

Landmarks Used in Medial Patellofemoral Ligament Reconstruction Have Variable Topography



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Purpose: To describe the morphology of the adductor tubercle (AT), medial epicondyle (ME), and gastrocnemius tubercle (GT); to quantify their relationships to the medial patellofemoral ligament (MPFL) footprint location; and to classify the reliability of each landmark based on measurement variability. **Methods:** Eight cadaveric specimens were dissected to expose the following landmarks on the femur: MPFL footprint, AT, ME, and GT. Using the MicroScribe 3D digitizer, each landmark was projected into a 3-dimensional coordinate system and reconstructed into a complex, closed polygon. For each specimen tubercle, the base surface area, volume, height, base:height ratio, sulcus point, and distance from the MPFL footprint center were calculated. Levene's test was performed to evaluate differences in variance of the morphologic parameters between the three osseous structures. **Results:** The ME had significantly greater variance in volume than the GT ($P = .032$), and the AT (17.5 ± 3.9) and GT (19.5 ± 3.6) were significantly less variable in base:height ratio than the ME (95.3 ± 19.2 ; $P < .001$). The GT was the closest to the MPFL footprint center (7.1 ± 3.1 mm) compared with the AT (13.4 ± 3.6 mm, $P = .002$) and ME (13.2 ± 2.7 mm, $P = .003$). However, the tubercles were equally variable in terms of distance to the MPFL footprint center ($P = .86$). Lastly, the sulcus point was estimated to be on average 1.9 ± 2.9 mm distal and 2.0 ± 2.0 mm posterior to the MPFL center point. **Conclusions:** The 3 major osseous landmarks of the medial femur have significantly different variances in volume and base:height ratio. Specifically, the variability and elongated morphology of the ME differentiated this landmark from the AT and GT, which demonstrated the most consistent morphology. **Clinical Relevance:** The results of this study may be useful to accurately locate landmarks for femoral tunnel placement and determine the isometric MPFL point during reconstruction.

Reconstructions of the medial patellofemoral ligament (MPFL) have become a central component of surgical stabilization in the treatment of lateral

patellar instability, with demonstrated improvements in patient-reported outcomes, return to sport, and low rates of redislocation.¹⁻⁴ Within the medial patellofemoral complex, the MPFL acts as the primary passive restraint to lateral patellar displacement in the first 30° of flexion.⁵ Its anatomic origin has been described previously at variable distances from several nearby landmarks, including the medial epicondyle (ME), adductor tubercle (AT), and medial collateral ligament.⁶⁻⁸

Proper femoral tunnel placement is essential for replicating native patellofemoral kinematics and contact pressures. Both computational and cadaveric studies have demonstrated that 5 mm of femoral attachment malpositioning was associated with overload of the medial patellofemoral joint, an increase in graft tension, and anisometry of the ligament.^{9,10} Given the associated concern for graft attenuation/failure, loss of range of motion, or progression of patellofemoral arthritis, several methods have been described for accurate femoral tunnel localization. Palpation of local osseous landmarks, including the AT and ME, is one

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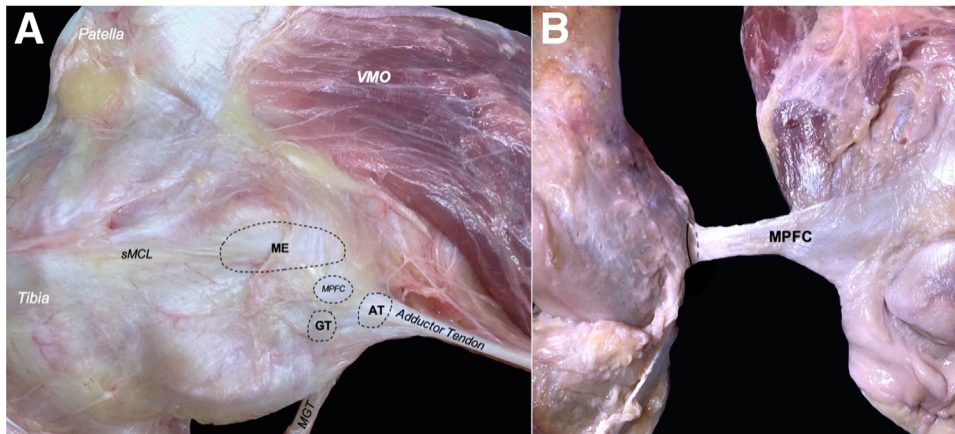


Fig 1. Dissection of specimens for identification of medial landmarks performed by (A) palpation and verification of osseous landmark location by intact soft tissue (AT, MCL, MGT) and (B) reflection on the extensor mechanism after lateral parapatellar arthrotomy and identification of the medial patellofemoral ligament band under tension. The MPFL is dissected from the retinaculum and followed to its femoral footprint. (AT, adductor tubercle; GT, gastrocnemius tubercle; MCL, medial collateral ligament; ME, medial epicondyle; MGT, medial gastrocnemius tendon; MPFC, medial patellofemoral complex; MPFL, medial patellofemoral ligament; sMCL, superficial medial collateral ligament; VMO, vastus medialis oblique.)

described method for localization. Chen et al.¹¹ described a broad, consistently palpable sulcus located between the ME and AT, which reliably contained the MPFL attachment. Despite this, previous studies have demonstrated palpation to have low precision, and the reliability of the sulcus landmark has yet to be formally characterized and quantified.^{12,13}

Although several studies have sought to describe the spatial relationships between the MPFL and various landmarks, the tubercles frequently have been simplified to a single point in space. Topographic characteristics of these tubercles and their relative interspecimen consistency could potentially drive heterogeneity in anatomic measurements and precision of palpation. The purposes of this study were to describe the morphology of the AT, ME, and gastrocnemius tubercle (GT); to quantify their relationships to the MPFL footprint location; and to classify the reliability of each landmark based on measurement variability. We hypothesized that these landmarks would demonstrate significant differences in variability of topographic characteristics and spatial relationships to the MPFL footprint.

Methods

Specimen Preparation

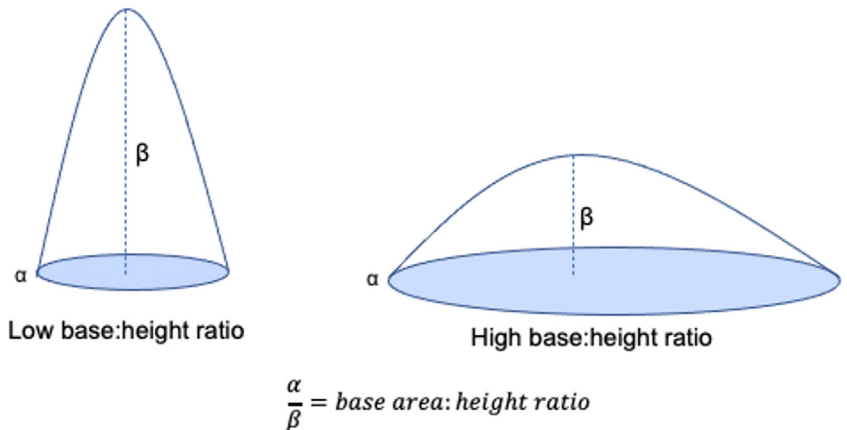
Institutional review board approval was not required for this cadaveric study, according to institutional policy. Eight nonpaired, fresh-frozen human cadaveric knees without previous injury, surgery, or a history of knee osteoarthritis were used for this study. The mean anteroposterior femoral shaft diameter was 32.0 ± 2.54

mm (range: 27.4-36.0 mm). To ensure accurate delineation of landmarks for this anatomic study, on-table dissection was performed for optimal visualization. These cadaveric specimens were dissected of skin and subcutaneous tissue, and the following landmarks were identified by palpation with visual confirmation of the osseous prominence and known soft-tissue attachments by one fellowship-trained orthopaedic surgeon (A.B.Y.): AT, ME, and medial GT. A lateral parapatellar arthrotomy was then performed to reflect the extensor mechanism and identify the borders of the entire MPFL band structure within the medial retinaculum while manually tensioning the patella. This band was then isolated by dissection and followed to a well-circumscribed footprint on the femur (Fig 1). The boundary of the MPFL footprint was demarcated by the placement of 4 flat-headed pins at its most superior, inferior, anterior, and posterior boundaries during careful reflection of the footprint attachment as to maintain its original shape. Other than the footprint attachment, other soft-tissue attachments remained intact to replicate clinical palpability.

MicroScribe Testing and Data Collection

Anatomic landmarks (ME, GT, AT) were measured using a 3-dimensional coordinate capture system (MicroScribe; Solution Technologies, Oella, MD). Each tubercle was marked by circumferential points around the periphery of its base and midlevel. The most palpable point at the apex of the tubercle was marked as its peak. Due to the elongated, ridge-like morphology of the ME, the centermost point along the palpable ridge was selected as its peak. The MPFL footprint was

Fig 2. Schematic representation of base:height ratio, which quantifies the tubercle topographical contrast with local environment.



marked at its 4 boundaries (superior, inferior, anterior, posterior) demarcated by pins.

All landmarks were projected onto a 3-dimensional coordinate system within Rhinoceros 5.0 software (McNeel North America, Seattle, WA). Each set of points was then constructed into a complex, closed polygon within the software. This allowed for the calculation of each tubercle's base area, volume, and distance to the MPFL footprint centroid. The tubercle height was calculated based on known volumetric equations for triangular prisms (ME, $Volume = \frac{1}{2} \text{base area} \times \text{height}$) and hemispheres (AT, GT, $Volume = \frac{1}{3}[2\pi \times \text{height}^3]$). These geometric shapes were chosen as they best captured the approximate shapes of the tubercle projections within the 3-dimensional coordinate system. The sulcus point was calculated for each specimen as 12 mm from the AT to ME and 6 mm perpendicular and posterior, as described by Chen et al.¹¹ Since the MPFL was defined by 4 points, the footprint area was calculated by a known equation for a quadrilateral in a coordinate plane ($Area = \frac{1}{2} |(x_1y_2 - x_2y_1) + (x_2y_3 - x_3y_2) + (x_3y_4 - x_4y_3) + (x_4y_1 - x_1y_4)|$), where x_n and y_n represent the coordinates of vertex n .

Lastly, to quantify the topographical contrast of each tubercle with its local environment, the tubercle base area: height ratio was calculated for each specimen (Fig 2).

Statistical Analysis

Statistical analyses were performed in R, 4.1.0 (R Foundation for Statistical Computing, Vienna, Austria). Descriptive statistics are reported as mean \pm standard deviation. Comparisons of anatomic measurements between tubercles were performed by one-way analysis of variance with post-hoc Tukey honestly significant difference tests for significant tests. To compare variance of all measures between landmarks, Levene's test with post-hoc Tukey honestly significant difference performed on sample absolute residuals for significant tests. A priori power analysis was not performed for this largely exploratory study due to inability to estimate a

relevant effect size based on existing literature. Therefore, a sample size of 8 was chosen based on previous anatomic studies of the medial patellofemoral complex.^{14,15} Testing was 2-sided and significance was established at $P < .05$.

Results

Tubercle Morphology

The ME had the largest base surface area at a mean of $103.2 \pm 26.2 \text{ mm}^2$, which was significantly greater than the AT ($41.6 \pm 8.0 \text{ mm}^2$, $P < .001$) and the GT ($29.7 \pm 4.9 \text{ mm}^2$, $P < .001$). Similarly, the ME also demonstrated the greatest volume $59.1 \pm 25.5 \text{ mm}^3$, which was significantly greater than the AT ($30.3 \pm 10.8 \text{ mm}^3$, $P = .005$) and the GT ($8.6 \pm 4.9 \text{ mm}^3$, $P < .001$). The AT, however, demonstrated the greatest peak height of $2.4 \pm 0.3 \text{ mm}$, compared with the GT ($1.6 \pm 0.3 \text{ mm}$, $P < .001$) and the ME ($1.1 \pm 0.3 \text{ mm}$, $P < .001$). The AT (17.5 ± 3.9) and GT (19.5 ± 3.6) had significantly lower base:height ratios than the ME (95.3 ± 19.2 ; $P < .001$) (Table 1).

Spatial Relationships and Distance to the MPFL Footprint

All tubercle and MPFL footprints are depicted in Figure 3. The MPFL footprint had a mean area of $15.1 \pm 3.0 \text{ mm}^2$. The GT was the closest to the MPFL footprint center ($7.1 \pm 3.1 \text{ mm}$) compared with the AT ($13.4 \pm 3.6 \text{ mm}$, $P = .002$) and ME ($13.2 \pm 2.7 \text{ mm}$, $P = .003$). Specifically, the MPFL footprint center was located $1.9 \pm 1.9 \text{ mm}$ proximal and $5.0 \pm 1.7 \text{ mm}$ anterior to the GT, $11.4 \pm 2.8 \text{ mm}$ distal and $1.7 \pm 1.0 \text{ mm}$ anterior to the AT, and $9.6 \pm 3.9 \text{ mm}$ proximal and $7.2 \pm 1.6 \text{ mm}$ posterior to the ME. The AT–ME distance ($24.5 \pm 4.9 \text{ mm}$) was significantly greater than the GT–ME distance ($17.7 \pm 4.0 \text{ mm}$, $P = .007$) and the AT–GT distance ($14.2 \pm 2.8 \text{ mm}$, $P < .001$). The MPFL center was located on average $1.9 \pm 2.9 \text{ mm}$ proximal and $2.0 \pm 2.0 \text{ mm}$ anterior to the projected sulcus point (Fig 4).

Table 1. Anatomic Measurements of Osseous Landmarks

	Base Area, mm ²	Height, mm	Volume, mm ³	Distance to MPFL center, mm	Base:Height Ratio
Medial epicondyle	103.2 ± 26.2	1.1 ± 0.3	59.1 ± 25.5	13.2 ± 2.7	95.3 ± 19.2
Gastrocnemius tubercle	29.7 ± 4.9	1.6 ± 0.3	8.6 ± 4.9	7.1 ± 3.1	19.5 ± 3.6
Adductor tubercle	41.6 ± 8.0	2.4 ± 0.3	30.3 ± 10.8	13.4 ± 3.6	17.5 ± 3.9

MPFL, medial patellofemoral ligament.

There was no significant difference in variance between each tubercle distance to the MPFL center ($P = .86$).

Variation in Topography

Variances of all tubercle measures are listed in Table 2 and demonstrated in Figure 5. There were significant differences in variance between tubercle volumes and base:height ratio. Specifically, the ME had significantly greater variance in volume than the GT ($P = .032$). The AT and GT were significantly less variable in base:height ratio than the ME ($P < .001$).

Discussion

The primary finding of this study is that topographic morphology is different, which may affect a surgeon’s ability to accurately locate landmarks for femoral tunnel placement and determine the isometric MPFL point

during reconstruction. Specifically, the ME displays an elongated, ridge-like morphology that is highly variable in volume and topographical contrast with its local environment. Both the AT and GT demonstrated the greatest homogeneity in volume and topographical contrast. An understanding of the morphology and variation of these landmarks is important when using them for localization of the MPFL femoral attachment.

Herschel et al.¹³ quantified the accuracy and perceived difficulty of identifying the femoral entry point for MPFL reconstructions by palpation. Among 3 surgeons of varying training levels, 23% of femoral tunnel placements were more than 5 mm displaced from the correct tunnel position, defined by Schöttle’s point.¹³ Furthermore, inaccuracy did not correlate with surgeon experience or perceived difficulty, which suggest an unreliable learning curve for experience-based

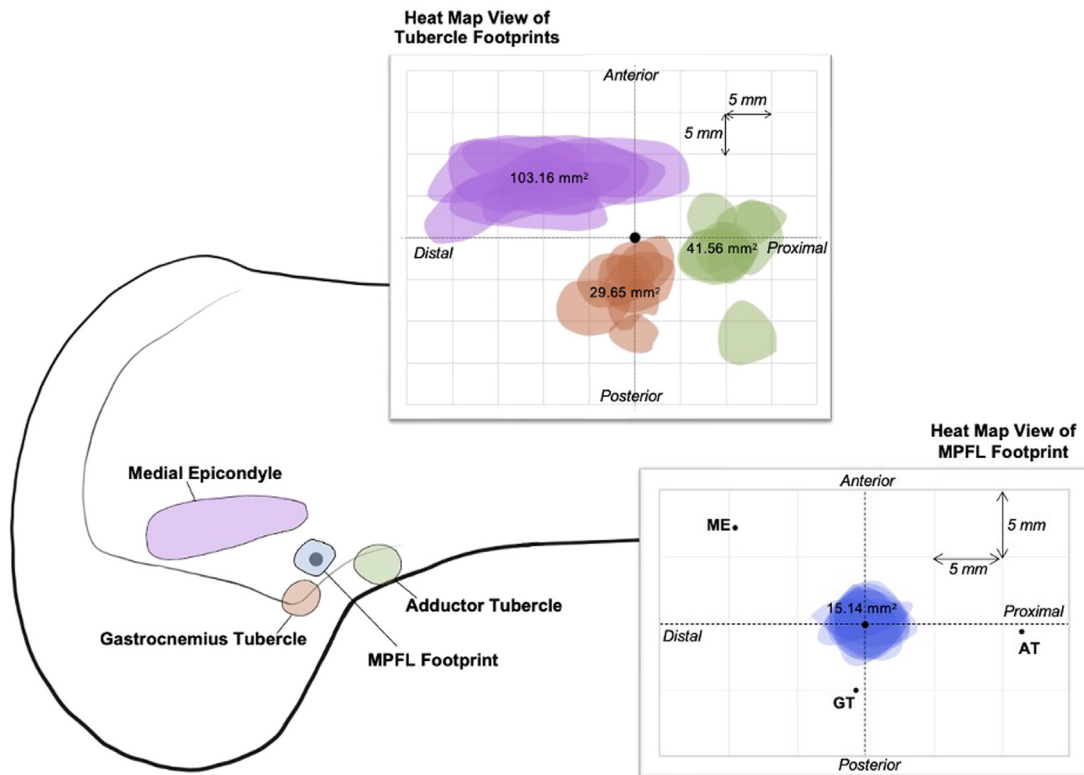


Fig 3. Representative figure of osseous landmarks with heatmap view of base footprints with mean area, placed relative to the medial patellofemoral ligament (MPFL) footprint center (black dot), as well as heatmap of MPFL footprint area relative to the average peak points of the osseous landmarks. Darker color indicates greater overlap between specimens. (AT, adductor tubercle; GT, gastrocnemius tubercle; ME, medial epicondyle.)

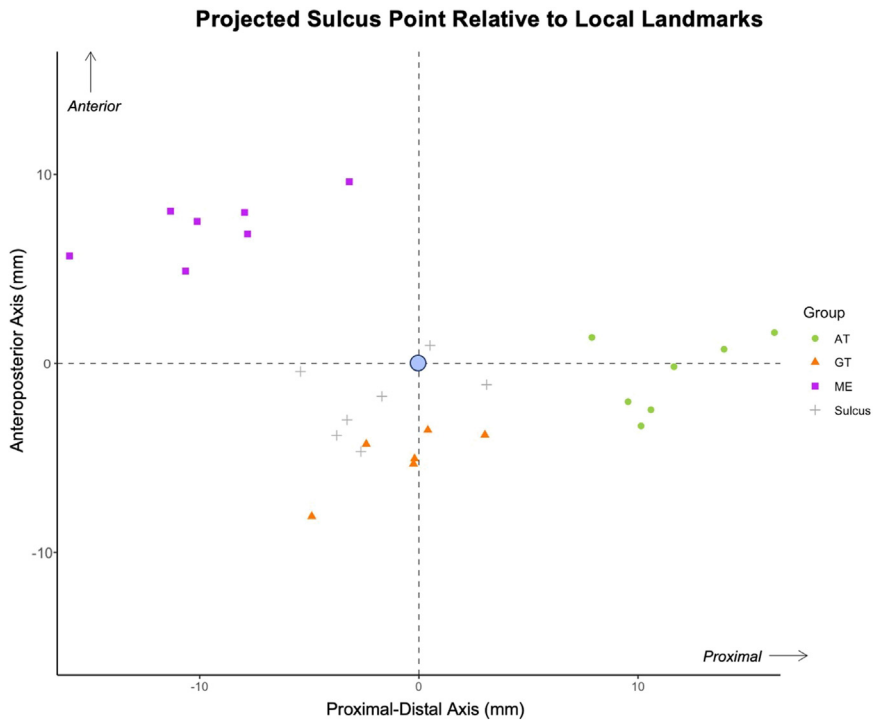


Fig 4. Plot of major landmark peaks relative to the medial patellofemoral ligament footprint center (origin, blue dot) demonstrating projected sulcus point. (AT, adductor tubercle; GT, gastrocnemius tubercle; ME, medial epicondyle.)

improvement in the palpation technique. This is further supported by a study performed among members of the International Patellofemoral Study Group, in which 38 members performed a single-turn localization of the MPFL footprint by palpation alone.¹⁶ Subsequent radiographic analysis demonstrated an average distance of 3.2 mm from the attempts to the native MPFL insertion, with 18% of attempts exceeding the acceptable threshold of 5 mm.¹⁶ Several factors may underlie the poor reliability of the palpatory technique. First, although a small incision (2-3 cm) is preferred to limit soft-tissue dissection intraoperatively, limited visualization increases the technical complexity of identifying the local and global anatomy for placement of the guide pin. In the pathological setting, patients may also have significant soft-tissue injury or scarring, which can further obscure local anatomy.

The palpatory sequence has been described frequently using the AT and ME as the primary landmarks. One of the primary findings of this study was the distinct elongated morphology and variability of the ME. Specifically, it demonstrated the lowest height and

greatest variation in volume. In addition, its relatively low contrast with local topography, as measured by the base:height ratio, may contribute to interrater variation in defining the exact center point of the landmark. Despite this, several anatomic studies have continued to use the ME as a reference point. One study by Fujino et al.¹⁷ uniquely characterized the ME as difficult to palpate, as it appeared flat or as a shallow groove to the authors. Therefore, it was excluded from their measurements in favor of the AT.¹⁷ The findings of our study validate these methods and provide a quantifiable basis for the difficulty in palpation of the subjective, palpated center of the ME.

In addition to the difficulty of palpation, the morphology of the ME may further explain the range of anatomic measurement and trends in error identified in previous studies. A similar study by Koenen et al.¹² demonstrated a 48% occurrence of unacceptable tunnel placement with palpation alone. Specifically, within their study, the direction of error with palpation skewed distally without a specific anteroposterior trend. This effect could potentially be explained by the

Table 2. Variance of Anatomic Measures (σ^2)

	Base Area	Height	Volume	Distance to MPFL	Base:Height Ratio
Medial epicondyle	685.48	0.07	649.43	7.19	369.32
Gastrocnemius tubercle	24.24	0.09	24.13	9.66	13.12
Adductor tubercle	63.18	0.10	116.34	13.20	14.81

MPFL, medial patellofemoral ligament.

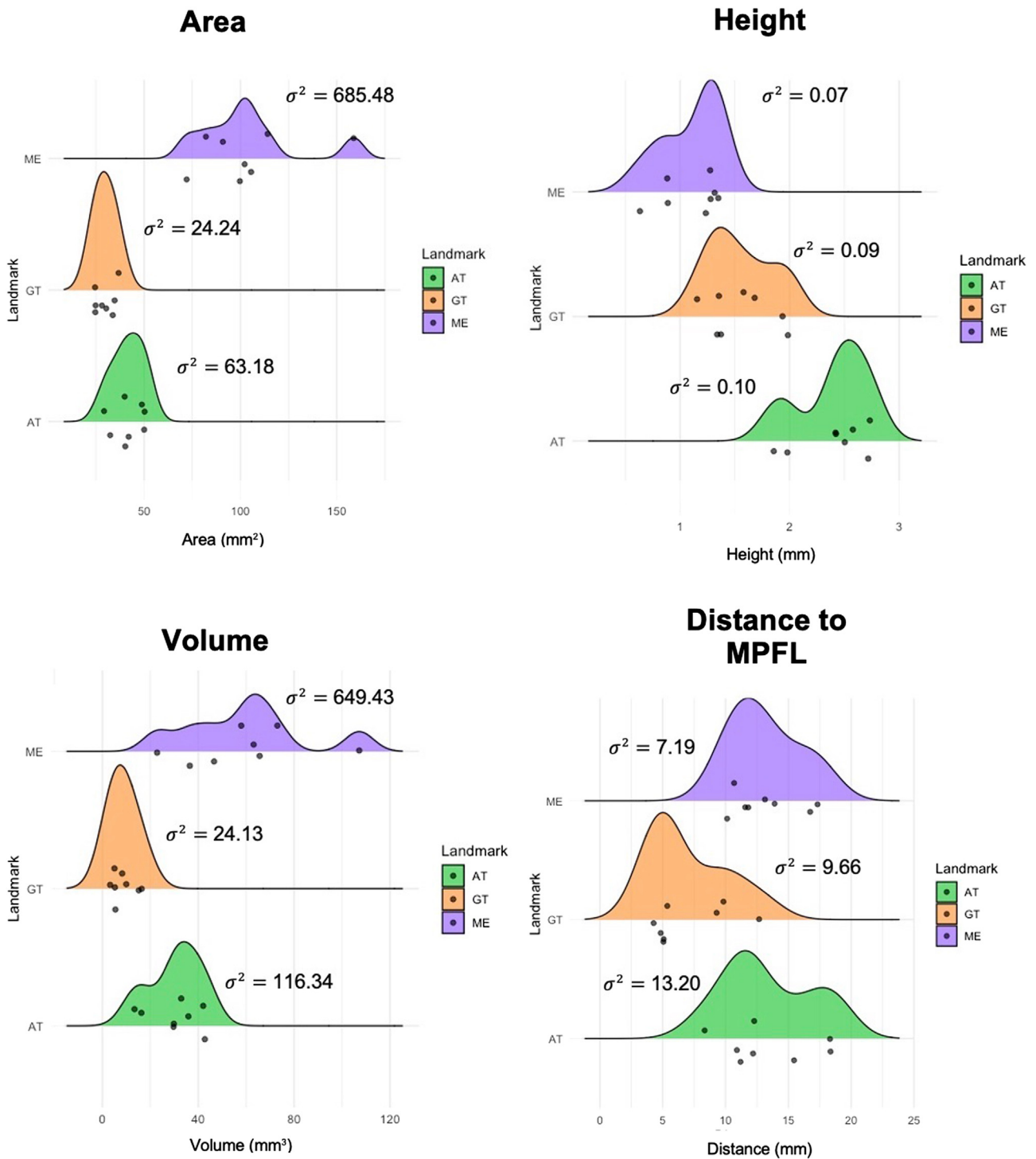


Fig 5. Density plots representing the relative distributions and variance of each anatomic parameter between landmarks. Dots represent individual specimen data points. σ^2 = variance. (AT, adductor tubercle; GT, gastrocnemius tubercle; ME, medial epicondyle.)

elongated morphology of the ME. This proximal–distal variability is similarly evident across anatomic studies of the MPFL, with the center of the MPFL footprint ranging from 3.1 to 14.3 mm (mean distances) proximal to the ME.^{18,19} For reference, in the same plane,

the mean distance of the MPFL center to AT has been reported to range from 3.8 to 8.3 mm distally.^{18,20} Notably, Chen et al.¹¹ identified that several radiographic reference points (Schöttle, Redfern, and Fujino) on average exceeded an acceptable distance from the

sulcus point. The discrepancy in acceptable rates between the studies can be attributed to different thresholds for acceptable distance (5 mm by Chen et al., and 7 mm by Koenen et al.). This further highlights the difference in variability when comparing distances between local landmarks.

Error in the proximal–distal axis is concerning when considering the implications of tunnel malpositioning. When examining the effect of tunnel placement on patellofemoral kinematics, Stephen et al.⁹ identified that femoral tunnels placed 5 mm proximal or distal from the anatomic MPFL center led to significantly increased peak and mean medial patellar contact pressures. However, the study did not differentiate outcomes between proximal and distal tunnel placement. A separate study by Stephen et al.²¹ also compared the extent of MPFL length changes between different femoral attachment points. Specifically, 5-mm shifts of the femoral attachment point in the proximal–distal axis significantly increased and decreased MPFL length, respectively, whereas anterior or posterior shifts of the same distance did not significantly alter length changes.²¹ Based on the risk associated with error in the proximal–distal axis for estimation of the femoral attachment point of the MPFL, as well as variable local topography, isometricity should be confirmed by some method before final fixation. Fluoroscopic localization for femoral tunnel placement may also be considered. Schöttle et al.²² defined a radiographic localization method that relies on triangulation of the point based on a reference line through the posterior cortex, with 2 perpendicular lines at the intersection of the posterior femoral condyle and through the most posterior portion of the Blumensaat line. Although the use of fluoroscopy does limit variability in tunnel localization between readers, this method of localization still may not accurately identify the anatomic footprint in all cases.^{23,24} Furthermore, fluoroscopy may not be universally available in all operative settings. If unavailable, this study suggests that palpation of the AT and GT may be more reliable due to decreased variability and greater topographical contrast.

Study Limitations

This study is not without limitations. As this was a descriptive cadaveric study, this study is limited to anatomic data without clinical correlation of surgeon interrater reliability for palpation. This study was performed as a single-investigator, single-turn investigation, and therefore, conclusions regarding the relationship between morphology and accuracy and precision of palpation could not be drawn. Furthermore, as this study aimed to accurately and thoroughly describe anatomy, the on-table dissection was more extensive than surgical exposure. This should be considered in context when applying these anatomic concepts in a surgical setting.

Lastly, MPFL reconstructions are performed most frequently in pediatric, adolescent, or young adult populations. However, this study was unable to comment on the morphology or chronologic development of these osseous landmarks during growth.

Conclusions

The 3 major osseous landmarks of the medial femur have significantly different variances in volume and base:height ratio. Specifically, the variability and elongated morphology of the ME differentiated this landmark from the AT and GT, which demonstrated the most consistent morphology.

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