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Anatomy of the Medial Patellofemoral Ligament: A Meta-Analysis

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SUMMARY

Purpose. To consolidate the anatomical data on medial patellofemoral ligament's (MPFL) morphology and relationships with surrounding structures of the knee and contribute towards facilitating planning reconstruction surgeries.

Methods. Electronic databases were searched for articles containing quantitative data regarding MPFL's morphology and distances to surgically relevant radiographic and anatomic landmarks from inception to April 2025. To synthesize the results of the included studies, a random-effects model via the Comprehensive Meta-Analysis Version 4 software was employed.

Results. Initially, 7,263 articles underwent evaluation. Ultimately, 64 articles met the inclusion criteria and were included. When measured at its midline in 0° degrees of flexion, the length was 56.87 mm (95%CI 54.38-59.37 mm). MPFL was widest at patellar insertion (23.17 mm; 95%CI 20.99-25.35 mm) and narrowest at femoral insertion (11.96 mm; 95%CI 10.63-13.29 mm). Its thickness in the middle part measured 1.17 mm (95%CI 0.91-1.43 mm). The center of MPFL's femoral insertion was located on average 9.17 mm (95%CI 7.38-10.97 mm) distally, 10.81 mm (95%CI 8.54-13.08 mm) proximally, 6.82 mm (95%CI 0.94-12.07 mm) posteriorly and 2.22 mm (95%CI 1.45-2.99 mm) anteriorly in relation to adductor tendon tubercle and on average 6.21 mm (95%CI 4.18-8.23 mm) posteriorly, 9.03 mm (95%CI 6.79-11.27 mm) proximally, and 4.77 mm (95%CI -0.30-9.84 mm) anteriorly in relation to the medial femoral epicondyle.

Conclusions. The presented data facilitates graft harvesting and optimal femoral tunnel placement for reconstruction.

Study registration. This study has been registered at the International Prospective Register of Systematic Reviews (PROSPERO, No CRD42023488062).

KEY WORDS

Medial patellofemoral ligament; lateral patellar dislocation; anatomy; knee surgery.

INTRODUCTION

The medial patellofemoral ligament (MPFL) is a part of a medial patellofemoral complex (MPFC) that provides 50-60% of the restraining force against lateral patellar dislocation. Therefore, rupture of this ligament, typically at the femoral origin, is an essential lesion causing lateral translation of the patella. Although first-time lateral dislocation of the patella is usually treated non-operatively, patients with MRI-confirmed MPFL avulsions are at high risk for reinjury, and early surgical intervention should be considered (1). When determining which patients experiencing their first dislocation might benefit more from operative intervention, it is important to take into account the patients' level of dysplasia and laxity (2).

Various surgical reconstruction techniques, typically with semitendinosus tendon, gracilis tendon, partial quadriceps tendon auto, or allografts or synthetic grafts, are being used, but a consensus regarding the most optimal method remains elusive. However, it is widely acknowledged that a clear understanding of the anatomy and morphology of the natural MPFL is crucial to achieving favorable surgical outcomes (3). Therefore, conducting a meta-analysis of MPFL anatomy and its relationship with surrounding structures is essential to guide more effective reconstructions. This is particularly important because an ideal MPFL graft should have anatomical and biomechanical similarities with the native ligament. A detailed meta-analysis of MPFL anatomy could help clinicians avoid significant discrepancies in the measurements and shape of the intact ligament and graft used for reconstruction, which can lead to complications such as patellar overload, medial patellofemoral arthritis, or even loss of postoperative movement (4). Another compelling reason to undertake a meta-analysis in this area is that the pivotal step during reconstruction is accurately identifying the ligament's origin of insertion. The femoral attachment site, which plays a critical role in ensuring proper isometry of the graft, remains controversial, as it has been described in several different locations (3-6). An additional justification for this research is that a thorough understanding of its anatomy is crucial, because placing the graft too proximally to the medial femoral epicondyle (MFE) can lead to a reconstructed MPFL being loose during extension and tight during flexion, potentially limiting knee flexion and causing excessive pressure, leading to chondral loss on the medial patellar facet. Conversely, positioning the femoral origin MPFL reconstruction too distally from the medial epicondyle can lead to tightness during extension and laxity during flexion lead to tightness during extension and laxity during flexion (5, 6).

Despite the current knowledge about MPFL being comprehensive, encompassing its anatomical structure, biomechanics, and clinical significance, there is no updated meta-analysis on this subject. In light of the previously discussed importance of detailed anatomical understanding for successful reconstructive surgery, the primary objective of this study was to integrate and consolidate the available anatomical data regarding its morphology and relationships with other structures of the knee. The anticipated outcomes of this meta-analysis are expected to contribute towards facilitating planning and performing surgeries on this anatomical entity and harvesting grafts with optimal properties for reconstruction.

MATERIALS AND METHODS

This meta-analysis was conducted in accordance with the PRISMA™ (Preferred Reporting Items for Systematic Reviews and Meta-Analysis) statement (7). In addition, this study has been registered at the International Prospective Register of Systematic Reviews (PROSPERO, No CRD42023488062). As this is a systematic review with meta-analysis with no direct reports of human and/or animal subjects data, conducting it required neither approval of an ethics committee nor participant informed consent.

Search Strategy and Information Sources

Major online databases (PubMed, Web of Science, and Embase) were searched to gather relevant studies regarding the MPFL anatomy. The collection of data was carried out between November 2022 and April 2025 by three independent authors (MKCh, KS, JD). The Boolean technique was employed to conduct the search in PubMed, using the following search terms: "lateral patellar dislocation" OR "Medial Patellofemoral Ligament" OR "Medial patellar retinaculum". The search query for Embase and Web of Science databases followed the same general framework with regard to the specific syntactic needs of these search engines (all search queries are presented in **supplement 1**. The PICO (Person, Intervention, Comparison, Outcomes) algorithm that guided this search was as follows: the Person component focused on skeletally mature, adult individuals or cadavers. The Intervention involved the collection and analysis of anatomical data regarding the MPFL's morphology and its relationship with surrounding knee structures. For comparison, the study analyzed different anatomical measurements of the MPFL across various studies to establish a standardized reference for surgical planning. Finally, the Outcomes were the consolidation of anatomical data to facilitate optimal graft harvesting and femoral tunnel placement for MPFL reconstruction, ultimately improving surgical outcomes. Neither language, date, article type, nor text availability filters were applied. To ensure comprehensive data collection, a manual search through the references of the identified studies was performed. Throughout the study, the preferred reporting items for systematic reviews and meta-analyses (PRISMA) (7) were carefully followed.

Eligibility Criteria

Three authors independently assessed the articles' eligibility. Only the studies that fulfilled the following criteria were included: 1) complete, unambiguous data regarding MPFL morphometry and/or its distances to anatomic and/or radiographic landmarks; 2) MRI, cadaveric, and/or radiographic;

3) studies performed on at least 5 knees; 4) subjects being skeletally mature. The following articles were excluded: 1) case reports and series performed on 4 and less knees, due to low statistical significance, review articles, unpublished manuscripts, letters to the editor, and studies carried out on 2) animals; 3) computer-simulated models of knees, and 4) pediatric populations (meaning less than 18 years of age). Records not meeting the criteria were ineligible because the results for the outcome were not measured or reported. Language was not an exclusion criterion; non-English reports were translated by medical professionals fluent in the language of the publication. These criteria were established based on the existing literature and our experience (8).

Data extraction

Two reviewers (JD, KS.) independently screened titles and abstracts based on predefined inclusion and exclusion criteria, followed by a detailed analysis of the full texts of relevant publications. Studies that met the established criteria were included in the analysis. In cases of disagreement, a third reviewer (MKCh) was consulted to assist with the assessment.

Types of articles included in the study were original research articles conducted on 5 or more knees. Both cadaveric and radiographic studies were included. Qualitative data, such as year of publication, region of origin, gender of the subjects, and data collection methodology, were gathered. Quantitative data regarding sample size and its characteristics (age), prevalence among subjects, distances concerning surroundings (adductor tendon tubercle (ATT), medial femoral epicondyle (MFE), gastrocnemius tubercle (GT), perpendicular line posterior-most to Blumensaat line, posterior femur cortex line) of the MPFL, length at different degrees of flexion, width at patellar, vastus medialis oblique, vastus intermedius, and femoral insertion, width in the middle, thickness at femoral and patellar insertion, and thickness in the middle were collected.

Quality assessment

In order to evaluate the quality, potential bias, and reliability of the studies included in the meta-analysis, the researchers used the Anatomical Quality Assessment (AQUA) tool (9). Reports underwent assessment in the following domains: 1) objectives and study characteristics; 2) sample design; 3) methodology characterization; 4) descriptive anatomy, and 5) reporting of results. Each domain was rated as having a high, low, or unclear risk of bias. Every record used was evaluated for the risk of bias by two reviewers who worked independently. Additionally, the Critical Appraisal Tool for Anatomical Meta-Analysis (CATAM) was used to ensure the highest-quality finding (10).

Statistical analysis

In synthesizing the results of the included studies, a random-effects model via the Comprehensive Meta-Analysis Version 4 (Borenstein, M., Hedges, L., Higgins, J., & Rothstein, H. Biostat, Englewood, NJ 2022) software was employed. The preliminary assessment of the studies indicated variability among the study outcomes, which could not have been attributed to sampling error. The random effects approach was deemed appropriate, as a certain degree of heterogeneity across the studies was anticipated. This model delivered a more conservative effect size estimate than the fixed-effects model.

To assess heterogeneity, the Q-tests and the I-squared statistics were employed. The Q-test provided the researchers with a test examining the possibility of all studies in the meta-analysis sharing a common effect size. Q P-value < 0.1 was considered significant. The I-squared statistic was used to determine whether the proportion of the total variation across studies was due to heterogeneity rather than chance. In relation to the I-squared statistic, the heterogeneity was found to “may not be significant” at values of 0-40%, “may indicate moderate heterogeneity” at 30-60%, “may indicate substantial heterogeneity” at 50-90%, and “may represent considerable heterogeneity” at 75-100%.

Furthermore, the tau and tau-squared statistics were employed to estimate the standard deviation of the underlying effects across studies. These were essential to understanding the distribution of the effect sizes and the degree of variability beyond sampling error.

RESULTS

Initially, 7,263 articles underwent evaluation. A total of 7,251 records were identified from major electronic databases (PubMed, Embase, Web of Science); an additional 12 were found by citation searching. The duplicate removal process ruled out 3,459 records; the remaining 3,804 underwent the screening process. Of these, 284 records met all predefined inclusion criteria and were subsequently sought for retrieval for full-text assessment. All 284 records were successfully obtained and evaluated for eligibility. During the eligibility assessment, records were excluded based on the following criteria: 144 records were excluded due to incomplete or irrelevant data; 56 records were excluded due to inappropriate publication types, including 30 reviews, 21 case series, and 5 letters to the editor (these issues were

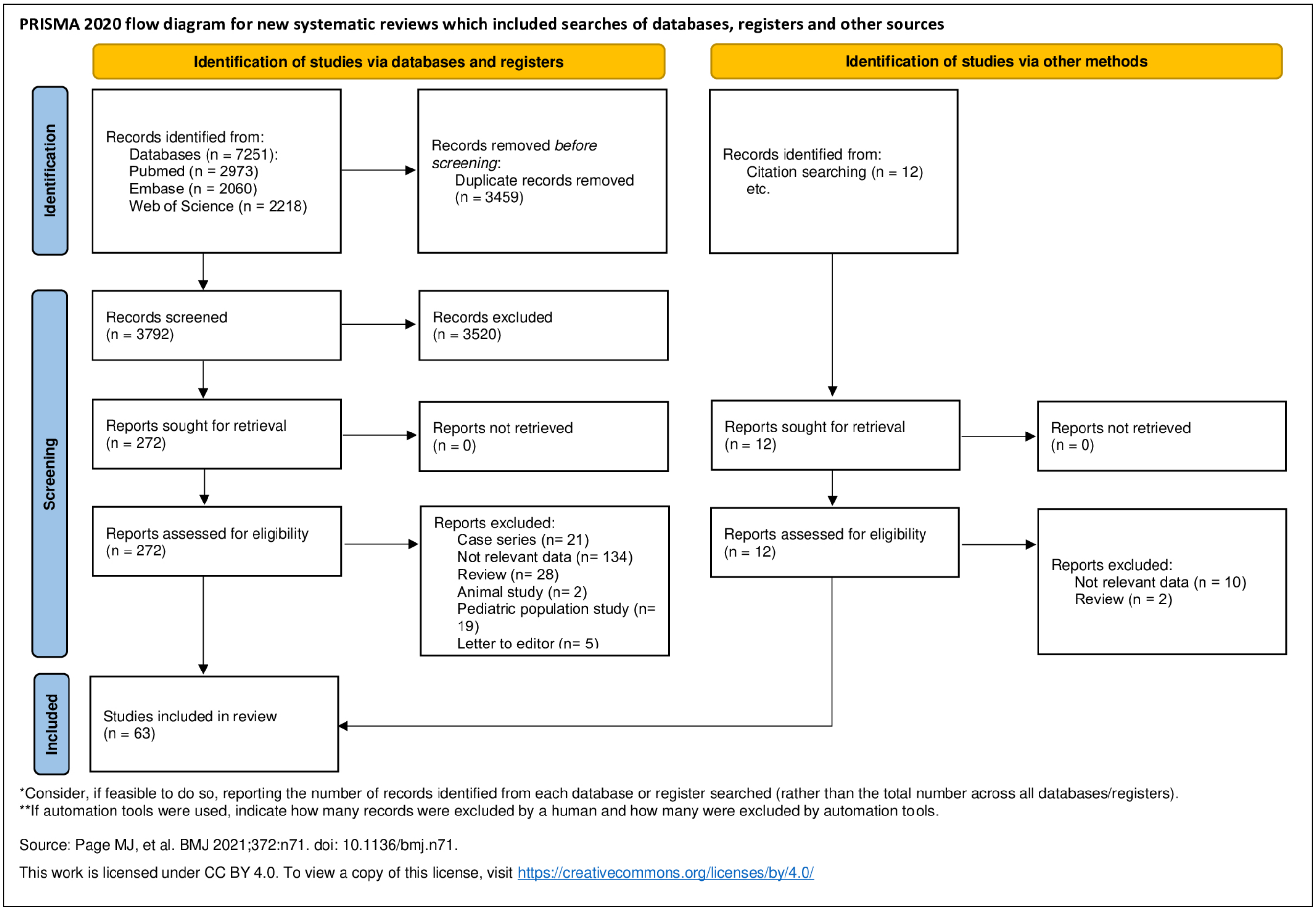

Figure 1. Flowchart of the meta-analysis.

not identifiable during abstract screening); 21 records were excluded due to an ineligible study population, comprising 19 studies involving pediatric populations and 2 animal studies, which could not be determined during the abstract screening phase. Ultimately, 64 (3, 4, 11-13, 15-17, 19, 24-33, 35, 40-83) articles met the inclusion criteria and were included in this meta-analysis. The studies that were included in this meta-analysis presented a low risk of bias in the AQUA score (9). Furthermore, all of the articles achieved at least 30 points in the CATAM (10) score, which is interpreted as "Good" or "Very Good" quality. A flow chart (**figure 1**) illustrates the process of data collection. A total of 2510 knees were included in this study. The characteristics of the included studies are depicted in **supplement 2**.

Quality assessment

Based on the AQUA tool's evaluation, the majority of the papers included in this meta-analysis showed a "low" risk of bias in each of the five domains. The domain with the highest risk for bias was "objectives and study characteristics" because of the not clearly defined characteristics of the subjects studied. **Supplement 3** presents the results of the quality assessment.

MPFL length

The MPFL is an extracapsular structure situated within layer II of the medial aspect of the knee. It consists of transverse fibers extending from the medial border of the patella and attaching to the area surrounding the adductor tubercle and medial epicondyle.

The length of MPFL was reported in the literature in three different ways. Measurements were made either at the superior edge of MPFL, at the inferior edge of MPFL, or in the middle of the ligament. Nevertheless, all studies reported the length of the MPFL as the distance between its patellar and femoral insertions. Moreover, MPFL lengths were reported at different angles of knee flexion. When measured at the inferior margin of the MPFL, its length was 61.49 mm (95%CI 55.20-67.79 mm) at 0° of knee flexion; 61.02 mm (95%CI 55.02-67.02 mm) at 30°; 61.56 mm (95%CI 56.41-66.70 mm) at 60°; 60.47 mm (95%CI 52.34-68.60 mm) at 90°; and 58.51 mm (95%CI 46.53-70.49 mm) at 120° of knee flexion. MPFL measured at the superior margin in the same (0°, 30°, 60°, 90°, and 120°) knee flexion degrees was, respectively, 64.74 mm (95%CI 59.66-69.82 mm), 62.04 mm (95%CI 58.89-65.18 mm), 62.34 mm (95%CI 58.97-65.70 mm), 61.37 mm (95%CI 50.33-72.42 mm), and 59.19 mm (95%CI 42.60-75.78 mm) long. Majority of studies assessing the length (28 studies (4, 13, 15, 17, 18, 24, 25, 27, 30, 41-43, 45, 47, 51, 52, 54, 56-58, 62, 63, 66-68, 76, 79, 80)) reported MPFL length as measured throughout a line in the middle of the ligament. Such MPFL lengths were given for 0°, 20°, 30°, 45°, 60°, 90°, and 120° knee flexion degrees and measured 56.87 mm (95%CI 54.38-59.37 mm), 54.94 mm (95%CI 50.92-58.97 mm), 52.77 mm (95%CI 48.36-57.19 mm), 50.95 mm (95%CI 39.13-62.78 mm), 49.65 mm (95%CI 45.23-54.06 mm), 47.60 mm (95%CI 44.04-51.17 mm), and 41.86 mm (95%CI 38.52-45.20 mm), consequently. Specific data describing the length of MPFL is shown in **supplement 4**. **Figure 2** shows length changes of the superior, inferior margins, and middle of the ligament during motion.

MPFL width

The authors provided data about MPFL's width at three different points: at its patellar insertion (23 studies (3, 4, 13, 16, 17, 24-26, 42, 45, 49, 51, 57, 60, 63-65, 70, 72-74, 76, 83)), femoral insertion (20 studies (3, 4, 13, 16, 17, 25, 42, 45, 46, 51, 54, 57, 64, 65, 70, 72, 75, 76, 78, 83)), and in the middle of the ligament (10 studies (3, 4, 16, 41, 42, 47, 50, 51, 68, 83). MPFL was widest at its patellar insertion (23.17 mm; 95%CI 20.99-25.35 mm) and narrowest at its femoral insertion (11.96 mm; 95%CI 10.63-13.29 mm). The width of the middle part of the MPFL was 14.65 mm (95%CI 11.06-18.24 mm) (**supplement 5**).

MPFL thickness

The analysis of nine studies provided data about the thickness of the MPFL in its middle part, which was 1.17 mm (95%CI 0.91-1.43 mm). Thickness of MPFL was also assessed at its patellar and femoral insertions by 6 (4, 51, 52, 54, 64, 67) and 5 (51, 52, 54, 67, 75) authors, respectively, and measured consequently at 1.45 mm (95%CI 0.95-1.96 mm) and 1.04 mm (95%CI 0.77-1.32 mm). Additional information about MPFL thickness can be found in **supplement 6**.

Lengths of MPFL soft tissue attachments

Apart from the femoral bony insertion, part of MPFL's fibers end in the tendons of two muscles that constitute the medial part of the thigh: the vastus medialis oblique (VMO) muscle and the vastus intermedialis muscle (VIM). The analysis of 7 studies (16, 24, 26, 54, 68, 70, 77) revealed that the mean length of the MPFL insertion site at the VMO muscle is 28.46 mm (95%CI 20.50-36.42 mm). 3 studies (24, 26, 54) reported the mean length of the MPFL insertion site at the VIM, which was 21.37 mm (95%CI 11.51-31.24 mm). Detailed data regarding the length of these two insertions can be found in **supplement 7**.

Distances to radiographic landmarks

The authors reported data regarding distances from MPFL's femoral insertion to the posterior femur cortex line (7 studies (31-33, 59, 61, 75, 81)), and a line perpendicular to the posterior-most aspect of Blumensaat line (5 studies (31, 33, 35, 59, 61)). The mean distances were as follows: 4.33 mm (95%CI 1.84-6.83 mm) anterior to posterior femur cortex line, and 2.51 mm proximal (95%CI 1.20-3.82 mm) to the perpendicular line to the posterior-most aspect of Blumensaat line (**supplement 8**).

MPFL's relation to the ATT

The authors reported substantial variability regarding MPFL's relations to ATT. The center of MPFL's femoral insertion was described to be located distally (9 studies (3, 4, 16, 29, 33, 46, 61, 63, 75)), proximally (3 studies (46, 61, 83)), anteriorly (6 studies (3, 29, 46, 61, 63, 75)), and posteriorly (3 studies (16, 46, 83)) in relation to ATT. In respective studies, the center of MPFL's femoral insertion was located on average 9.17 mm (95%CI 7.38-10.97 mm) distally, 10.81 mm (95%CI 8.54-13.08 mm) proximally, 6.82 mm (95%CI 0.94-12.07 mm) posteriorly and 2.22 mm (95%CI 1.45-2.99 mm) anteriorly in relation to ATT. Twelve authors (11, 13, 29, 33, 48, 49, 58, 61, 64, 65, 70, 78) measured the distance between MPFL's femoral insertion and ATT in a straight line, which averaged 10.59 mm (95%CI 8.54–12.65 mm) (**supplement 9**).

MPFL's relation to the MFE

8 studies (3, 16, 29, 32, 40, 63, 68, 75) observed the center of MPFL's femoral insertion posteriorly from MFE; 9 studies (3, 16, 29, 33, 46, 61, 63, 68, 75) reported its location proximally to MFE; and 3 studies (40, 46, 61) described the center of MPFL's femoral insertion as being anterior relative to MFE. In respective studies, the center of MPFL's femoral insertion was located on average 6.21 mm (95%CI 4.18–

8.23 mm) posteriorly, 9.03 mm (95%CI 6.79-11.27 mm) proximally and 4.77 mm (95%CI -0.30 to 9.84 mm) anteriorly in relation to MFE. 10 authors (13, 29, 33, 48, 49, 60, 61, 65, 68, 70) measured the distance between MPFL's femoral insertion and MFE in a straight line without specified directions, which averaged 11.21 mm (95%CI 9.18-13.23 mm) (**supplement 10**).

MPFL's relation to the GT

The center of MPFL's femoral insertion was described to be located anteriorly (3 studies (29, 46, 61)) and proximally (4 studies (29, 33, 46, 61)) in relation to GT. In respective studies, the center of MPFL's femoral insertion was located on average 7.79 mm (95%CI 5.32-10.26 mm) anteriorly and/or 2.54 mm (95%CI 1.25-3.83 mm) proximally in relation to GT. Four authors (13, 29, 33, 61) measured the distance between MPFL's femoral insertion and GT in a straight line, which averaged 10.66 mm (95%CI 8.75-12.56 mm) (**supplement 11**).

MPFL's insertion area

The area of MPFL's patellar insertion was reported by 4 studies (13, 51, 54, 61) and averaged 53.02 mm^2 (95%CI 40.93-65.12 mm^2). Femoral insertion of MPFL (reported by 7 authors (11, 13, 27, 29, 40, 51, 61)) had a much smaller surface, being only 36.60 mm^2 (95%CI 26.67-46.54 mm^2) (**supplement 12**).

DISCUSSION

This meta-analysis focuses on anatomical features of the MPFL useful for proper graft harvesting and localizing original insertion sites.

This study provides a detailed analysis of the length changes of the superior margin, inferior margin, and middle of the ligament at different knee angles. We observed a similarity in the length change pattern of the upper and lower ligament fibers, while the fibers of the middle part of the ligament shortened much more with the degree of knee flexion.

MPFL's shape description varies among different studies, from being polygon-shaped (11), trapezoidal (12, 13), hourglass (14, 15), more triangular (3, 16), Y-shaped (17), or sail-like (3, 4) structure. Our study indicates that the ligament exhibits a sail-like, trapezoid shape, with its widest part at the patellar insertion, narrowing towards the middle, and being narrowest at the femoral insertion. Therefore, double-bundle (DB) grafts with anatomical anchoring are more anatomical and provide a better physiological stress distribution. In a study by Wang *et al.* (18), the DB technique scored greater than single-bundle (SB) in terms of Kujala Score and subjective questionnaire score.

We confirmed that MPFL is an anisometric ligament with the biggest mean length at full extension of the knee and shows a relative isometry between 30° and 90° of motion for the superior and inferior margins. It did not demonstrate isometry when measured at its midline. Although the ligament should be reconstructed in the position where it is subjected to the highest strain-according to our study at 0° flexion-fixation in full extension is challenging due to the lack of proper guidance of the patella by the trochlear groove (19, 20). Failure to sustain an optimal graft length can result in complications such as patellofemoral overload, medial patellofemoral arthritis, persistent lateral instability, and loss of postoperative movement (20). When employing a DB technique for reconstruction, the focus is on reconstructing the portions of the ligament that demonstrate near-isometric behavior within the range of 30° to 90° of flexion. Moreover, considering the fact that the patella is most susceptible to subluxation at 30° of flexion (20), this range of angle could be considered optimal to prevent ligament laxity during this critical phase of patellar tracking.

This study found that the thickness of native MPFL in its middle part was 1.17 mm, and at its patellar and femoral insertions measured accordingly at 1.45 mm and 1.04 mm. Although Wong *et al.* (21) found no correlation between postoperative pain, arthritis, graft failure, and graft thickness, Elias *et al.* (22) noted that even though graft properties are not detrimental when they are positioned properly, graft sources that closely mimic the intact MPFL can minimize the risk of overloading the medial cartilage after reconstruction. Hamstring tendon grafts could be too thick and necessitate a fixation with a bony procedure at the patella, which can be a source for patellar fracture and violation of the anterior cortex or chondral surface of the patella (23).

Anatomical data regarding the length of the MPFL's insertion sites on the VMO and the VIM was compiled. The MPFL adheres to the inferior surface of the VMO, proximal to the patellar insertion (24). Ji *et al.* (24) distinguished two anatomic functional regions of the MPFL fibers: the overlap region, where VMO's and MPFL's fibers overlie each other, and the non-overlapping region, proposing that only the injuries of the overlap region can be cured with nonsurgical treatment. In a study published by Panagiotopoulos *et al.* (25), strong "meshing" of the fibers of the VMO and MPFL was described. These results correspond with this study's findings regarding a wide insertion site of 28.46 mm to the VMO, which might indicate its substantial role in strengthening and dynamizing the ligament during early flexion. There-

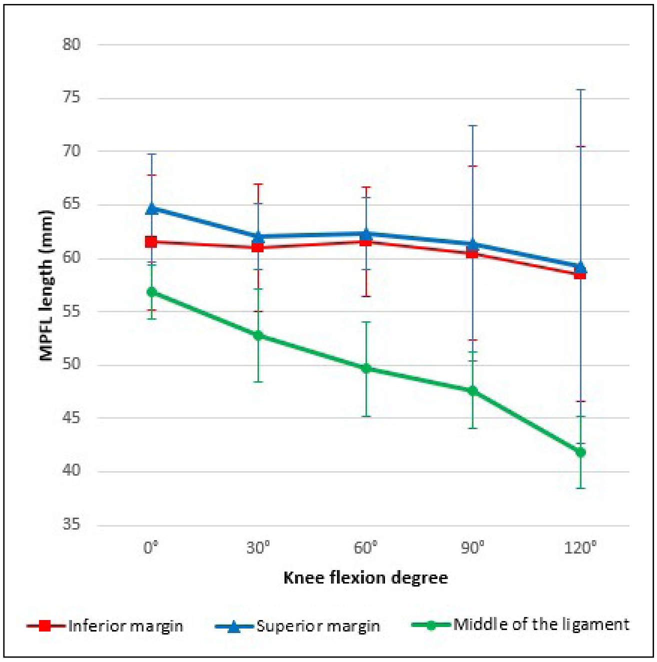

Figure 2. Graph presenting the length changes of the MPFL according to the degree of the knee flexion.

fore, the authors of this study advocate that whenever grafts are being used for reconstruction of the ruptured MPFL, "meshing" to the VMO should be restored. The MPFL insertion to the VIM is at the medial margin of its tendon (26). Studies (26, 27) present varying findings on how tightly the ligament is attached to these muscles, possibly due to different dissection techniques. It's widely recognized that nearly 90% of MPFL tears happen at the femoral insertion (24). This study confirms that this could be because the attachment to the patella is broader, and tension is spread out due to wide insertion and overlapping areas with these muscles.

Recent anatomical studies report that the MPFL is situated in a groove between the ATT and the MFE. However, this location is difficult to palpate (28, 29), making it challenging to locate during surgery. Consequently, several articles propose using radiographic landmarks to identify the MPFL instead (30). This study details the MPFL relationship to the projected radiographic lines, which allows for more consistent radiographic assessments of anatomic repairs and reconstructions. This paper confirms that the mean distance from the femoral attachment was 2.51 mm distal to the perpendicular line at the posterior-most aspect of the Blumensaat line. This line is reported to be easier to identify (31) than the landmarks initially described by Shottle *et al*. (32), which included the posterior cortical extension line and a perpendicular line intersecting the posterior origin of the medial femoral condyle for guiding femoral tunnel placement. This study concludes that the MPFL femoral origin is 4.33 mm anterior to the posterior femoral cortical line. Therefore, quantitative differences between the findings of this meta-analysis and studies that describe radiographic landmarks used for identifying femoral attachment (31-33) were found. In the study by Schottle *et al.* (32), this attachment was reported to be located 1.3 mm anterior to the posterior femoral cortex line and 5.5 mm proximal to the perpendicular line at the posterior-most aspect of the Blumensaat line. According to the results of this meta-analysis, the most accurate location could be combining Barnett's (6.31) point distance of 3.8 mm anterior to posterior femoral cortical line and Wijdick's (33) point of 2.6 mm proximal to the posterior-most aspect of the Blumensaat line.

Despite numerous studies suggesting that radiographic landmarks could effectively pinpoint the femoral attachment of the MPFL, Sanchis-Alonso *et al.* (34) found only 36.7% and 25.5% overlap in the anatomical tunnel area using Schottle's (32) or Stephen's (35) methods, respectively. These differences may stem from challenges in obtaining a true lateral radiograph or variations in trochlear morphology. Balcerak *et al.* (36) reported that a deviation as small as 5° from the true lateral fluoroscopic view might lead to a critical shift of approximately 5 mm from the native femoral insertion point in reconstruction surgery.

Few studies focus on femoral tunnel malpositioning and its correlation to clinical outcomes after MPFL reconstruction. Hopper *et al.* (37) demonstrated that Kujala and Lysholm scores significantly improved when the femoral tunnel was positioned within 10 mm of the MPFL's anatomical insertion point. In contrast, Servien *et al.* (38) and McCarthy *et al.* (39) did not find any connection between femoral tunnel misplacement and poor clinical outcomes, despite their femoral tunnels being located 7 mm and 9 mm away from the anatomical MPFL center, respectively. These varying findings may result from the fact that most biomechanical studies define the center of the anatomical origin as the "functional" point of the MPFL (40). This research study revealed that the MPFL femoral insertion area spans 36.6 mm², suggesting that femoral tunnel placement may be somewhat forgiving as long as it falls within this region.

The ATT is sometimes described in the literature as the "lighthouse of the medial knee" because once it is found, it enables surgeons to find all the other landmarks (30). This study reports that the center of MPFL's femoral insertion was located on average 9.17 mm distally, 10.81 mm proximally, 6.82 mm posteriorly, and 2.22 mm anteriorly to ATT.

While Chen *et al.* (28) described a broad, easily detectable sulcus between the MFE and ATT, where the MPFL is usually located, prior studies have shown poor accuracy of palpation as a method to localize femoral tunnel placement (29). This meta-analysis provides detailed measurements of the distances from the center of the MPFL to MFE, AT, and GT in both the proximal-distal and anterior-posterior axes. Kernkamp *et al.* (30) demonstrated that adjusting the femoral attachments in the proximal-distal direction significantly affected length changes, while adjustments in the anterior-posterior axis had a smaller but still significant impact. Stephen *et al.* (35) noted that even small errors of 5 mm in the proximal-distal axis from the anatomical MPFL center during femoral tunnel placement resulted in increased peak and mean medial patellar contact pressures. Furthermore, shifts of the femoral attachment point by 5 mm in the proximal-distal axis significantly altered MPFL length, whereas shifts in the anterior or posterior directions of the same magnitude did not have significant effects on length changes (41). Considering the risks associated with inaccuracies in estimating the femoral attachment point of the MPFL and the center of the anatomic attachment on the femur being the most isometric position for the femoral tunnel placement, the findings of this study could be valuable for planning reconstruction surgery by providing a detailed description of the ligament's anatomy. Authors of this paper advocate for femoral tunnel placement localization with ATT, which is sometimes a palpable osseous anatomic landmark, followed by a confirmation with a true lateral radiograph.

This current study unquestionably has limitations. Potential bias may be present, as the accuracy of data compiled from various publications limits the outcomes of this meta-analysis. Some analyses could not be conducted by the authors due to a lack of consistent data availability. The limitations of this study include the mean age of subjects much greater than the age of the typical patient experiencing lateral dislocation (42). Consequently, there is a possibility that degenerative changes have influenced the results of the analyzed studies. Another limitation is the fact that some studies report the native location of the MPFL attachments in normal knees, which might not fully apply to individuals experiencing lateral patellar dislocation or recurrent instability. Moreover, if a procedure alters the knee's anatomy, such as a tibial tubercle osteotomy or trochleoplasty, the original location of the femoral attachment may no longer be suitable for graft attachment. Patients with patellar dislocation often exhibit various abnormal anatomical features, such as patella alta, increased Q-angle, rotational deformities, and trochlear dysplasia, which could impact the accuracy of included studies that detail the MPFL insertion site anatomy (41). Anatomical differences between sexes were not taken into account. Biometrics, such as subjects' height, patella size, and limb length, were not available for most of the studies. The nature of data collection also generated a high level of heterogeneity among the studies. The review pooled studies employing cadaveric observation, MRI, X-ray, and CT scans as methods of measurement. Considering the available data on this subject were varied in terms of sources and observation methods, the results were pooled, and averages were presented. While this method is not ideal for a review of this type, statistically significant results could not have been generated if the studies reviewed had been segmented. The random effects model aids this somewhat as each study is weighted inversely proportional to its variance, where less varied studies have more influence on the overall effect size.

Subgroup and sensitivity analyses, such as leave-one-out analyses would generally aid the robustness of the conclusions. A meta-regression could have been useful to isolate certain characteristics of the studies that significantly contribute to the difference in effect size.

CONCLUSIONS

A better understanding of the anatomy of MPFL is necessary among physicians in treating patients with lateral patellar dislocation, especially those who perform reconstruction surgeries. With consideration to the findings of this meta-analysis, the authors conclude that DB technique with anatomical anchoring allows for the recreation of the "fan-shaped" or "sail-like" shape and biomechanics of the original ligament. Authors advocate for the "meshing" of the MPFL grafts with VIM and VMO to restore its natural soft tissue insertions and provide enhanced support. Proper knowledge of MPFL's morphology and its relationship to surrounding structures enables proper graft harvesting and both femoral and patellar tunnel placements.

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DATA AVAILABILITY

Data are available under reasonable request to the corresponding author.

CONTRIBUTIONS

MKC: conceptualization, project administration, data curation, writing – original draft. JD: data curation. KS: data curation, formal analysis, data management, writing – original draft. FP: formal analysis, writing – original draft. JS: data management, writing – review & editing.

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CONFLICT OF INTERESTS

The authors declare that they have no conflict of interests.

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