factors to determine their influence on graft function.[34,43] Stephen et al[43] reported that when the tibial tuberosity was displaced laterally to create a tibial tuberosity to trochlear groove (TT-TG) distance >20 mm, MPFC

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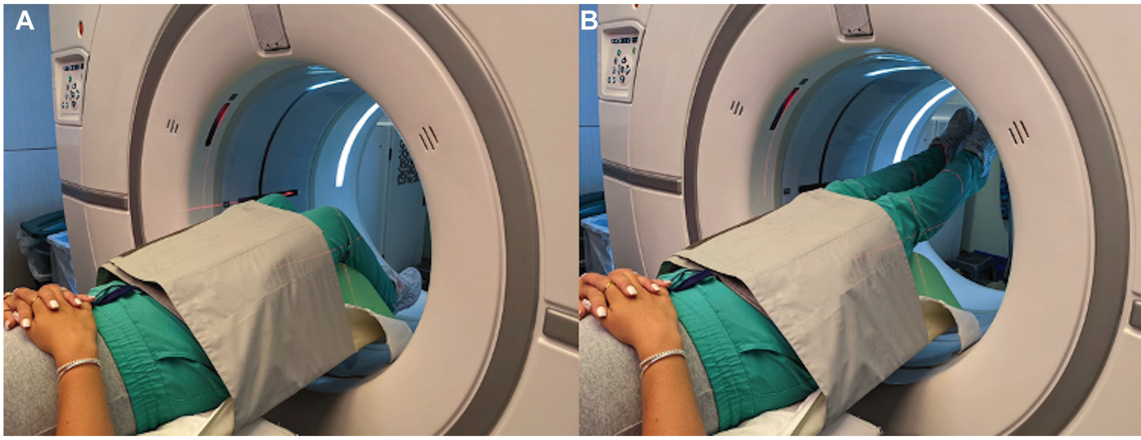

Figure 2. (A) The knees are positioned within the gantry on a foam wedge, and (B) the patient is instructed to fully extend both knees and lower them to the original position over the course of 10 seconds.

reconstruction did not properly restore patellar kinematics. Redler et al[34] further demonstrated in a biomechanical study that the combination of risk factors created by altering the position of the tibial tuberosity to reflect Caton Deschamps Index (CDI) >1.4 and TT-TG distance >20 mm led to the greatest MPFC length changes between 20° and 110°.

While the association between simulated morphological risk factors and MPFC length change patterns has been demonstrated in cadaveric studies, length changes in the intact MPFC in patients with morphological risk factors have not been described. Furthermore, these studies have yet to incorporate the expansion of MPFC fibers that include the broad attachments on the extensor mechanism and femur. As morphologic abnormalities have been shown to occur in both knees of patients with unilateral patellar instability,[5] the purpose of this study was to describe in vivo length changes between the attachments of the MPFC fibers in knees with anatomic risk factors for patellar instability and to assess the influence of morphologic risk factors, including patella alta, tuberosity lateralization, and trochlear dysplasia, on these patterns. Through this, we aimed to identify the optimal attachment sites for MPFC reconstruction. We hypothesized that MPFC length between attachment sites would vary by flexion angle, and that the number of morphologic risk factors present in each knee would correlate with the magnitude of length changes. We further hypothesized that the primary risk factor influencing length changes would vary based on the location of attachment sites on the extensor mechanism and femur.

METHODS

This study was approved by our institutional review board. Patients of the primary author (M.J.T.) with unilateral recurrent patellar instability underwent dynamic computed tomography (CT) imaging as part of routine workup for patellar stabilization surgery, and their contralateral asymptomatic knees were included in the study. Inclusion criteria were patients with a history of unilateral recurrent patellar instability between the ages of 12 and 40 years who had no symptoms in the contralateral knee. Exclusion criteria were bilateral knee symptoms or a history of injury or previous surgery in the nonoperative knee.

Dynamic Imaging

Dynamic CT imaging of both knees was performed using an adaptation of the description by Cosgarea and Carrino and colleagues.[7,51] All scans were performed on the GE Revolution CT scanner in cine mode. Patients were positioned in the gantry in a supine position with a wedge under the knees, resulting in 50° of knee flexion (Figure 2A). Over the course of 10 seconds, patients were instructed to actively extend both knees to full extension (Figure 2B) and then lower them to the original position. Twenty 0.5-second, 15 cm–long acquisitions were obtained over the 10-second scan, preceded by 1 static scan in knee extension with the quadriceps relaxed.

Static Imaging Measurements

On static CT images obtained in extension, the morphologic characteristics of each knee were recorded using standardized measurements of patellofemoral morphology. The morphology of the trochlea was quantified by measuring trochlear depth.[1] Using the axial view of the femur that best demonstrated the Roman arch of the intercondylar notch, we measured the trochlear depth by subtracting the distance from the trochlear groove to the posterior condylar axis from the mean of the height of the medial and lateral femoral condyles (Figure 3A). As a measurement of patellar height, the CDI was measured on sagittal images as the ratio between a line from the distal articular pole to the anterior tibia and the articular length of the patella[3] (Figure 3B). To quantify tuberosity lateralization, TT-TG distance was measured as the lateral distance from the deepest point of the trochlear groove to the center of

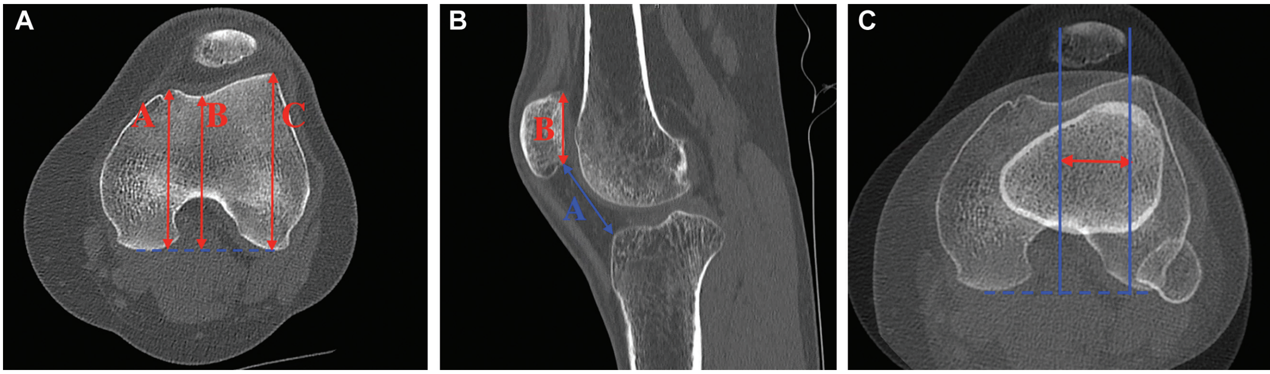

Figure 3. (A) Trochlear depth was measured by subtracting the distance of the trochlear groove to the posterior condylar axis from the mean height of the medial and lateral femoral condyles ([*A* + *C*]/2 – *B*). (B) The Caton Deschamps Index was measured as the ratio between a line from the distal articular pole to the anterior tibia and the articular length of the patella (A/B). (C) The tibial tuberosity to trochlear groove distance was measured as the lateral distance of the tibial tuberosity to the deepest point of the trochlear groove, along the axis of the posterior condyles.

the tibial tuberosity, along the axis of the posterior condyles[4] (Figure 3C).

3-Dimensional Measurements

Volume-rendered 3-dimensional (3D) digital knee models were derived from each frame of the dynamic CT as images of the knee were captured during active extension and flexion. Images were assessed at 0°, 10°, 20°, 30°, 40°, and 50° of knee flexion. At each flexion angle, the MPFC length was calculated based on the distance between the known anatomic attachment points on the extensor mechanism and femur.

On the extensor mechanism, the midpoint of the MPFC attachment was identified at 19% of the patellar articular length distal to the superior pole, which has previously been described as the radiographic midpoint of the anterior MPFC attachment.[52,53] Given the 30-mm attachment on the patella and quadriceps tendon that has been described, the MPFC landmarks were assigned as the following: Q, representing the most proximal MQTFL fibers at the proximal margin of the complex, 15 mm in the proximal direction along the quadriceps tendon border[47]; M, at the midpoint of the MPFC; and P, representing the distal-most MPFL fibers 15 mm in the distal direction on the medial border of the patella (Figure 4).

On the femur, a point 1 cm distal to the prominence of the adductor tubercle was identified as the center of the MPFC footprint, as has been previously described.[42,54] The femoral footprint was re-created in its anatomic position, with a length of 10 mm at a 14° angle relative to the axis of the femur.[46] The femoral landmarks were assigned as follows: 1, the most proximal aspect of the footprint, indicating the MQTFL fibers; 2, the midpoint of the footprint, 1 cm distal to the adductor tubercle; and 3, the most distal aspect of the femoral footprint, consistent with MPFL fibers (Figure 4).

All points were selected by a sports medicine–trained orthopaedic surgeon (M.J.T.) with expertise in patellofemoral surgery. The distance between the defined points on the femur and extensor mechanism were measured in the following conditions: (1) anatomic MPFC fibers, including the proximal (Q-1), middle (M-2), and distal (P-3) fibers; (2) nonanatomic configurations with attachments on the quadriceps tendon (Q-2 and Q-3); and

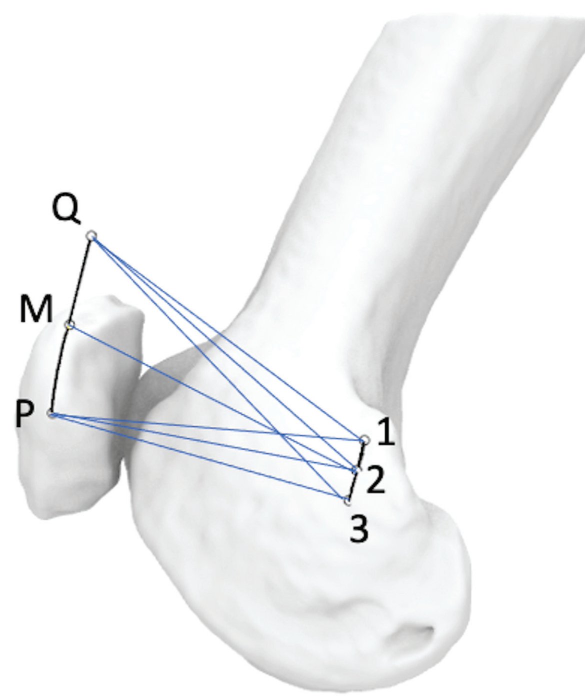

Figure 4. On the extensor mechanism, the most proximal attachment (*Q*) of the medial patellofemoral complex, midpoint (*M*), and distal attachment (*P*) were marked as a 30-mm attachment. On the femoral side, the proximal (*1*), middle (*2*), and distal (*3*) aspects of the 10-mm footprint were identified.

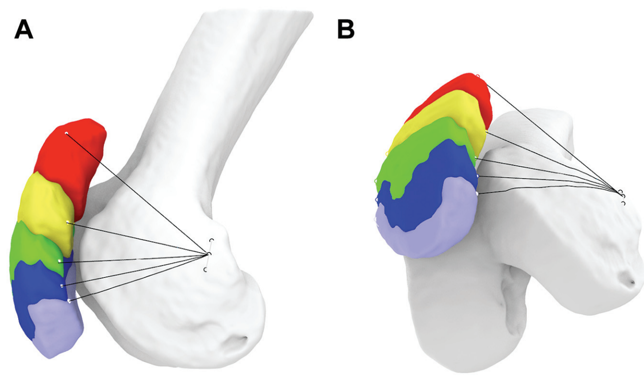

Figure 5. A 3-dimensional model of a right knee is shown from the (A) medial and (B) inferomedial views. The distances from the selected points on the femur and extensor mechanism were calculated at each knee flexion angle, with straight line representation of the fibers allowed to wrap around the femoral condyle to ensure accurate length measurements.

(3) nonanatomic configurations with attachments on the patella (P-1 and P-2). The distances between each set of points were calculated, with straight line representation of the fibers allowed to wrap around the femoral condyle to ensure accurate length measurement between the selected patellar and femoral points (Figure 5). All 3D measurements and analyses were performed using Rhinoceros 3D Software Version 6 (McNeel).

Statistical Analysis

A sample size calculation was performed based on changes in MPFC length at flexion angles between 0° and 50° of knee flexion. The variation in length changes between flexion angles was estimated to be ±3.0%. A sample size of 18 knees provides 80% power to detect an overall 8.5% length difference at flexion angles between 0° and 50° as described by Kernkamp et al,[23] with an alpha error of 10%. A secondary aim of the study was to evaluate potential morphological risk factors for MPFC length changes. To ensure the sample size was adequate for an exploratory analysis, a second sample size calculation was performed. In a cadaveric model, identifying potential risk factors would require morphological variables including trochlear dysplasia, patella alta, and tuberosity lateralization to demonstrate medium size effects (0.5) on MPFC length changes. A sample size of 22 knees provides 80% to detect a medium effect (0.5) with an alpha error of 10% in linear multiple regression model with 3 risk factors. Sample size calculations were performed using G*Power Version 3.1.9.6.

Descriptive statistics were used to describe MPFC length based on each configuration at each knee flexion angle. Length changes were presented in percentage change to account for differences in patient size. One-way analysis of variance testing with the post hoc Tukey Honestly Significant Difference test was performed to assess for significant differences in MPFC fiber length at each knee flexion angle.

Knees were then categorized by the number of morphologic risk factors present. Each morphologic abnormality was deemed to be present or absent based on known normal values, with CDI ≥1.2 indicating patella alta, TT-TG distance ≥20 mm indicating coronal malalignment, and trochlear depth ≤4 mm indicating dysplasia.[13] The cumulative number of risk factors was used to categorize each knee from 0 to 3 (0, no risk factors; 3, having all 3 risk factors including patella alta, tuberosity lateralization, and trochlear dysplasia).

Linear regression analysis was performed to assess the relationship between percentage change in MPFC length between attachment sites and the number of morphologic risk factors present. Stepwise multiple linear regression analysis was performed to identify independent relationships between MPFC length changes in each configuration and morphologic measurements of trochlear depth, CDI, and TT-TG distance.

All analyses were performed using Real Statistics Resource Pack software (Release 7.2) in Excel (Microsoft). Statistical significance was set at P value ≤.05.

RESULTS

In total, 29 patients with unilateral patellar instability underwent dynamic CT imaging. Six knees were excluded for not having adequate images for analysis that reached full extension, and 1 was excluded because of lack of optimal quality of imaging. A total of 22 asymptomatic knees were included in this study (8 male, 14 female), with a mean patient age of 22.3 ± 6.6 years. The characteristics of the knees included in the study group are shown in Table 1.

The results of MPFC length measurements are shown in Figure 6A. In the configurations representing the native MPFC fibers (Q-1, M-2, and P-3), the calculated length was greatest at 0°, with significant differences when compared with 20° (P = .024-.049), 30° (P = .004-.040), 40° (P = .001-.012), and 50° (P < .001 to .003) of knee flexion. No significant length differences were noted between other combinations of knee flexion angles. No differences in total length change between 0° and 50° were observed between the anatomic configurations (Q-1, M-2, and P-3).

In the nonanatomic configurations, attachments to the quadriceps tendon (Q-2 and Q-3) demonstrated significant length differences between 0° versus 20° to 50° (P < .001 to .015), as well as between 10° versus 40° and 50° (P < .001-.033) (Figure 6B). Nonanatomic attachments to the patella (P-1 and P-2) demonstrated no differences in mean length throughout range of motion (Figure 6C). However, nonanatomic attachments to the patella more frequently demonstrated unfavorable length change patterns with a shorter distance at 0° than 50°, which is consistent with graft tightening in flexion, when compared with quadriceps tendon attachments (40.9% vs 6.8%; P < .001).

MPFC length changes based on the number of morphological risk factors present in each knee are shown in Table 2 and Figure 7. A significant difference in length change was identified when comparing knees with 0 or 1 risk

TABLE 1
Characteristics of the Knees Included in This Study[a]

Number of Risk Factors (n of knees)	Female	Age	Trochlear Depth	CDI	TT-TG Distance
0 (n = *6*)	4 (66.7)	20.3 ± 3.7	5.8 ± 0.8	1.0 ± 0.1	13.5 ± 2.8
1 (n = *4*)	0 (0)	18.6 ± 0.8	4.2 ± 0.8	1.0 ± 0.1	21.1 ± 1.7
2 (n = *9*)	7 (77.8)	22.3 ± 4.6	3.0 ± 1.5	1.2 ± 0.1	17.7 ± 4.1
3 (n = *3*)	3 (100)	31.0 ± 13.1	1.8 ± 0.7	1.3 ± 0.1	22.0 ± 2.3

[a]Data are presented as n (%) or mean ± SD. CDI, Caton Deschamps Index; TT-TG, tibial tuberosity to trochlear groove.

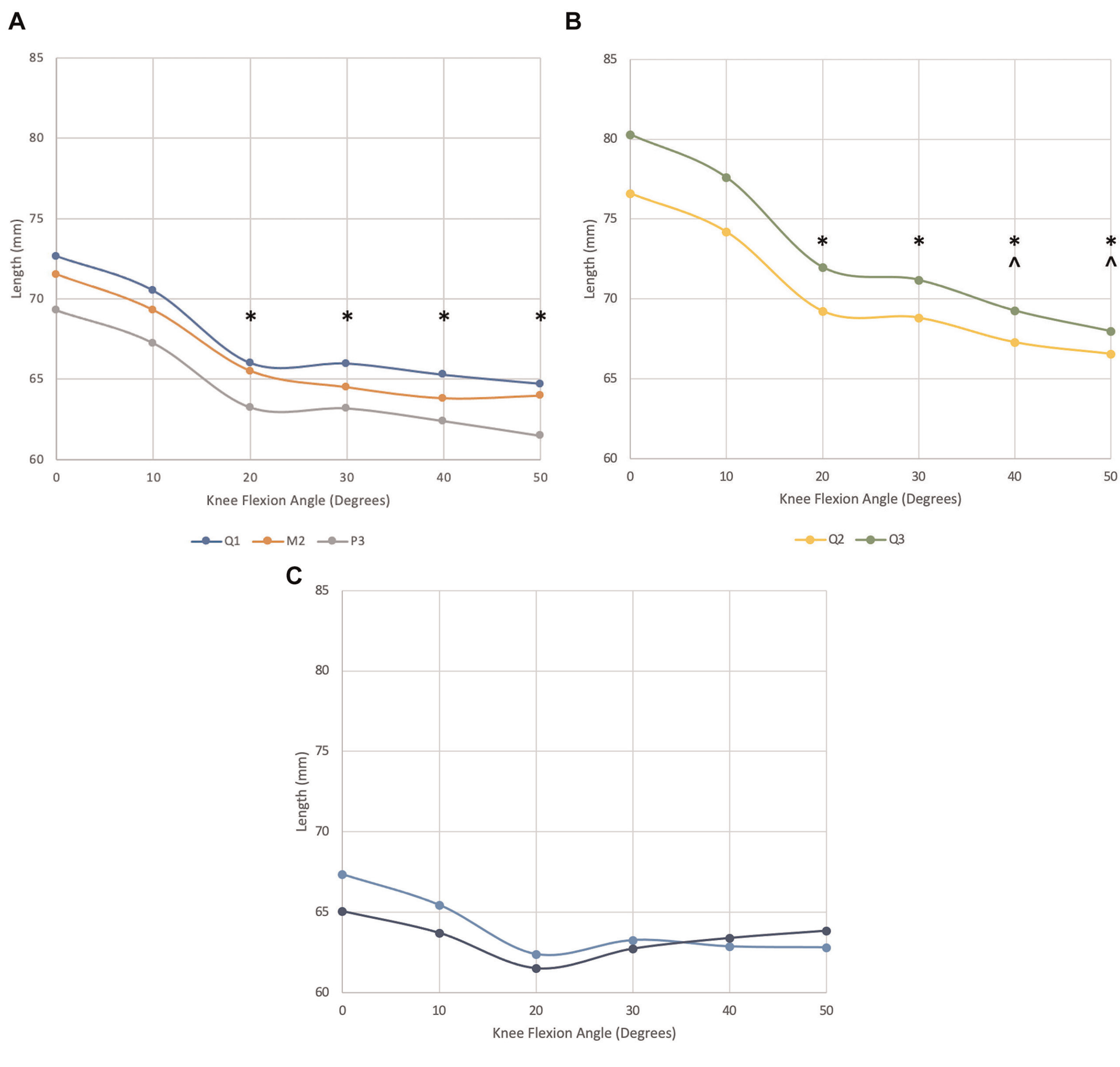

Figure 6. (A) Mean calculated lengths of native medial patellofemoral complex fibers are shown from 0° to 50° of knee flexion. *Significant differences in all conditions when compared with values at 0°. (B and C) Mean calculated lengths of nonanatomic graft attachments from 0° to 50° of knee flexion. *Significant differences in all conditions when compared with values at 0°; ^significant differences in all conditions when compared with values at 10°. See text for definitions of fiber lengths.

TABLE 2
Medial Patello Femoral Complex Length Changes and Comparisons Based on Number of Morphological Risk Factors Present in Each Knee[a]

	No. of Anatomic Risk Factors, %				
	0 (n = 6)	1 (n = 4)	2 (n = 9)	3 (n = 3)	Significance (0 and 1 vs 2 and 3)
Anatomic					
Q-1	3.3 ± 4.3	6.3 ± 11.4	18.7 ± 10.2	23.1 ± 11.0	<.001
M-2	1.7 ± 3.1	5.6 ± 4.6	17.0 ± 6.4	26.7 ± 6.8	.001
P-3	1.0 ± 4.5	5.9 ± 5.7	17.9 ± 9.8	33.6 ± 7.9	<.001
Nonanatomic					
Q-2	6.6 ± 6.0	10.2 ± 9.5	20.1 ± 10.3	25.9 ± 9.4	<.001
Q-3	10.1 ± 6.9	12.4 ± 9.8	23.8 ± 10.0	38.5 ± 8.8	<.001
P-2	–4.2 ± 5.2	1.9 ± 4.8	11.9 ± 9.5	27.7 ± 9.5	.002
P-1	–8.4 ± 4.8	–2.9 ± 4.0	5.7 ± 8.9	21.7 ± 10.8	.002

[a]Data are presented as mean ± SD.

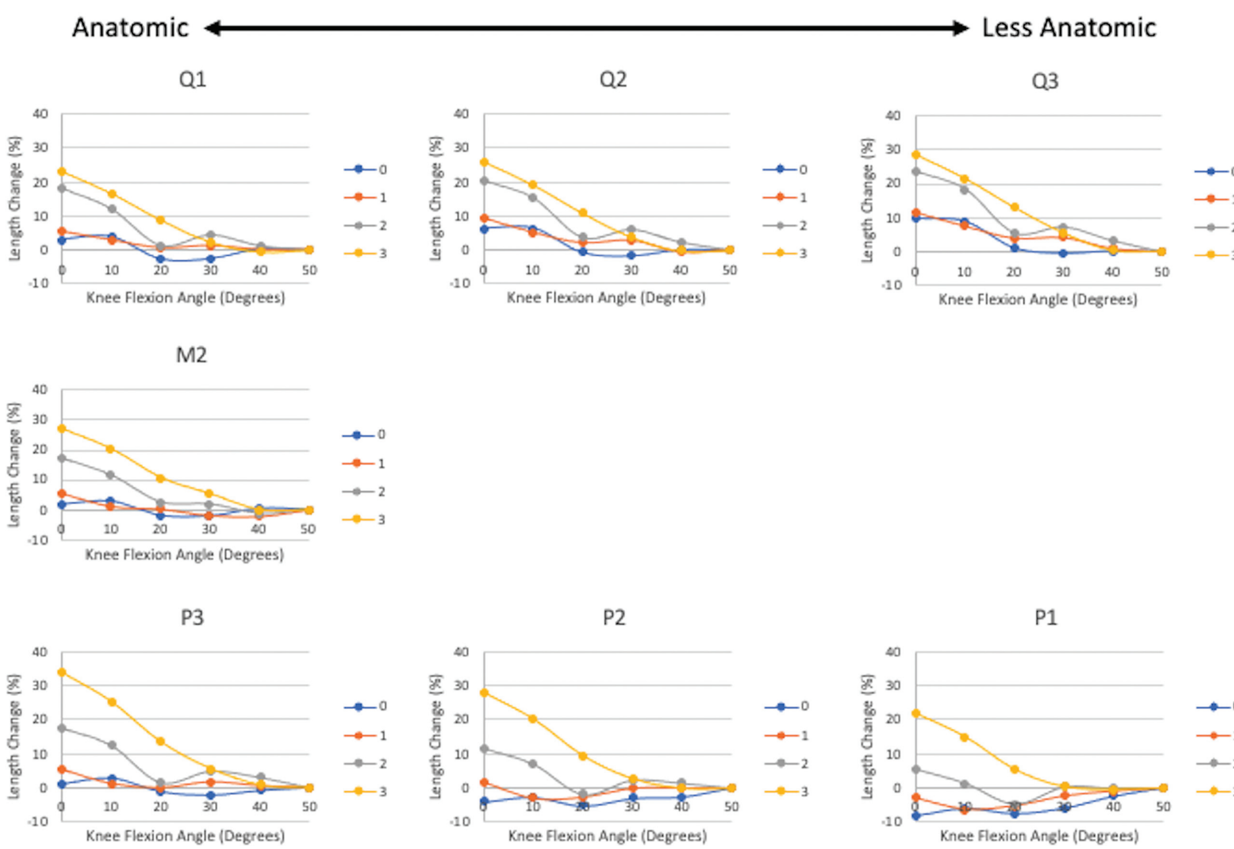

Figure 7. Differences in medial patellofemoral complex fiber length changes by percentage based on the number of morphological risk factors present in each knee.

factors versus knees with 2 or 3 risk factors in all conditions ($P < .001$ to $P = .002$).

In all groups, the number of morphologic risk factors present in each knee demonstrated a strong relationship with percentage change in length between 0° and 50° of knee flexion (R = 0.62-0.85) (Figure 8). Of the linear regression models, the greatest slope was found in configurations with patellar attachments.

Stepwise multiple regression analysis demonstrated no significant relationships with anatomic measurements in knees with 0 or 1 risk morphologic factor. In knees with 2 or 3 risk factors, stepwise multiple regression

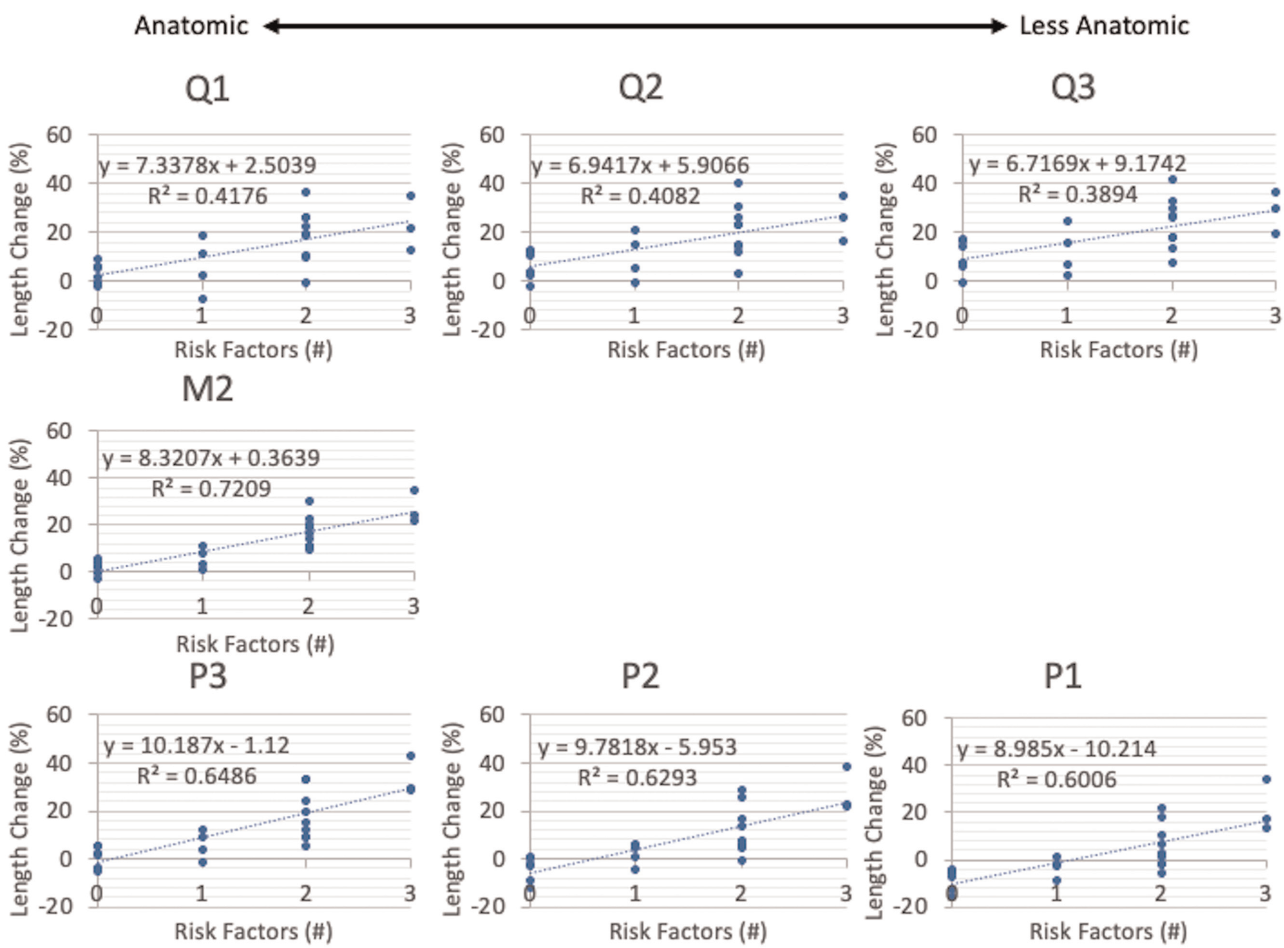

Figure 8. The association between number of morphological risk factors present and medial patellofemoral complex fiber length changes.

demonstrated an independent positive relationship between increasing length change and TT-TG distance in patella-based attachments, including P-3 (R = 0.60; R^2 = 0.36; slope = 1.6; P = .040), P-2 (R = 0.59; R^2 = 0.35; slope = 1.7; P = .041), and P-1 (R = 0.60; R^2 = 0.36; slope = 1.7; P = .038). A trend toward an independent, negative relationship with CDI was noted with length changes when attached to the quadriceps tendon in Q-1 (R = 0.51; R^2 = 0.26; slope = –4.2; P = .092), Q-2 (R = 0.55; R^2 = 0.30; slope = –4.5; P = .065), and Q-3 (R = 0.55; R^2 = 0.30; slope = –4.3; P = .065).

DISCUSSION

The most important finding in this study was that in asymptomatic knees with morphologic risk factors for patellar instability, MPFC length changes between 0° and 50° increased with the number of anatomic risk factors present. Furthermore, patella alta was found to influence length changes in the setting of proximal fixation on the extensor mechanism, and TT-TG distance influenced length changes in the setting of distal fixation.

Previous studies have described the function and length changes of the MPFL, before the expanded understanding of its anatomy that led to use of the term "MPFC." Smirk and Morris[42] initially described the isometric function of the MPFL in a cadaveric study to determine the optimal attachment sites during reconstruction. In their study, they considered length change patterns to be appropriate if there was <5-mm length change throughout range of motion. The authors reported that the optimal attachment sites included the proximal one-third of the patella and a location 1 cm distal to the adductor tubercle on the medial femur. Similarly, Stephen et al[44] reported in a cadaveric study that using the central MPFL attachment sites led to 2.1 ± 2.3 mm length changes in the graft between 0° and 40° of knee flexion. Since these studies were published, our understanding of MPFC anatomy has evolved to incorporate the expansion of fibers attaching to the quadriceps tendon, as well as the corresponding elongated femoral footprint. By incorporating these additional components of the native MPFC, we similarly found that knees with no morphological risk factors demonstrated minimal length changes ranging from 1.0% to

3.3% in the anatomic configurations, which is equivalent to <2 mm based on the mean MPFC length in this study group. However, nonanatomic configurations, even if attached within the known anatomic footprints, led to unfavorable length changes. We additionally found that the presence of ≥2 morphologic risk factors led to greater length changes in the intact MPFC between 0° and 50°, suggesting that MPFC function in knees with anatomic risk factors may not reflect those described in cadaveric biomechanical studies.

To assess the in vivo function of the MPFC, other studies have measured MPFC length changes using dynamic imaging in the knees of healthy patients.[23,56] Kernkamp et al[23] assessed in vivo length changes of the MPFC during a lunging motion using a combined CT and biplanar fluoroscopic imaging technique. Using 3D measurements at the central aspect of the MPFC, they found that the ligament was longest in extension and decreased by 8.5% around 30° of flexion, remaining nearly isometric in >30° of knee flexion. Similar patterns of length changes were reported by Wang et al,[56] with the MPFC remaining isometric in >35° of knee flexion.[23] Our study utilized a comparable technique to calculate MPFC length and confirmed similar patterns of decreasing length between 0° and 30° with no significant change in >30° of flexion, as evidenced by 1.0% to 6.3% length change in the group with 0 or 1 risk factors. While our study confirms that patterns of length change remain constant in >30° of flexion, we additionally found that the magnitude of length change varies by the number of risk factors present. Further study is needed to understand the clinical significance of these changes that were observed in asymptomatic knees, as well as to identify the role of reconstruction to re-create the normal function of the MPFC in knees with anatomic risk factors.

Oka et al[30] measured distances between MPFC attachments in healthy volunteers using a combination of CT and biplanar radiographs at 0° to 120° in 30° increments. In their study, they defined the patellar insertion site at the most medial aspect of the patella, which is comparable with point P in our study. They also found that proximal malpositioning on the femoral attachment led to unfavorable length changes, similar to our study. In our study, we included additional points on the extensor mechanism that demonstrated the importance of anatomic configurations when varying the attachment sites on the extensor mechanism or femur. Using preprogrammed conditions of graft length, the authors described the role of a simulation system to predict the optimal femoral insertion site of the MPFC. Further studies are needed to evaluate the utility of such a program with additional attachment sites on the extensor mechanism and consideration of the role of anatomic risk factors.

The influence of morphological risk factors on MPFC graft function has been shown previously in cadaveric studies, based on prior anatomic descriptions. Stephen et al[43] demonstrated that MPFC reconstruction did not adequately restore patellofemoral kinematics and contact pressures when the tibial tuberosity was lateralized >10 mm from its anatomic position, which is consistent with a TT-TG distance >20 mm. The authors measured patellar tracking and contact pressures at 0°, 10°, 20°, 30°, 60°, and 90° of knee flexion before and after reconstruction, while adding lateralizing tibial tuberosity osteotomy in 5-mm increments. They found the patella was positioned 2.0 ± 5.0 mm laterally with the tuberosity in a normal position, and 6.9 ± 7.0 mm with the tuberosity lateralized 15 mm from its anatomic position, which did not correct to its normal position with MPFC reconstruction alone. On this basis, the authors suggested that MPFC reconstruction in the setting of increased TT-TG distance may result in high graft tension and subsequent abnormal patellofemoral contact stresses. Similarly, Redler et al[34] demonstrated increased length changes in MPFC grafts in the setting of greater TT-TG distance and patella alta. In their cadaveric study, the authors measured length changes using a suture between a point at 41% of the medial border of the patella and the Schöttle point on the femur. They performed a tibial tuberosity osteotomy to create conditions of patella alta, as well as increased TT-TG distance, and a combination of both. The authors reported a length change between 20° and 110° of 3.9 ± 1.4 mm with a CDI of 1.4, 3.0 ± 0.5 mm with a TT-TG distance of 25 mm, and 4.7 ± 1.4 mm with the combination of both abnormalities. They concluded that patella alta had the greatest effects on MPFC anisometry, but that the presence of both patella alta and increased TT-TG distance led to the greatest changes. Their reported length changes were smaller than in our study, however the authors analyzed length changes from 20° to 110°, while we performed analyses from 0° to 50°, and the first 30° of flexion has been shown to demonstrate the greatest length changes.[23,42,44,56] We similarly found that the presence of tuberosity lateralization and patella alta led to increased length changes between attachment sites, particularly when >1 risk factor was present. Additionally, we incorporated the broad attachment of the MPFC fibers and found that length change patterns were influenced by different anatomic factors based on the proximal versus distal attachments on the extensor mechanism, with CDI influencing the proximal attachments and TT-TG distance influencing the distal attachments. Further study is needed to identify the optimal reconstructive techniques to re-create the normal function of the MPFC based on individual anatomy.

Length changes of the MPFC as they relate to trochlear dysplasia have not been commonly described, and multiple definitions and radiographic parameters defining trochlear dysplasia currently exist. Campos et al[2] compared radiographs of patients with and without patellar instability and identified the isometric point based on the center of best-fit circles to match the trochlear groove on lateral views. They compared the distance from the isometric point to Schöttle point on the femur and found that knees with severe dysplasia, as defined by trochlear boss height, had an isometric point that was increasingly anterior to the Schöttle point. The authors suggested based on these findings that fixation of an MPFC graft at the Schöttle point in the setting of trochlear dysplasia could lead to a significantly anisometric graft. In our study, we based our landmarks on 3D anatomy and quantified dysplasia on CT imaging using axial measurements to assess the depth of the trochlea. As the role of axial measurements has been shown to be limited when evaluating the shape of the distal femur, further study of the optimal quantitative measurement to define trochlear dysplasia is needed to understand its role in the function of the MPFC graft.[28]

To identify the differential roles of the MPFC fibers, Huddleston et al[22] performed a cadaveric study to measure length changes between the MPFC midpoint on the femur at the Schöttle point and multiple attachment sites on the extensor mechanism, including the middle of the patella, the proximal patella, the MPFC midpoint, and the proximal MPFC on the quadriceps tendon. The authors measured length changes between 0°, 20°, 40°, 60°, and 90° of knee flexion and reported that length changes were greatest with proximal attachments and smallest with distal attachments. However, this study utilized only the midpoint of the femoral attachment (landmark 2 in our study). In our study, the equivalent configurations using Q-2, M-2, and P-2 (indicating nonanatomic configurations on the quadriceps tendon and patella) showed that the smallest length changes exist in P-2, as was found in their study. However, while the authors did not note how many of the specimens demonstrated unfavorable length changes that were longer in flexion than extension, we found that the greater occurrence of this in the setting of distal/patellar fixation outweighs the benefit of an apparently improved isometric location. In contrast, fixation on the patella with a corresponding anatomic distal attachment on the femur (P-3) was found to have significantly fewer unfavorable patterns ($P < .001$), which were comparable with the other anatomic (M-2 and Q-1) fibers. These findings are consistent with those of Matsushita et al[25] and Kernkamp et al.[23] In Matsushita et al's study, the authors performed intraoperative evaluation of MPFC graft length changes. They reported that in 9 of 44 knees, when fixation was on the proximal one-third and center of the patella, fixation at the Schöttle point demonstrated unfavorable length change patterns that were corrected by moving the femoral position 5 to 7 mm distally or posterodistally, which is supported by our findings.

Identifying the appropriate femoral attachment site remains a challenge during MPFC reconstruction, and multiple anatomic and radiographic tools have been described to intraoperatively identify the midpoint of the femoral footprint.[38,39,44] If attaching a graft to the femoral midpoint during MPFC reconstruction, as is commonly performed, our findings suggest that using the corresponding MPFC midpoint on the extensor mechanism (at the junction of the medial quadriceps tendon and patella, or 19% distal to the superior articular pole) is optimal, as this re-creates M-2, or the central fibers of the MPFC. In our study, this configuration demonstrated the smallest length changes in the setting of low rates of unfavorable length change patterns and furthermore demonstrated the least influence of anatomic risk factors on length changes. Future studies should additionally examine the role of anatomic, fiber-specific MQTFL and MPFL reconstructions to better understand the efficacy and role of these procedures in the setting of patellar instability.

Limitations

This study has several limitations. While the calculated attachment points were considered to be anatomically accurate and were similar to those used in other studies, the actual anatomic attachment sites of the MPFC for each patient were not able to be identified and may differ from the points that were chosen. Furthermore, this study calculated length changes but did not assess biomechanical parameters such as graft strain, which may be useful in the assessment of MPFC function and its influence on patellar contact pressures. Last, while the knees in this study were confirmed to be asymptomatic with no patellar instability based on history and physical examination, quantified patient-reported function of the knee was not included, which may have provided further information on the clinical significance of the MPFC length changes.

CONCLUSION

In vivo length change patterns in the MPFC fibers demonstrated an increase in length changes in knees with a greater number of morphological risk factors for patellar instability present. These patterns were less favorable in the setting of nonanatomic configurations. This suggests that the function of the intact MPFC in patients with anatomic risk factors may not reflect previously described findings in patients with normal anatomy. Further studies are needed to understand the pathoanatomy related to these changes, as well as the implications for graft placement and assessment of isometry in MPFC reconstruction techniques.

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