Joints

Patellofemoral anatomy and biomechanics: current concepts

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Abstract

The patellofemoral joint, due to its particular bone anatomy and the numerous capsuloligamentous structures and muscles that act dynamically on the patella, is considered one of the most complex joints in the human body from the biomechanical point of view. The medial patellofemoral ligament (MPFL) has been demonstrated to contribute 60% of the force that opposes lateral displacement of the patella, and MPFL injury results in an approximately 50% reduction in the force needed to dislocate the patella laterally with the knee extended. For this reason, recent years have seen a growing interest in the study of this important anatomical structure, whose aponeurotic nature has thus been demonstrated. The MPFL acts as a restraint during motion, playing an active role under conditions of laterally applied stress, but an only marginal role during natural knee flexion. However, it remains extremely difficult to clearly define the anatomy of the MPFL and its relationships with other anatomical structures.

Key Words: biomechanics, medial patellofemoral ligament, knee, patellar instability, patellofemoral joint.

Introduction

The patellofemoral (PF) joint, due to its particular bone anatomy and the numerous capsuloligamentous structures and muscles that act dynamically on the patella, is considered one of the most complex joints in the human body from the biomechanical point of view. Indeed, abnormalities in one or more of these structures may result in pathological behavior of the PF joint. Anterior knee pain and patellar instability are the best described clinical entities, although the variability of the multifactorial pathogenesis underlying patient-specific pathological conditions is such that simple categorization of patients is not always possible. The complexity of the anatomy and biomechanics of the PF joint is underlined, in particular, by the large number of surgical options available, which do not always give satisfactory results.

Bone anatomy

Normal development of the femoral trochlea is one of the most important elements for correct PF biomechanics. Indeed, trochlear dysplasia, characterized by a flat or even convex trochlea, prevents the patella from engaging properly in the trochlear groove throughout the range of motion, but especially in the early degrees of flexion. It has been estimated that the impact of this condition on PF kinematics is more severe than that of a lesion of the medial patellofemoral ligament (MPFL) or a muscular imbalance involving the *vastus medialis obliquus* (VMO) (1). The height of the patella with respect to the trochlear groove also plays a decisive role in correct kinematics, given that during contraction of the quadriceps the patella moves proximally above the trochlea, in an area that lacks side support. In the presence of patella alta, knee flexion is associated with a delay in the engagement of the patella in the trochlear groove, which increases the risk of lateral dislocation (2, 3). The height of the patella

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influences PF joint pressure as well. This pressure is, in fact, increased at high degrees of flexion and reduced near full extension in cases of patella alta, while the opposite behavior occurs in the presence of normal patellar height (4).
Furthermore, the overall morphology of the lower limbs can modify the mechanical behavior of the PF joint. In fact, femoral anteversion is classically associated with increased patellar tilt, instability and osteoarthritis (5-7). This morphological abnormality, sometimes associated with external tibial torsion, determines an unfavorable lever arm of the quadriceps muscle, which, when contracting, moves the patella laterally, increasing the risk of instability. A similar situation has been described in the case of the valgus morphotype (8).

Soft tissues

Dysplasia of the extensor mechanism may be responsible for PF symptoms, with even small variations being liable to affect the delicate muscle complex that controls PF kinematics.
Increased tension of the lateral retinaculum increases stress on the lateral patellar facet and predisposes to malalignment and instability (9). Similarly, excessive tension of the iliotibial band, through its expansion on the quadriceps and patellar tendon, causes a lateral patellar shift predisposing to lateral dislocation (10). A similar effect is determined by true VMO hypoplasia (11, 12). It has been demonstrated that the VMO is oriented at 47° ± 5° with respect to the medial femoral axis, while the orientation of the vastus lateralis is 35° ± 4° (13). Furthermore, relaxation of the VMO at 20° of knee flexion determines a 30% reduction of lateral stability (14). Despite normal development of the medial structures, an imbalance of neuromuscular activation and coordination also determines an alteration of patellar behavior during flexion-extension (15).
The passive stabilizers of the PF joint include the MPFL, the medial patellotibial ligament (MPTL) and the retinaculum. It has been shown that MPFL and MPTL contribute, respectively, 60% and 22% of the force that opposes lateral displacement of the patella (16), and that the force needed to determine a lateral patellar displacement is less at 20° of knee flexion (17). Furthermore, MPFL injury has been proven to reduce by almost 50% the force needed to dislocate the patella laterally with the knee extended (18). For this reason, the scientific community has, in recent years, shown a growing interest in the study of this important anatomical structure.
Medial patellofemoral ligament damage, in fact, has been shown to be one of the leading causes of lateral dislocation of the patella (19-21). Although reconstruction of an injured MPFL gives better results today than in the past, a recent systematic review of the literature suggested that there is a need for a better understanding of the capacity of the reconstructed MPFL to prevent alterations in PF kinematics and cartilage degeneration (22).
Kinematic *ex vivo* studies can provide extremely realistic models of knees with intact MPFL. However, analyzing the mechanical behavior of the patella in cases of MPFL injury or reconstruction is less straightforward (23-27). There are also conflicting results regarding MPFL tension at rest with the knee extended (19, 20). These differences are likely attributable to the use of different reference systems, to difficulties defining the points of MPFL insertion on the femur and the patella (19, 27-29), and to differences in specimen preparations due to the complexity of MPFL dissection and resection.

The anatomy and kinematics of the MPFL

We performed a study in collaboration with the Lyon-Ortho-Clinic to analyze the role of the MPFL in PF kinematics, considering its femoral insertion, the influence of lateral load, and the morphology of the trochlea, using a surgical navigation system (30).
Six frozen, non-paired, amputated-at-the-hip-joint human lower limbs, obtained from donors with a mean age of 50 years, were prepared by cutting the skin and subcutaneous tissues to 20 cm from the knee joint, both proximally and distally, preserving the extensor mechanism. A tracker with a sensor detectable by a navigation system (BLU-IGS, Orthokey, LLC, Lewes, Delaware) was positioned on the femoral shaft, tibial shaft and patella. The limb was blocked at the level of the proximal portion of the femoral shaft, maintaining the free of flexion-extension movement of the tibia. The acquisition of specific anatomical landmarks (femoral and tibial axis, transepicondylar line, upper and lower patellar pole, medial and lateral patellar border, tibial tuberosity) allowed the reconstruction of the axes of the lower limb. The femoral and patellar insertions of the MPFL were localized isolating them from the medial tibio-meniscal ligament and the VMO tendon. Two fibers were selected to represent

the upper border of the MPFL and two to represent its lower border; a further two fibers were selected in the MPFL body. A 60N force was applied to the quadriceps tendon with a pulley. The position of the patella and its orientation were recorded with intact and resected MPFL, manually applying a force of 25N directed laterally on the medial border of the patella. At the end of the kinematic tests, after dissection, the surface of the trochlea, tibial plateau, patella, and femoral and patellar insertion of the MPFL were acquired. In this way, a 3D model of the knee was reconstructed on which sulcus angle and trochlear morphology were measured. For each sample, the relationship between the insertion of the MPFL and the medial epicondyle was described using values expressed as means ± standard deviation. The Mann-Whitney test ($p = 0.05$) was used: to compare the difference between the sulcus angle and the position of the patella at 0°, 30° and 60° of flexion, and to quantify the difference between the amplitude of the trochlea and the position of the patella at the three angles of flexion (0°, 30°, 60°). To analyze the relationship between the anatomical landmarks of the trochlea and displacement of the patella after sectioning of the MPFL, the Spearman correlation test was used. The Wilcoxon test ($p = 0.05$) was used to compare the orientation and tilt of the patella in the knee with and without load in all degrees of flexion. Comparison of the distance between the insertion points of the MPFL fibers at four different degrees of flexion was performed using the Kruskal-Wallis test.

This study certainly had limitations, the first being small number of samples studied. In addition, femoral anteversion was eliminated and it was not possible to study the effect of internal rotation of the femur on patellar tracking. Furthermore, given that the purpose of the study was to determine the anatomy and kinematics of the isolated MPFL, the influence of the VMO and medial collateral ligament (MCL) on the MPFL was not considered. However, the study produced interesting results regarding several important issues, namely: MPFL anatomy and kinematics, patellar behavior with and without lateral stress, and trochlear morphology.

MPFL anatomy

The geometric center of the MPFL femoral insertion, with respect to medial epicondyle, showed considerable variability between the samples (30). The average width of the MPFL femoral insertion was 14.2 ± 1.9 mm, while its length was 2.2 ± 0.5 mm. The proximal insertion was on average 5 ± 7.2 mm posterior and 6.5 ± 3.8 mm proximal to the medial epicondyle, while the distal insertion was 10.1 ± 8.2 mm posterior and 2.3 ± 2.3 mm distal to the medial epicondyle. The surface area of the MPFL femoral insertion was 36.5 ± 11.74 mm^2 (**Fig. 1**). This variability of the femoral MPFL insertion was consistent with the current literature (28, 29, 31) and could be attributable to differences in specimen preparations, due to the complexity of MPFL dissection (28, 31, 32), but may also be linked to the fact that the

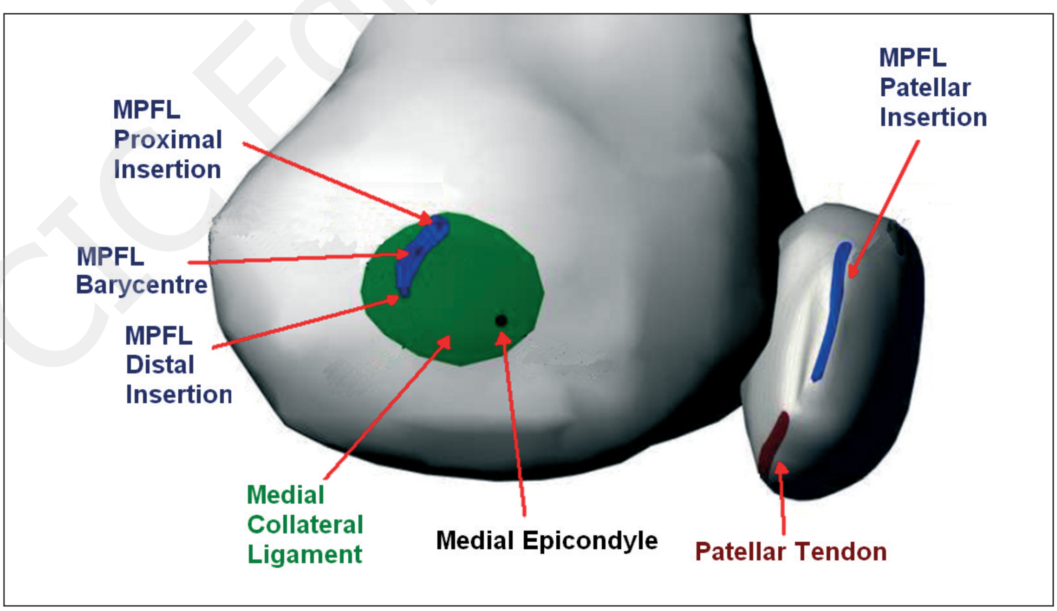

Fig. 1. Femoral and patellar MPFL insertion.

MPFL is not a true ligament, but rather an extensive expansion, to different structures, of a layer of the retinaculum. However, the size of the femoral MPFL insertion reported in our study was comparable with the width described previously using standardized dissection techniques (10.6 ± 2.9 mm; range, 6-15 mm). Furthermore, the femoral MPFL insertion is reinforced by two resistant bundles located between the branches of the medial descending geniculate artery: the upper transverse bundle, which originates from the point of Nomura and merges with the tendon of the VMO, and the inferior oblique bundle, which intersects with the superficial MCL. The literature contains other evidence that demonstrates how the fibers of the VMO and MCL merge with the MPFL (19, 21, 28, 33). The VMO acts through the MPFL (34) during the first 30° of flexion, causing a slight medial displacement of the patella above the trochlea (35). MPFL reconstruction combined with VMO advancement has been reported to give better results than isolated MPFL reconstruction in recurrent patellar dislocation (36).
With regard to MPFL reconstruction, the point of Nomura (an area measuring 10.6 mm^2 between the medial epicondyle and the adductor tubercle) may be the better insertion point for the femoral MPFL component (28). Controversies related to the MPFL tensioning at rest could be resolved by considering the role of the VMO insertion of the MPFL (19, 21, 22, 27), tensioning or releasing the fibers in the cranial part of the ligament depending on the state of contraction of the quadriceps.

MPFL kinematics

During knee flexion, the distance between the insertion points of the different fibers showed an asymmetrical reduction in the specimens with intact MPFL. The upper fibers maintained almost isometric behavior at each degree of flexion, while the lower fibers showed a shortening, in particular at 90° (30).
According to the results of our study (30), the MPFL showed non-isometric behavior during knee flexion, with the insertion points of the two lower fibers tending to converge, while the distance between the upper ones remained unchanged. This reduction of the distance between the insertion points of the lower fibers may be comparable to the elongation of the lower fibers of the MPFL observed by Victor et al. (37), while the isometric behavior of the insertion points of the upper fibers observed in our study can be compared to the behavior of the central isometric fibers in the study by Victor et al. (37). Instead, in our study (30), no fibers showed a kinematic behavior similar to that described by Victor et al. (37) for the upper part of the MPFL. This is probably because in this study the upper portion of the MPFL, which largely consists of aponeurosis at the point of VMO insertion, was detached during the dissection, causing a lateral displacement of the patella in cases of resected MPFL (37).

Patellar behavior without lateral stress

Maximum medial patellar displacement with intact MPFL was observed at 20-25° of flexion, while there was no medial patellar displacement with resected MPFL. Furthermore, lateralization of the patella was evident even in the absence of laterally directed stress. At 60-90° of flexion, the variability of patella movements was reduced in a similar manner both in preparations with intact and in those with resected MPFL. Moreover, the patella showed no medial tilt at 20-25°, while the lateral tilt was reduced at 85° of flexion both in samples with intact and in those with resected MPFL, thus maintaining wide variability (30).
In samples with intact MPFL, medial shift of the patella was appreciated at 20-25°, while beyond 90° of knee flexion, the patella showed a lateral displacement, as reported in the recent literature (38-42). There is less agreement, instead, regarding PF kinematics in the presence of an injured MPFL (23-27). Several papers suggest that the patella follows its normal course in the absence of a loading condition; differently, our study showed a slide and a lateral tilt of the patella.
Ostermeier et al. (25) reported a lateral displacement of the patella of 4.0 mm (SD 2.5 mm) at 9.1° of flexion in samples with MPFL lesion and in the absence of laterally directed load. Another study showed, instead, an unspecified slight lateral mobility of the patella without load, not compensated for by the MPFL (20). These differences may be due to detachment of the VMO insertion from the MPFL during the dissection, performed in our study (30) and in the most recent ones (25). Therefore, the studies that found normal patellar movement in the absence of load in specimens with injured MPFL (23-27) probably maintained the VMO insertion of the MPFL during the dissection (19, 27, 42-44).
In contrast to what is reported in the literature (1, 38, 39, 41, 42), we found that patellar tilt was very variable since we did not observe any medial inclination at the first degree of flexion in the samples with intact MPFL. A reduction of lateral patellar tilt at 85° has instead been reported in specimens with both intact and injured MPFL (27-29, 43). The study by

Ostermeier et al. (25) reported a similar medial tilt, but at 102°. The variability of the patellar tilt at more than 60° of knee flexion is probably due to differences in the bone morphology of the trochlea.

Patellar behavior with laterally directed force

The application of force on the medial side of the patella and directed laterally significantly increased the lateral displacement at each degree of knee flexion in specimens with resected MPFL compared to those with intact MPFL. When a laterally directed force was applied on the medial aspect of the patella, the maximum lateral displacement in the samples with resected MPFL was between 30° and 50° of flexion.

Differently, the effect of lateral stress was attenuated after 60° of knee flexion (30). These results were consistent with current literature evidence (20, 45), reflecting the maximum tensioning of the MPFL at the first degrees of flexion, and its role as a stabilizer of the patella in the trochlear groove after 60° of flexion (35, 45). Intra-group variability, most evident in samples with injured MPFL (23-27), may reflect differences in the MPFL insertion, the resection point of the MPFL and the VMO effect (19, 40, 46).

Trochlear morphology

No significant differences between samples were found in the sulcus angle and the trochlear morphology at 0°, 30°, and 60° of flexion, the values being found to fall within the range of the those described in the most recent literature (27). We observed a statistically significant mean reduction of the sulcus angle from 0° to 30° ($p = 0.0226$) and then at 60° ($p = 0.0175$), with progressive deepening of the trochlea. No sample showed signs of dysplasia. No correlation was found between sulcus angle, trochlear morphology and patellar displacement (30). We did not find any relation between the intra-group variability of the PF kinematics and trochlear morphology in the specimens with injured MPFL (47, 48). The proximal trochlea was studied between 0° and 60° since most dysplasia is found in this range (48). The differences in the sulcus angle at different degrees and the differences in the medial and lateral condyle morphology were comparable to values reported in the literature (34, 44).

Conclusion

Factors involved in the biomechanics of the PF joint are numerous and complex, and their different penetrance and association may be responsible for different clinical presentations, making it very difficult to manage patients with PF problems and to choose the correct therapeutic approach. Considering the most recent evidence, it is clear that the MPFL has the characteristics of an aponeurosis and acts as a passive constraint during knee motion, playing an active role under conditions of laterally applied stress, but an only marginal one during the natural knee range of motion.

Moreover, in MPFL reconstruction surgery, it is crucial to ensure MPFL graft tensioning and fixation in a single femoral insertion point slightly above the patella with the knee in 30° of flexion, since this is the degree at which the MPFL fibers are at their maximum length. Clear definition of the relationship of this complex ligament with the other surrounding anatomical structures remains extremely difficult.

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