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Patient-Individualized Identification of Medial Patellofemoral Ligament Attachment Site to Femur Using "CLASS" MRI Sequences

Marc Barrera Uso, MD, Grégoire Thürig, MD, Alexander Frank Heimann, MD, Joseph M. Schwab, MD, Raul Panadero-Morales, MEng, José Luis Peris, MS, Moritz Tannast, MD, and Daniel Petek, MD

Investigation performed at the Department of Orthopaedic Surgery and Traumatology, Hospital and University of Fribourg, Fribourg, Switzerland, and the Biomechanics Institute of Valencia, Universitat Politècnica de València, Valencia, Spain

Background: Malposition of the femoral tunnel during medial patellofemoral ligament (MPFL) reconstruction may increase the risk of recurrence of patellar dislocation due to isometric changes during flexion and extension. Different methods have been described to identify the MPFL isometric point using fluoroscopy. However, femoral tunnel malposition was found to be the cause of 38.1% of revisions due to patellar redislocation. This high rate of malposition has raised the question of individual anatomical variability.

Methods: Magnetic resonance imaging (MRI) was performed on 80 native knees using the CLASS (MRI-generated Compressed Lateral and anteroposterior Anatomical Systematic Sequence) algorithm to identify the femoral MPFL insertion. The insertions were identified on the MRI views by 2 senior orthopaedic surgeons in order to assess the reliability and reproducibility of the method. The distribution of the MPFL insertion locations was then described in a 2-plane coordinate system and compared with MPFL insertion locations identified with other methods in previously published studies.

Results: The CLASS MPFL footprint was located 0.83 mm anterior to the posterior cortex (line 1) and 3.66 mm proximal to the Blumensaat line (line 2). Analysis demonstrated 0.90 and 0.89 reproducibility and 0.89 and 0.80 reliability of the CLASS method to identify the anatomical femoral MPFL insertion point. The distribution did not correlate with previously published data obtained with other methods. The definitions of the MPFL insertion point in the studies by Schöttle et al. and Fujino et al. most closely approximated the CLASS location in relation to the posterior femoral cortex, but there were significant differences between the CLASS method and all 4 previously published methods in relation to the proximal-distal location. When we averaged the distances from line 1 and line 2, the method that came closest to the CLASS method was that of Stephen et al., followed by the method of Schöttle et al.

Conclusions: The CLASS algorithm is a reliable and reproducible method to identify the MPFL femoral insertion from MRI views. Measurement using the CLASS algorithm shows substantial individual anatomical variation that may not be adequately captured with existing measurement methods. While further research must target translation of this method to clinical use, we believe that this method has the potential to create a safe template for sagittal fluoroscopic identification of the femoral tunnel during MPFL surgical reconstruction.

Level of Evidence: Prognostic Level II. See Instructions for Authors for a complete description of levels of evidence.

The medial patellofemoral ligament (MPFL) is the main medial restraint of the patella, preventing lateral patellar dislocation from 0° to 30° of knee flexion[1,2]. Patellar dislocation accounts for approximately 3.3% of all knee injuries[3]. According to the literature, 80% to 96% of MPFL ruptures occur after a first dislocation[4-6] and the rate of recurrent patellar dislocation after initial nonoperative treatment reaches almost 50%[7,8]. Among the surgical options for treatment of patellar dislocation, MPFL reconstruction has taken a major role. Anatomical reconstruction of the MPFL is the

Disclosure: The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (http://links.lww.com/JBJSOA/A561).

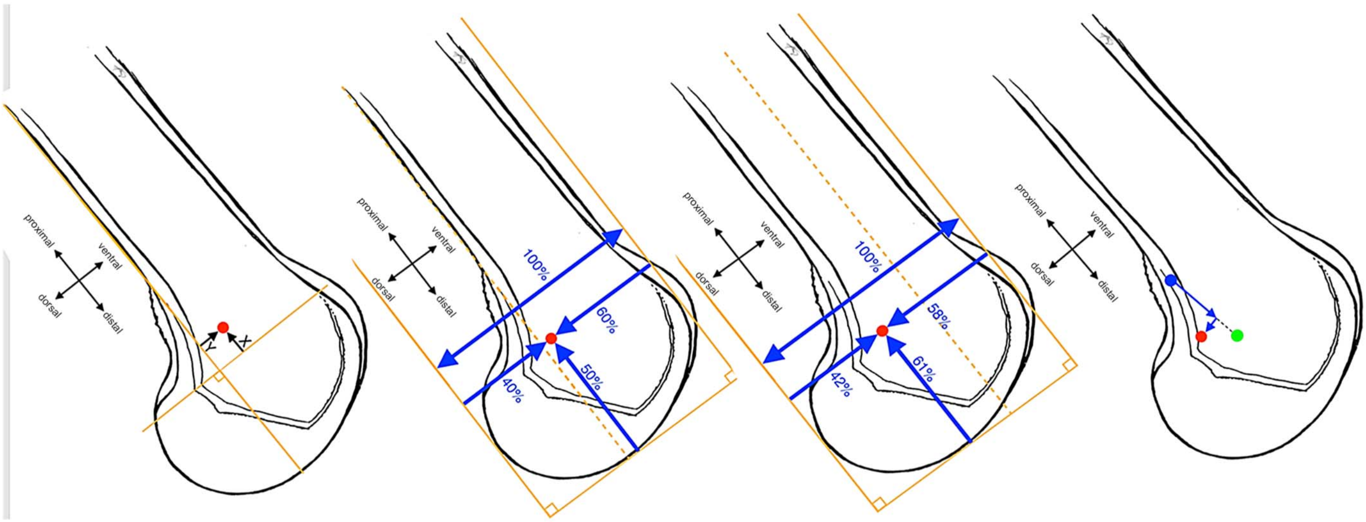

Fig. 1
Methods for radiographic determination of the femoral MPFL footprint according to (from left to right) Schöttle et al.[19], Stephen et al.[20], Fujino et al.[17], and Chen et al.[18].

primary aim, as malposition of the femoral tunnel during reconstruction may lead to changes in the length of the MPFL, which can increase the medial peak pressure on the patellofemoral joint during knee flexion[9-11]. Reoperation rates after MPFL reconstruction are reported to be around 3.1%, with the most common indication for a reoperation being femoral tunnel malposition (38.1%)[12].

Over the last years, research has aimed to describe the anatomical insertion of the MPFL on the femur as well as its relationship to the adductor tubercle and the medial epicondyle[10,13-16]. Based on these findings, different methods have been proposed to reliably identify the femoral insertion point of the MPFL (Fig. 1, Table I)[17-20]. While each technique has its proponents, there is controversy regarding which best identifies an individual's ideal anatomical location of the MPFL femoral tunnel. We thought that there was an opportunity to identify the MPFL anatomical footprint more accurately and reliably for a given patient.

It is widely recommended that fluoroscopy be used during routine surgical MPFL reconstruction to identify the femoral footprint on a lateral view. Being able to determine an individualized insertion point for the MPFL on a preoperative lateral radiographic view of the knee could help reduce reconstruction failures related to femoral tunnel malposition. To test our belief that the magnetic resonance imaging (MRI)-generated Compressed Lateral and anteroposterior Anatomical Systematic Sequence (CLASS) algorithm described by Thürig et al.[21] can be used to better understand and locate an individualized MPFL femoral insertion[22], we proposed the following study questions: (1) What is the location of the anatomical MPFL femoral insertion identified with the CLASS MRI technique in reference to a standardized coordinate system? (2) What are the intrarater reproducibility and interrater reliability for identifying the anatomical MPFL femoral insertion using the CLASS MRI technique? (3) How does the location of the MPFL insertion determined with the CLASS MRI technique compare with the locations identified with previously described methods?

Materials and Methods

This was a diagnostic retrospective cohort study conducted at the Department of Orthopaedic Surgery and Traumatology, Fribourg Hospital, University of Fribourg, Switzerland.

TABLE I Method Definitions

Method	Definition of Location of MPFL Footprint
Schöttle	1.3 mm anterior to the posterior cortex extension and 2.5 mm distal to the posterior origin of the medial femoral condyle, proximal to the posterior point of the Blumensaat line
Stephen	Taking the anterior-posterior diameter of the medial femoral condyle as 100%, the footprint is identified 40% from the posterior, 50% from the distal, and 60% from the anterior border
Fujino	10.6 ± 2.5 mm distal to the apex of the adductor tubercle on the long axis of the femur, or the proximal-distal (x = 61%) and anterior-posterior (y = 42%) ratios for the center of the femoral insertion of the MPFL
Chen	11.7 mm from the apex of the adductor tubercle (AT) to the medial epicondyle (ME), and 5.6 mm posterior to the border connecting the AT and ME

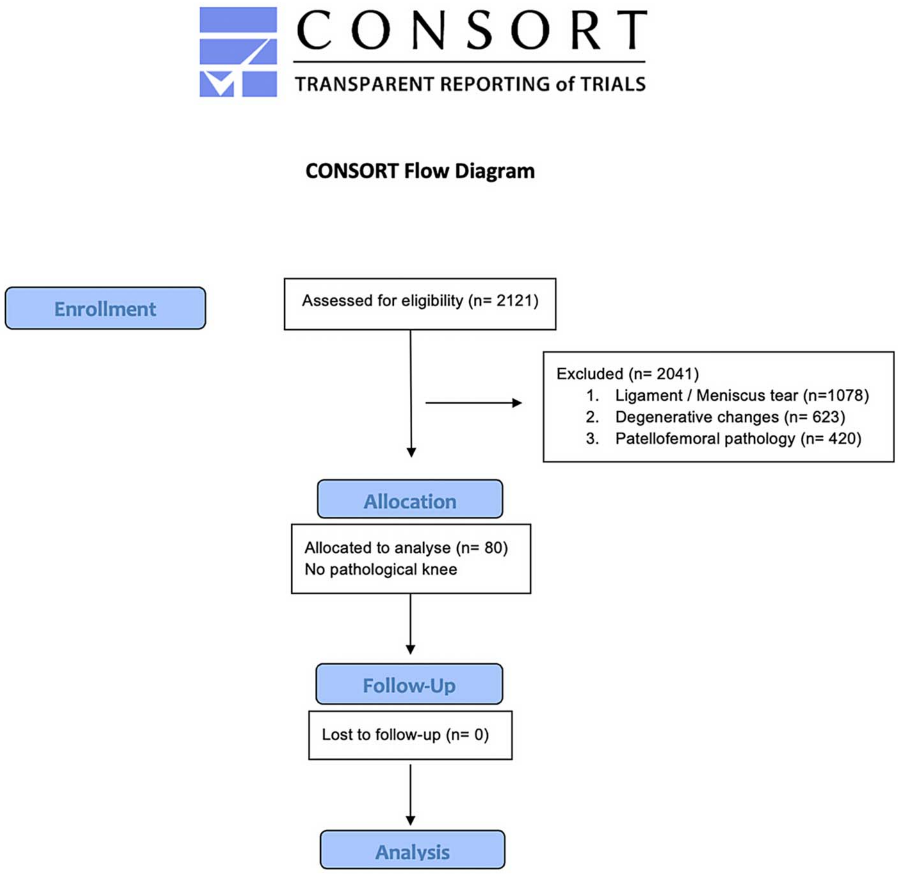

Fig. 2
Patient selection flow diagram.

The study was performed in accordance with the requirements of the local ethics committee (CER-VD 2021-00818).

Patient Selection

All knee MRI views obtained at the Fribourg Cantonal Hospital between 2015 and 2021 were acquired via the institution's picture archiving and communication system (PACS; GE Healthcare). A total of 2,121 MRI views of patients from 18 to 65 years old were available for inclusion. After the exclusion criteria were applied (Fig. 2, Table II), 80 patients (80 knees) were available for further analysis. All 80 MRI views were ordered by general practitioners for a variety of problems, none of which required further evaluation by an orthopaedic surgeon. The demographic data for the included patients are shown in Table III.

CLASS MRI

All knee MRI views were acquired using a standardized MRI technique and an Optima MR360 1.5T Advance scanner (GE Healthcare). The sequences included a sagittal proton density fat-saturated isotropic 3D sequence with an isovoxel of $0.6 \times 0.6 \times 0.6$ mm. The MPFL femoral attachment site, the adductor tubercle, and the medial epicondyle were each identified separately by 2 senior orthopaedic knee surgeons, using the multiplanar reformatting tool available in Materialise Mimics software (Materialise NV). Once these structures were located using the methodology described by Dirim et al.[22] in a cadaveric and MRI study, the MRI views underwent software compression to 2D images of the knee (anteroposterior and lateral views). It was then verified that the previously identified points appeared clearly on both reconstructed views (Fig. 3 and Fig. 4).

Intrarater Reproducibility and Interrater Reliability

The individualized MPFL footprints of all 80 knees were identified on the 2D images by one of the board-certified orthopaedic

TABLE II Inclusion and Exclusion Criteria*

Inclusion Criteria	Exclusion Criteria
Patients without detectable knee joint abnormalities who underwent CLASS knee MRI	History of traumatic knee lesions (meniscus, ligaments, bones)
Age between 18 and 65 years	Patellofemoral abnormality
No history of knee surgery	Degenerative changes

*CLASS = Compressed Lateral and anteroposterior Aanatomical Systematic Sequences, and MRI = magnetic resonance imaging.

TABLE III Patient Characteristics (N = 80)

Mean age ± SD* *(yr)*	33 ± 11
Female sex *(no. [%])*	45 (56)
Right side *(no. [%])*	34 (43)

*SD = standard deviation.

surgeons mentioned above. Following this, 30 sets of knee images were randomly selected to assess the reproducibility and reliability of the MPFL identification. This subset was surveyed a second time by the original evaluator and was also evaluated twice, to identify the MPFL footprints, at 2 different time points with a minimum of 3 weeks between evaluations by the second board-certified orthopaedic surgeon.

Comparison of MPFL CLASS Footprint with Footprints Determined with Previous Methods

A biplanar coordinate system, described by Schöttle et al.[19], was used for each of the 80 2D lateral images. Line 1 was defined as a distal extension of the posterior femoral cortex. Line 2 was defined as perpendicular to line 1 and crossing the most posterior point of the Blumensaat line. We could then define any point on the femur by its distance in millimeters from line 1 and from line 2. Positive values were defined as anterior to line 1 and proximal to line 2, while negative values were defined as posterior (line 1) and distal (line 2), respectively. We chose to use this coordinate system because all of the other MPFL footprint identification methods that we utilized for comparison in this study were described using this coordinate system. While other osseous landmarks are used in some of these methods, the coordinate system is the only consistent way of describing each method's location. We believe that this process simplifies the comparisons between different methods.

Using the 2D reconstructed lateral image with the medial epicondyle, adductor tubercle, and CLASS MPFL insertion identified, each previously described method for MPFL localization[17-20] was performed and the insertion point was marked on the image. The definition of each of these methods is provided in Figure 1 and Table I. These points were then compared with the location of the insertion determined with the CLASS method (Fig. 5). The locations of each of these points, defined by the distances (in millimeters) from lines 1 and 2, were then analyzed using open-source ImageJ software (U.S. National Institutes of Health).

Statistical Analysis

The statistical analysis was carried out using MedCalc statistical software (version 20.106). We performed a Kolmogorov-Smirnov test to check for normality of the distribution. Since our measurement data were non-normally distributed, groups were compared using the Friedman test. With the significance level set at $\alpha = 0.05$, a test was considered significant if $p < 0.05$.

The intraclass correlation coefficient (ICC) was calculated to evaluate the intraobserver reproducibility and interobserver reliability of the measurements. In this study, an ICC of ≤0.21 was considered poor; >0.20 to 0.40, fair; >0.40 to 0.60, moderate; >0.60 to 0.80, good; and >0.80 to 1.00, almost perfect. Descriptive analysis was performed using SPSS, version 26.0 (IBM), as described by Montgomery et al.[23].

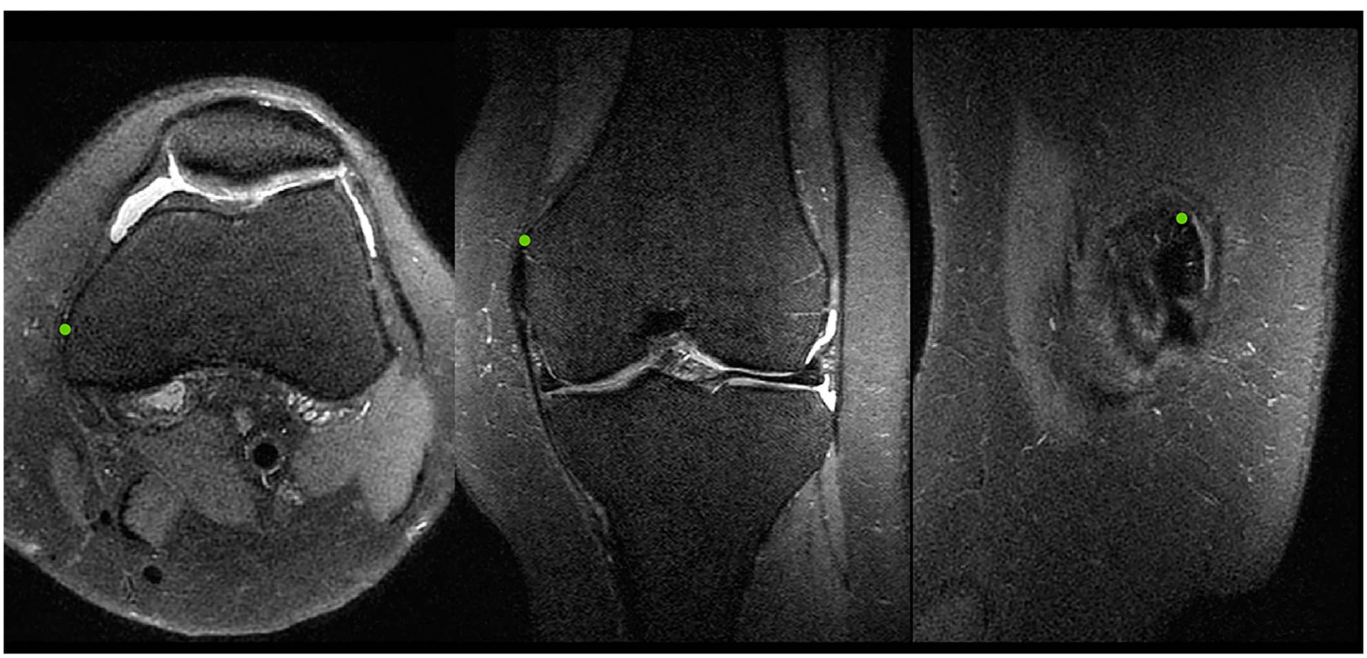

Fig. 3

The femoral attachment of the MPFL is marked in green in the axial (left), coronal (middle), and sagittal (right) planes on MRI scans.

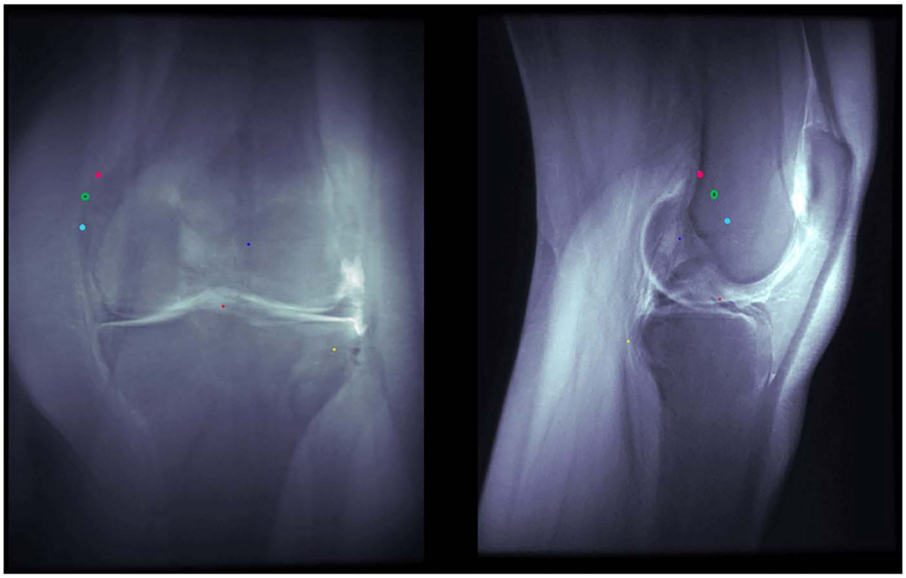

Fig. 4
MRI-generated Compressed Lateral (right) and anteroposterior (left) Anatomical Systemic Sequences (CLASS). The MPFL is marked in green; the adductor tubercle, in red; and the medial epicondyle of the femur, in blue.

Source of Funding
No external funding was received for this study.

Results

CLASS MPFL Location

The mean CLASS MPFL footprint was located 0.83 ± 3.8 mm (−7.5 to 9.8 mm) anterior to the posterior cortex and 3.66 ± 1.83 mm (−11.2 to 7.2 mm) proximal to the Blumensaat line (Fig. 6).

Intrarater Reproducibility and Interrater Reliability of CLASS Method

The intrarater reproducibility and interrater reliability for determination of the anatomical MPFL origin using CLASS MRI are shown in Table IV. The mean ICC values for the intraobserver reproducibility were 0.90 and 0.89 (95% confidence interval [CI] = 0.5 to 0.94) for the 2 observers. The interobserver reliability was 0.89 (95% CI = 0.75 to 0.95) for the distance from line 1 and 0.80 (0.54 to 0.91) for the distance from line 2.

Comparison of MPFL CLASS Footprint with Footprints Located with Previous Methods

The results of all of the measurement methods are shown in Figure 7 and Figure 8. We found no significant difference in the distance from line 1 when we compared the CLASS method with the Schöttle and Fujino methods, but we found significant differences ($p < 0.05$) when we compared the CLASS method with the Stephen and Chen methods. When measuring the distance from line 2, we found significant differences between the CLASS method and all 4 previous methods. When we averaged the distances from lines 1 and 2 for each method, the method that came closest to the CLASS method was the Stephen method, followed by the Schöttle method. The footprint identified with the Chen method was found to be the farthest from that located with the CLASS method and was mostly located distal to the Blumensaat line.

Discussion

MPFL reconstruction has become an important surgical procedure for the treatment of patellar instability. However, postoperative problems are often related to biomechanical changes in patellofemoral tracking[24,25]. The most common reason for patellofemoral tracking issues following correction is malposition of the femoral tunnel used to insert the MPFL

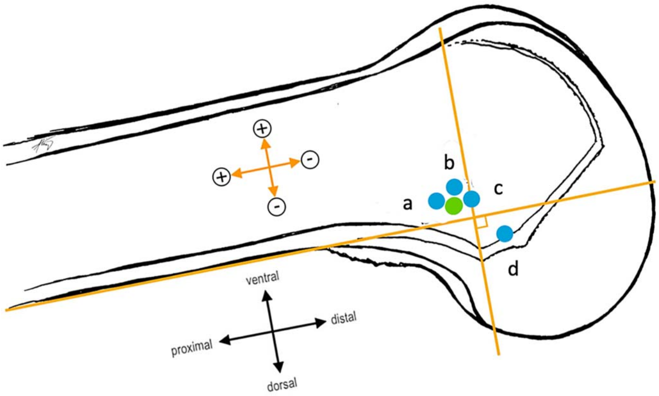

Fig. 5
Schematic representation of the spatial relationship (distance in millimeters) between the femoral MPFL insertion determined with the CLASS MRI method (green dot) and the MPFL insertions determined with the methods of Schöttle et al.[19] (a), Stephen et al.[20] (b), Fujino et al.[17] (c), and Chen et al.[18] (d) (blue dots).

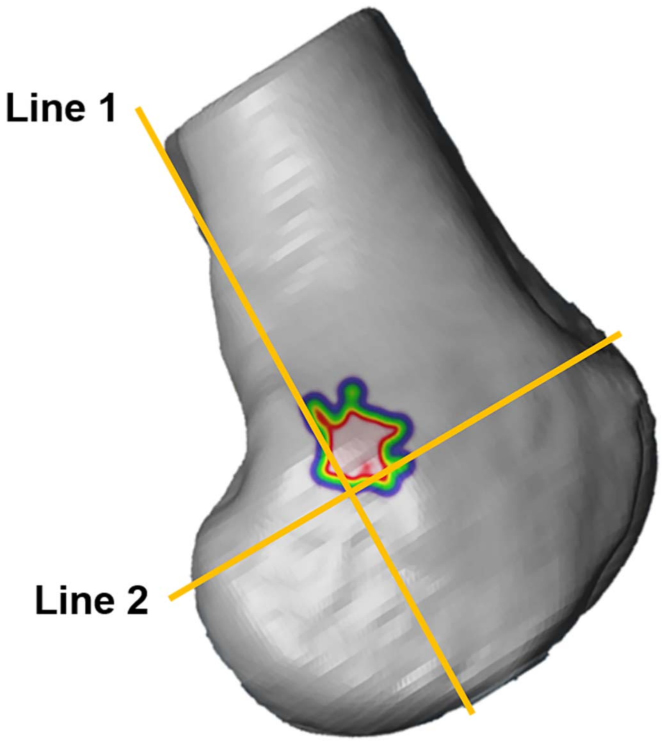

Fig. 6

Visualization of the distribution of the MPFL footprint determined by the CLASS method in a 3D reconstruction of a knee (lateral view) with respect to line 1 (distal extension of the posterior femoral cortex) and line 2 (running perpendicular to line 1 and crossing the posteriormost point of the Blumensaat line).

reconstruction graft, which accounted for 38% of revisions examined in a systemic review[12]. Although only 3% of patients sustain a patellar redislocation and need revision surgery, the population affected by patellar instability is young and we therefore think that it is crucial to have an accurate, patient-specific method to determine the anatomical femoral fixation site for a successful MPFL reconstruction[25].

Multiple studies have described the anatomy of the MPFL, first using anatomical dissection[9,14] and subsequently with radiographic analysis. One of the most widely accepted methods to localize the MPFL insertion was described by Schöttle et al.[19]. Their framework for describing the location of the MPFL insertion was supported by other authors, who developed various alternative ways of identifying the MPFL femoral anatomical point[16-18,20].

There was an observable difference regarding the identified location of the MPFL femoral insertion among the 4 methods (Table I) evaluated in this study. This raises the question of whether there is individual variability in this insertion. Sanchis-Alfonso[26] demonstrated that the insertion points obtained from current radiographic methods had very poor overlap when plotted simultaneously. They concluded that there is no standard radiographic method that allowed for precise anatomical femoral placement. Furthermore, they asserted that existing methods do not take into account factors of anatomical variation such as femoral anteversion or trochlear dysplasia[27,28].

In an effort to reduce the error of non-anatomical reconstruction of the MPFL, we evaluated an MRI-based method to localize a patient-specific MPFL femoral footprint that could then be identified intraoperatively using fluoroscopy. As described by Thürig et al.[21], MRI data have been used to generate 2D anteroposterior and lateral views of the knee. These could then serve as an intraoperative template during fluoroscopic determination of the optimal femoral tunnel placement. Our study used this method of 3D-to-2D compression to find a patient-specific MPFL insertion. Our results indicate that this method is both reliable and reproducible in a cohort of "normal" knee MRI views.

The first aim of the study was to determine the exact anatomical femoral MPFL origin using the CLASS method. This point was then analyzed in a 2D coordinate system, as described by Schöttle et al.[19], and we found the "average" position of the MPFL insertion to be 0.83 mm anterior to the posterior cortex and 3.66 mm superior to Blumensaat's line. However, the ranges that we discovered, −7.5 to 9.8 mm relative to the posterior cortex and −11.2 to 7.2 mm relative to the Blumensaat line, show an important variability among patients. This helps support the idea that the location of the MPFL femoral insertion should be patient-specific. We think that the substantial positional variation in the individual MPFL footprints is an important observation in our study and requires further investigation.

The second aim was to determine the intrarater reproducibility and interrater reliability of the CLASS method in identifying the MPFL insertion. Our results indicate that this method is both highly reliable and highly reproducible.

The third aim of the study was to compare our CLASS method with 4 previously accepted methods[17-20] (Fig. 1). Elias and Cosgarea[24] demonstrated, in a computational model, that 5 mm of malposition of the femoral tunnel, specifically in a proximal-distal vector, may be responsible for increased

TABLE IV Intrarater Reproducibility and Interrater Reliability for Determination of the Anatomical MPFL Origin Using CLASS MRI*

	Intraobserver					
	Observer 1		Observer 2		Interobserver	
	ICC	95% CI	ICC	95% CI	ICC	95% CI
Line 1†	0.90	0.86-0.95	0.93	0.86-0.97	0.89	0.75-0.95
Line 2†	0.89	0.5-0.94	0.86	0.82-0.93	0.80	0.54-0.91

*MPFL = medial patellofemoral ligament, CLASS = Compressed Lateral and anteroposterior Anatomical Systematic Sequences, MRI = magnetic resonance imaging, ICC = intraclass coefficient, and CI = confidence interval. †Line 1 = extension of the line along the posterior cortex, and line 2 = a line perpendicular to line 1 that passes through the distal point of the Blumensaat line, as described by Schöttle et al.[19].

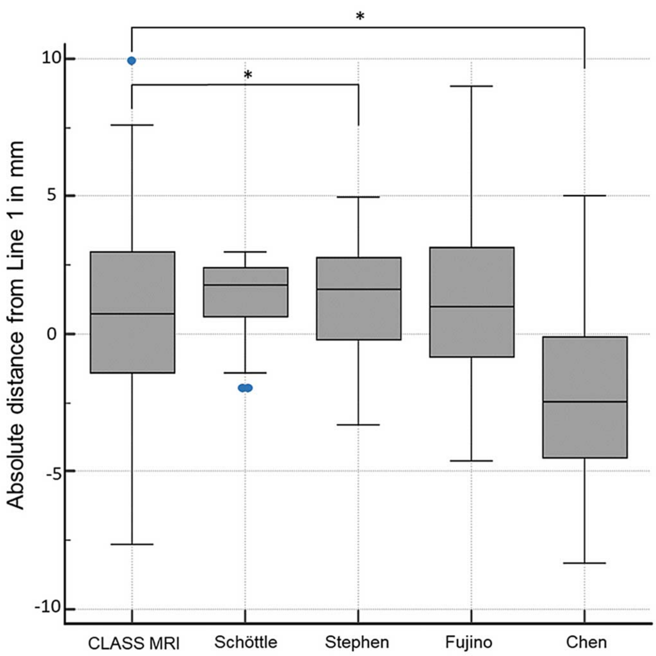

Fig. 7
Box plots indicating median (dark center line) and first and third quartiles (shaded boxes) of the absolute distance in millimeters of the footprints from line 1 as determined with the 5 methods. Whiskers are based on the 1,5 interquartile range values. Blue dots indicate measurement outliers. Significant differences between the parameters were assessed using the Friedman test and are depicted with an asterisk.

patellofemoral contact pressure. For that reason, we first analyzed, in all 80 knees, the distance in millimeters between the MPFL insertion point determined with each method and the 2 lines of a standard coordinate system. Then, we compared each method's coordinate location with the location determined by the CLASS method. The distance from line 1 did not differ significantly between the CLASS method and the methods described by Schöttle et al.[19] and Fujino et al.[17], but it differed significantly between the CLASS method and those described by Stephen et al.[20] and Chen et al.[18] ($p < 0.05$). The distance from line 2 determined with the CLASS method differed significantly from that found with all other methods. This change in the proximal-distal location could lead to an important change in the kinematics of the patellofemoral articulation.

There are limitations to this study. First, all MRI views were determined to have no abnormal findings, and it remains to be evaluated whether our findings are specifically applicable to patients with patellar instability, trochlear dysplasia, and/or known MPFL injury. Second, the CLASS MRI method is still an imaging assessment, and we did not correlate the radiographic landmark with cadaveric dissection. Radiographic-to-anatomical validation using cadaveric dissection is an important step toward using this method clinically during MPFL reconstruction. Third, we did not directly compare the MPFL locations identified by our surgeons with those determined by a musculoskeletal radiologist to ascertain if there were any differences. Nevertheless, we view this technology as a potential surgical planning tool that should be able to be used and interpreted by an orthopaedic surgeon.

Finally, while we believe that the CLASS method provides the best patient-specific location of the MPFL femoral insertion, biomechanical testing to determine patellofemoral tracking and pressure distribution at the patellofemoral joint would help confirm that this method determines the optimal location for reconstruction. Evaluating the clinical outcomes in patients who had been treated with his method would provide further validation, but such outcomes are not yet available. Recognizing these limitations, we believe the CLASS method could make it possible to adapt MPFL surgery to each patient.

Conclusion

The CLASS algorithm is a reliable and reproducible method to identify the MPFL femoral insertion from MRI views. Measurement using the CLASS algorithm showed substantial individual anatomical variation that may not be adequately captured with existing measurement methods. While further research must target translation of this method to clinical use,

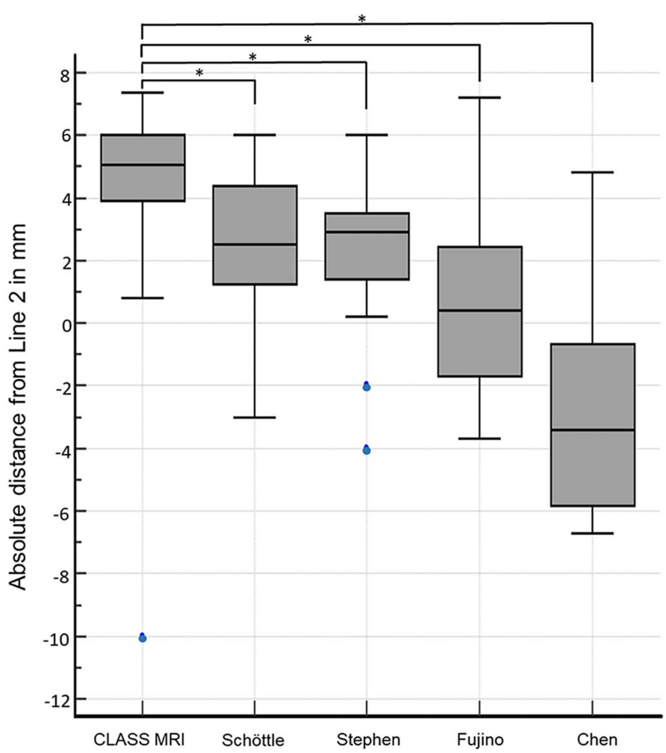

Fig. 8
Box plots indicating median (dark center line) and first and third quartiles (shaded boxes) of the absolute distance in millimeters of the footprints from line 2 as determined with the 5 methods. Whiskers are based on the 1,5 interquartile range values. Blue dots indicate measurement outliers. Significant differences between the parameters were assessed using the Friedman test and are depicted with an asterisk.

we believe that it has the potential to create a safe template for sagittal fluoroscopic identification of the femoral tunnel during MPFL surgical reconstruction. ■

Marc Barrera Uso, MD[1]
Grégoire Thürig, MD[1]
Alexander Frank Heimann, MD[1]
Joseph M. Schwab, MD[1]
Raul Panadero-Morales, MEng[2]
José Luis Peris, MS[2]
Moritz Tannast, MD[1]
Daniel Petek, MD[1]

[1]Department of Orthopaedic Surgery and Traumatology, Hospital and University of Fribourg, Fribourg, Switzerland

[2]Biomechanics Institute of Valencia, Universitat Politècnica de València, Valencia, Spain

Email for corresponding author: daniel.petek@h-fr.ch

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