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Update on Patellofemoral Anatomy and Biomechanics

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The anatomy of the patellofemoral (PF) joint is reflective of its primary function of knee extension and eccentric quadriceps contraction, as it operates as a functional unit to optimize weight-bearing during knee range of motion. Our understanding of PF anatomy continues to evolve with the use of new dissection methods, as well as improving imaging modalities. A proper understanding of PF anatomy allows us to describe the morphological abnormalities that may predispose to PF pain and instability, such as trochlear dysplasia, excessive lateral tilt, bony malalignment, and patella alta. With an understanding of PF biomechanics, clinicians can improve treatment of these disorders through targeted operative and nonoperative treatment options. The goal of this review is to provide a functional anatomical overview pertinent to the operative treatment of PF disorders.
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Introduction

The anatomy of the patellofemoral (PF) joint is reflective of its primary function in knee extension and eccentric quadriceps contraction, as it operates as a functional unit to optimize weight-bearing during knee range of motion. Our understanding of normal PF anatomy and function continues to evolve with the use of novel dissection methods, innovative technologies for biomechanical evaluation, and improving imaging modalities. In order to maintain its proper function, the PF joint needs to be stable and capable of withstanding forces applied to it. Stability and joint load capacity are provided by the integrity and shape of the osseous and cartilaginous structures, balance of the soft tissue stabilizers, and coordinated function of its dynamic restraints. Morphological abnormalities commonly contribute to PF disorders, particularly with regard to instability and/or reduced joint load capacity. These can include trochlear dysplasia, excessive lateral tilt, bony malalignment, and patella alta.[1-5]

PF dysfunction can be addressed through dynamic strengthening/stability, or bracing, and in cases of continued symptoms, operative management.[6] In each condition, a thorough understanding of the normal anatomy and biomechanics of the PF joint is required to identify the source of dysfunction, which then enables the clinician to provide individualized treatment that is specific to the patient's anatomy. The goal of this review is to provide an updated anatomical and biomechanical overview pertinent to the current operative treatment of PF disorders.

Bony Morphology

The osseous and cartilaginous architecture of the PF joint is the primary contributor to the stability and load capacity of the PF joint, particularly in greater degrees of knee flexion. The articulating bony architecture consists of the patella and the trochlear surface of the anterior distal femur. The PF joint is considered to be one of the most complex joints in the human body from a biomechanical point of view.[9] In normal patellar tracking, the patella functions to improve the mechanical advantage of the extensor mechanism of the PF

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joint. The patella does so by decreasing the quadriceps force required to facilitate knee extension.[10] Additionally, the patella integrates the divergent forces of the quadriceps, transmitting tension from the femur to the patellar tendon.[11]

The patella is the largest sesamoid bone in the body, with normal dimensions of 4.5 cm (range, 3.8-5.3 cm) in length, 4.7 cm (range, 4-5.5 cm) in width, and 2.3 cm (range, 1.9-2.6 cm) in thickness.[7,8] Patellar articular cartilage is also the thickest found in the body, measuring up to 7 mm,[10] with the average thickness in a study of 43 adults reported to be 4.1 ± 1.3 mm. The thickest region of the patella was found to be 54 ± 2.32% from the lateral border and 54 ± 7.9% from the superior pole.[12] The articular surface is only present on the superior two-thirds of the patella, as the distal pole acts as the insertion for the patellar tendon. There is a significant difference in the articular joint surface geometry and corresponding subchondral osseous anatomy of the patella and the femoral trochlea. The shape and geometry of the articular cartilage surfaces and corresponding osseous morphology vary significantly from superior to inferior and from medial to lateral.[13] The retropatellar articular cartilage ridge of the patella is located laterally to the corresponding subchondral osseous ridge in 63.3%, medially in 23.3%, and matching in contour in 13.3%.[13]

The trochlea is formed by the anterior aspect of the distal femur. It consists of a centralized trochlear groove (TG) with associated medial and lateral facets. The TG is covered by 2-3 mm of articular cartilage.[14] The articular cartilage in the groove is thicker compared to the trochlear facets. The deepest part of the intercondylar cartilage surface is located medially with respect to the deepest concavity of the osseous contour of the femoral trochlea in 63.3%, laterally in 13.3%, and congruent in 23.3%.[13] As with the patella, the lateral facet is larger and extends more proximally than the medial facet. As it moves distally, the TG deepens, and diverges laterally before terminating at the femoral notch. The facets transition into the medial and lateral femoral condyles.[15] The lateral condyle forms the lateral wall of the PF articulation and is the primary constraint to lateral patellar translation once the patella is engaged in the groove.[16] Trochlear dysplasia is characterized by a loss of the normal concavity of the TG, creating a flat or convex trochlea with highly asymmetrical facets. PF pain and instability disorders are often related to trochlear dysplasia.[17,18] Furthermore, Liebensteiner et al demonstrated that the morphology of the trochlea is significantly related to femoral anteversion (AV). Increased AV was associated with a flatter, more dysplastic trochlea, particularly true for AV in the distal femur.[18]

Contact pressures in the patellofemoral joint change throughout range of motion (Figure 1). Starting at 15-20° of knee flexion, the trochlea provides lateral reinforcement to prevent lateral subluxation of the patella, and at greater than 30° of knee flexion, the stability of the patella depends largely on the trochlea.[11,19-21] As knee flexion increases, the contact area moves both proximally and laterally on the patella, and at 90° of knee flexion, the contact area is at the medial and lateral patellar facets. At 130-135° of knee flexion, the medial facets of the patella contact the articular surface of the

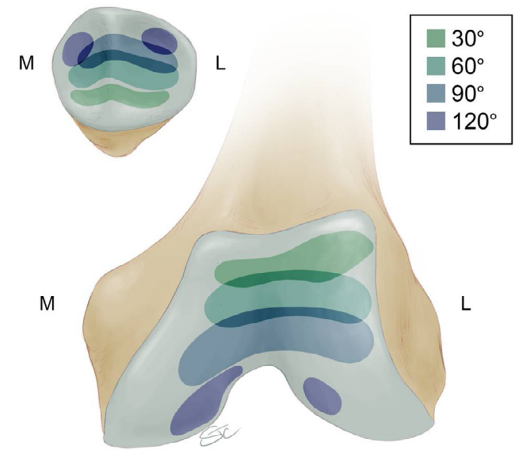

Figure 1 Schematic demonstrating the PF joint contact areas corresponding to the degree of knee flexion. Copyright 2018 by the Curators of the University of Missouri. (Color version of figure is available online.)

femoral condyles. The odd facet only makes contact with the femur in extreme flexion (ie, squatting).[22] The increases in PF joint contact area with knee flexion have been demonstrated by Besier et al[23] and Salsich et al.[24] Besier et al[23] reported that males had mean nonweight bearing PF joint contact areas of 210, 414, and 520 mm^2 at 0°, 30° and 60° of knee flexion, respectively. Females showed similar patterns in this study. In the same study, contact areas increased by an average of 24% under weight-bearing conditions. Furthermore, the lateral facet had an increased percentage of total contact area compared with the medial facet at each knee flexion angle, suggesting increased load-bearing potential.

The quadriceps angle (Q-angle) is formed between a line from the anterior superior iliac spine to the center of the patella, and a line from the patella to the tibial tuberosity (TT). An increased Q-angle may indicate excessive lateral quadriceps force during dynamic activities involving quadriceps muscle activity, predisposing these patients to maltracking.[25] Although this concept is important, precise and reproducible clinical measurements of the Q-angle have proven difficult.[26] The Q-angle changes during flexion and extension of the knee. This angle becomes smaller in flexion and is greatest close to full knee extension due to the external rotation of the tibia on the femur known as the "screw home mechanism".[27-29] A typical Q-angle in males is 8-16° in the supine position and 11-20° in the standing position. In females 15-19° is normal in the supine position and 15-23° in the standing position.[30-32] An abnormal Q-angle has been defined as >20° during extension and may lead to increased lateral displacement forces and increased patellar contact pressures.[6] An increased Q-angle has been correlated to medial patellar displacement and tilt in those with anterior knee pain (Fig. 1).[25]

Dynamic Stabilizers

The stability of the PF joint is also reliant on both the static and dynamic soft tissue structures, particularly when there is a deficiency in the osseous structures of the PF joint.[33] Static soft tissue structures that provide stability include the joint capsule, the extensor mechanism (quadriceps tendon and patellar tendon), and the medial and lateral ligamentous structures. Dynamic stability is further provided by the quadriceps muscles, and secondary dynamic stability is provided by the core musculature and hip external rotators.

The extensor mechanism is an important contributor to dynamic PF joint stability. The quadriceps complex is shaped by the convergence of the rectus femoris, vastus medialis (VM), vastus lateralis (VL), and vastus intermedius muscles. The muscles of the quadriceps complex are all innervated by the femoral nerve. The vastus medialis muscle belly occupies a greater proportion of the quadriceps cross-section area distally while the vastus lateralis occupies a greater proportion proximally.[34] The superficial portion of the vastus intermedius is attached to the vastus medialis and rectus femoris medially while its deep portion fuses to the vastus lateralis.[35] The quadriceps complex is the most important dynamic stabilizer of the patella. However, studies have shown quadriceps contraction has less influence on patellar tracking at 30° of knee flexion than at 0° flexion, which may be demonstrative of the increased stability of the patella in the trochlear groove (TG) at increased degrees of knee flexion.[36] Knowledge of this anatomy is important for muscular rehabilitation and for surgical procedures, particularly when the quadriceps tendon is used as a graft for ligamentous reconstruction and/or when lengthening of the quadriceps is required.

The vastus medialis and lateralis muscles connect to the tibia through attachments to the retinaculum. The vastus medialis oblique (VMO) is a part of the vastus medialis, which originates from the medial intermuscular septum and inserts at an angle of up to 65° on the proximal third of the medial border of the patella.[37] The VMO is an important dynamic medial restraint to lateral tracking of the patella. With atrophy, hypoplasia, or dysfunction of the VMO, there is decreased antagonism to the function of the vastus lateralis, consequently resulting in decreased restraint to lateral patellar translation.[38,39] Biomechanical in vivo and laboratory studies have shown that a delay in the activation of the vastus medialis and a decrease in the magnitude of VM activation relative to the VL are associated with increased patellar tilt,[40] and that decrease in loading forces from the VM increase lateral patellar shift.[39]

The muscles of the quadriceps complex converge ~5-8 cm superior to the patella, subsequently inserting as the quadriceps tendon onto the proximal pole of the patella.[6] The proximal four-fifths of the rectus femoris is fully distinct, whereas the distal fifth is fused with the vastus lateralis and vastus intermedius. This region where the rectus femoris combines with the vastus lateralis is known as the tendon mixed region.[41] There are 3 layers of the quadriceps tendon that can be identified. The superficial layer is composed of the tendon of rectus femoris (RF); the intermediate layer is composed mainly by the tendons of the vastus lateralis (VL) and vastus medialis (VM) with contributions of antero-medial portion of the vastus intermedius (VI); and the deep layer is composed by the tendon of the VI, chiefly its lateral portion.[35,42] The average quadriceps tendon length is reported as 6.87 ± 1.49 cm in pediatric populations (4 to 16 years old)[43] and 88.3 ± 8.4 mm (range, 78.3-99.7 mm) in adults.[44] The thickness is reported as 3.7 ± 1.2 mm in pediatric populations,[43] and 4.94 mm (0.7-9.78 mm) in adults.[45] Regarding the rectus femoris tendon, the inserted widths (ie, the distal one-fifth fused with the vastus lateralis and vastus intermedius) and discrete widths (ie, the proximal four-fifths of the tendon before fusion) are 3.20 ± 0.33 cm and 1.28 ± 0.25 cm, respectively. The length of the rectus femoris tendon is 6.96 ± 0.80 cm and the length of mixing zone is 3.81 ± 0.53 cm.[41]

Originating from the inferior pole of the patella, the patellar tendon inserts on the tibial tuberosity (TT). The patellar tendon has a reported length of 3.5-5.5 cm, and width of 2.4-3.3 cm.[8] Separating the posterior margin of the patellar tendon from the synovial membrane of the joint is the infrapatellar fat pad, with a bursa separating the tendon from the tibia more distally. Patella alta can be recognized in the seated position by an elongated patella tendon or when the patella faces upwards instead of forward in 90° of flexion. A mild J-sign can be present in this setting. This results from patellar disengagement from the proximal trochlea that occurs through a longer range of motion. The parameters of the height of the patella relative to the trochlea correlate with the parameters of trochlear morphology (ie, individuals with patella alta have a more dysplastic femoral trochlea). In a recent study by van Middlekoop et al comparing risk factors, patients with a higher Insall-Salvati (IS) ratio had the strongest association with abnormalities of the PF joint, including patellar bone marrow lesions, patellar osteophytes, and Hoffa synovitis.[46]

Medial Patellar Restraints

The medial soft tissue structures are important in controlling excessive lateral translation, mostly through the early arc (0-30°) of knee flexion.[19] The medial soft tissue structures can be divided into the proximal medial patellar restraints, which include the MPFL and medial quadriceps tendon femoral ligament (MQTFL), and the distal medial patellar restraints, including the medial patellotibial ligament (MPTL) and the medial patellomeniscal ligament (MPML) (Figs. 2 and 3). Knowledge of the anatomy of these medial patellar restraints is of utmost importance during the treatment of patellar instability with ligamentous reconstruction.

Proximal Medial Patellar Restraints

The MPFL originates at the medial femoral condyle and inserts onto the superomedial aspect of the patella, with expansions into the quadriceps tendon.[47-49] Some authors have termed these proximal fibers the MQTFL due to a distinct attachment onto the quadriceps tendon, while other authors have referred to the entire ligament as a single medial patellofemoral complex (MPFC), with variability in its attachment sites to the patella and/or quadriceps tendon (Fig. 2).[50]

Dimensions of the MPFL were reported in a systematic review by Placella et al[51] that included 17 studies and 312

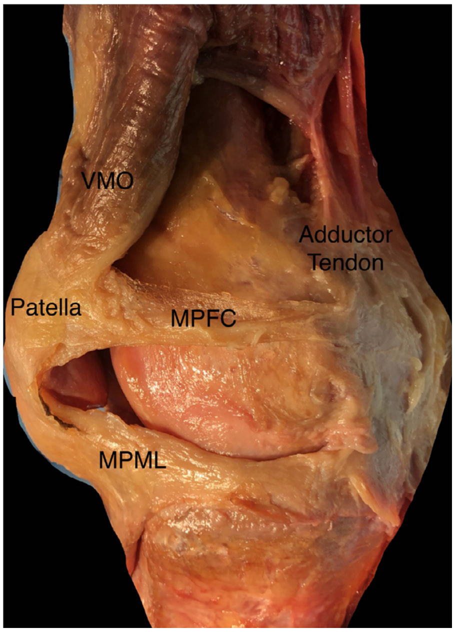

Figure 2 Medial view of a right knee shows the medial patellar restraints. The MPFC, as part of the proximal restraints, originates on the medial femur and extends to the patella and quadriceps tendon. The MPML serves as part of the distal patellar restraint. MPFC, medial patellofemoral complex; MPML, medial patellomeniscal ligament. (Color version of figure is available online.)

cadaveric knees. The ligament is fan-shaped with a wide anterior insertion of 26.0 mm (SD 4.53) ranging 14.0-52.0 mm, and a smaller femoral origin of 12.7 mm (SD 2.6) with a range of 6.0-28.8 mm. The average length of the MPFL was 56.9 mm (SD 4.69) with a range of 46.0-75.0 mm. The width at the midpoint was 17.8 mm (SD 4.4) with a range of 8.0-30.0 mm. Nomura et al reported the thickness of the MPFL to be 0.44 ± 0.19 mm.[52] At its midsubstance, the ligament decussates with the distal fibers of the VMO aponeurosis. It is important to note that the MPFL insertion and origin are elongated, and correspond to an area and not a point, in both in the patella and in the femur.[53-55]

Understanding the metric behavior of the MPFL is important for designing reconstruction techniques to stabilize the patella against lateral translation. Appropriate positioning of the femoral fixation site is crucial because the femoral site allows for isometric adjustments of the graft. In a study by Victor et al,[56] the MPFL was isometric between 0° and 40° of knee flexion, but beyond 40° of knee flexion there was significant linear shortening of 0.5 mm/10° of knee flexion, the total change being 4 mm at 120°. Steensen et al divided the insertion area of the MPFL in its cadaveric study into 3 parts.[55] They demonstrated that from 0° to 90° of flexion, the portion of the MPFL from the inferior patellar attachment to the superior femoral attachment was nearly isometric, showing a mean change in length of 1.1 mm. In addition, statistical analysis showed the superior femoral attachment to be most significant in determining isometric behavior. Stephen et al showed the mean length change of the MPFL (using the central femoral and patellar points) was 2.1 ± 2.3 mm from 0° to 40° of knee flexion. This can serve as a useful reference when assessing graft function during MPFL reconstruction. In regard to tension, the most cranial and caudal parts of the MPFL have been shown to behave differently: the cranial part of the MPFL was most taut at full extension, while the caudal portion was most taut at 30° of knee flexion.[56]

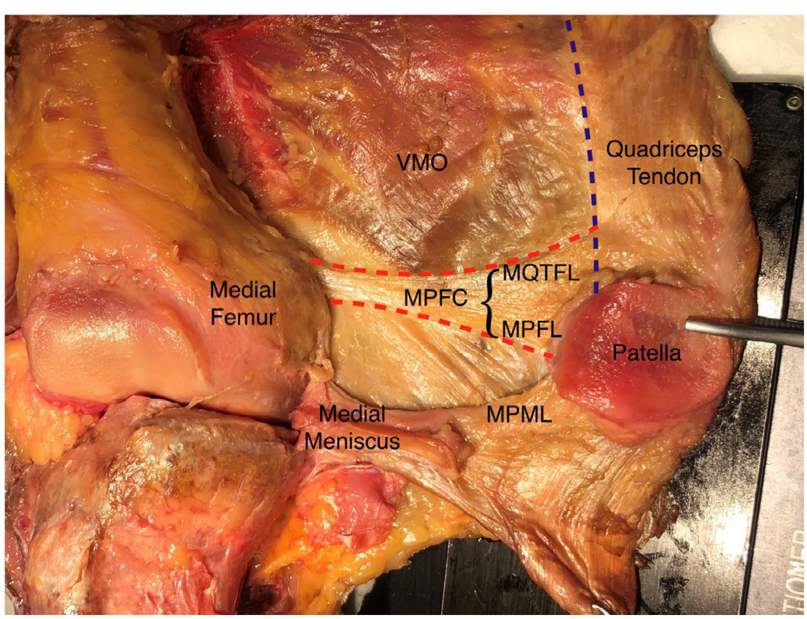

Figure 3 The extensor mechanism is reflected laterally to show the undersurface of the medial patellofemoral joint. The fibers of the MPFC can be clearly seen attaching to both the quadriceps tendon (MQTFL) and patella (MPFL). The MPML can be visualized extending between the medial meniscus and distal patella. MPFC, medial patellofemoral complex; MQTFL, medial quadriceps tendon femoral ligament; MPFL, medial patellofemoral ligament. (Color version of figure is available online.)

With regard to surgical landmarks, Placella et al reported the femoral origin of the MPFL to be at the adductor tubercle in 29.6 % of knees, at the medial femoral epicondyle in 17.8%, and between those 2 structures in 44% of knees.[51] Similar results were discussed by Tanaka et al.[57] The proximal 50% of the patella is the most commonly involved in the MPFL insertion.[48] The center of the insertion of the MPFL lays in the proximal patella, 12 to 22 mm from the proximal patellar border, at a ratio 26% of the patella length (from proximal to distal).[54,58]

Recently, increasing attention has been paid to the fibers that attach to the quadriceps tendon.[47,48,50,57,59] Kang et al described 2 separate bundles, an inferior-straight bundle attaching to the patella and a superior oblique bundle attaching to the quadriceps tendon, with an angle of 25.1° ± 2.1° between them.[60] This allows for the identification of the 2 portions of the medial patellofemoral complex. Tanaka[48] reported in a series of 28 cadaveric knees that most ligaments attached to both structures, with 57.3% ± 19.5% of fibers attaching to the patella and the remainder attaching to the quadriceps tendon. Furthermore, the insertion sites varied with one knee exhibiting 100% of fibers attaching to the patella and another with a sole attachment to the quadriceps tendon. The MQTFL had a mean insertion length of 29.3 mm on the medial aspect of the distal quadriceps tendon.[61] When considering the MPFL and MQTFL as a unit, its center is at a mean 2.3% of the articular length distal to the superior pole of the patella (Fig 3), and can be identified anatomically at the junction of the medial quadriceps tendon and the superior articular surface of the patella.[50]

Distal Medial Patellar Restraints

The distal medial patellar restraints include the MPTL and the MPTL, both of which have attachments on the distal patella. These have been shown to consist of dense connective-tissue of uniformly oriented collagen fibers in parallel intermingled with elongated fibroblasts, compatible with ligamentous tissue.[54] The MPTL is encountered in the second layer of the medial knee, first described by Slocum in 1974.[62] The patellar insertion is at the inferomedial border of the patella, 3.6 ± 3.6 mm proximal to the inferior pole of patella, at a ratio of 10% of the length of the patella.[54] The tibial origin is in the medial tibial tubercle,[58] 13-14 mm below the articular surface.[54,63] Its length is between 35 and 50 mm, and is 7 and 9 mm in width.[54,63] The angle of this ligament in relation to the patellar tendon is 18 -22° with the knee in 90° of flexion.[54,63]

The MPML is encountered in layer 3. It inserts on the inferomedial patella, directly proximal to the MPTL (5.7 ± 5.4mm proximal to the inferior pole of the patella), originating in the medial meniscus (anterior horn or transition of the anterior horn to the body).[54] The angle in relationship to the patellar tendon is 22-42° with the knee in 90° of flexion.[54,58,63]

While the MPFL as previously discussed contributes 50%-60% of patellar stability to lateral translation during early flexion, the function of the secondary restraints, the MPTL and MPML, should not be understated.[47,64-68] Their contribution as secondary stabilizers to lateral restraint increases from 26% in extension to 46% at 90° of flexion.[69] In addition, the influence of the MPTL and MPML in resisting lateral patellar tilt at 90° flexion is 72%.[69] The MPML has also shown importance in terminal extension, since its isolated lesion leads to subluxation in this knee position.[70] The lateral soft tissues are also important secondary stabilizers to lateral translation of the patella. In low degrees of knee flexion, the lateral retinaculum contributes 3% to 19% of the restraint to lateral displacement.[64,65,67,71]

In a biomechanical study by Hinckel et al,[54] the MPFL and MPTL ruptured at average deformations of 19.3 and 8.6 mm, respectively. In that same study, the MPTL was found to be stiffer than the MPFL (17.0 ± 8.5 mm^2 vs 8.0 ± 1.9 mm^2, respectively). In a study by LaPrade et al,[72] the mean ultimate load of the MPFL (178 ± 46 N) was not significantly greater than that of the MPTL (147 ± 80 N; P = .706) but was significantly greater than that of the MPML (105 ± 62 N; P = .001). In the same study, no significant difference was found in

Table 1 Contribution of the Medial Soft Tissue Structures (MPFL, MPTL, MPML, and MR) to the Stability of the PF Joint

Study	MPFL	MPTL	MPML	MR
Conlan 1993[64] 25 knees Slight flexion	53% (23 to 80%)	5% (0 a 21%)	22% (8 a 38%)	11% (0 a 24%)
Desio et al 1998[65] 9 knees 20° flexion	60% (41 to 80%)	3% (1 a 9%)	13% (4 a 35%)	3% (1 a 12%)
Panagiotopoulos et al 2006[67] 8 knees 20 a 30°	50%	13%	24%	13%
Philippot et al 2012[79] 9 knees extension	72%	26%		
Philippot et al 2012[69] 9 knees 90° flexion	52%	46%		

MPFL, medial patellofemoral ligament; MPML, medial patellomeniscal ligament; MPTL, medial patellotibial ligament; MR, medial retinaculum.

mean stiffness between the MPFL (23 ± 6 N/mm^2) and the MPTL (31 ± 21 N/mm^2; P = .169), but a significant difference was found between the MPFL and the MPML (14 ± 8 N/mm^2; P = .003) and between the MPTL and MPML (P = .028). In aggregate, these results support that the MPFL, MPTL, and MPML have biomechanical properties that contribute to an important function in maintaining patellar stability.

Lateral Patellar Restraints

The lateral soft tissue complex is composed of the iliotibial band extension to the patella (ITB-patella), the vastus lateralis, the lateral patellofemoral ligament (LPFL), lateral patellotibial ligament (LPTL) and lateral patellomeniscal ligament (LPML), with intimate connections between these structures.[73-77] The complex has superficial longitudinal fibers (superficial fibers of the ITB-patella) and deep transverse fibers (deep fibers of the ITB-patella, vastus lateralis, LPFL, lateral patellotibial ligament and lateral meniscal ligament).[73-77] The lateral LPFL's femoral insertion is 19.7 mm anterior to the posterior end of the lateral condyle and 16.5 mm proximal to the distal end of the lateral condyle[78]; and more frequently in the middle thirds in both the anteroposterior (75%) and proximal-distal axis (53.1%).

The ITB−patella is the strongest (load to failure 582 N) and stiffest (97 N/mm) of the lateral patellar restraints. The LPFL load to failure is 172 N, and stiffness is 16 N/mm. The lateral patellomeniscal ligament's load to failure is 85 N with 13 N/mm stiffness.[75] These structural properties suggest that most of the load in-vivo is transmitted to the patella by the ITB extension to the patella (Table 1).

Conclusion

The anatomy of the PF joint is reflective of its primary function of knee extension and deceleration as it operates as a functional unit to optimize weight-bearing capacity. Our understanding of PF anatomy continues to evolve with the use of new dissection methods, as well as improving imaging modalities. A proper understanding of PF anatomy and biomechanics is essential to allow the clinician to best treat disorders of this compartment. This includes an understanding of the bony morphology, as well as the dynamic and static soft tissue restraints. An adequate understanding of PF functional anatomy may lead to improved operative and non-operative treatment techniques.

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