Anatomy and Biomechanics of the Medial Side of the Knee and Their Surgical Implications

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Abstract: In order to reconstruct the medial knee to restore the original biomechanical function of its ligamentous structures, a thorough understanding of its anatomic placement and relationship with surrounding structures is required. To restore the knee to normal kinematics, the diagnosis and surgical approach have to be aligned, to successfully reconstruct the area of injury. Three important ligaments maintain primary medial knee stability: the superficial medial collateral ligament, posterior oblique ligament, and deep medial collateral ligament. It is important not to exclude the assistance that other ligaments of the medial knee provide, including support of patellar stability by the medial patellofemoral ligament and multiligamentous hamstring tendon attachments. Valgus gapping and medial knee stability is accounted for collectively by every primary medial knee stabilizing structure. The following will review the principal medial knee anatomic and biomechanical properties.

Key Words: posterior oblique ligament (POL), valgus stress, medial knee reconstruction, medial anatomy, medial collateral ligament (MCL), posteromedial knee

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Damage to ligaments and stabilizing structures of the medial knee are commonly seen knee ligament injuries, requiring definitive qualitative and quantitative analysis of the attachment sites to make progressive surgical procedures more accomplished in restoring normal knee kinematics.[1–4] Improved understanding of attachment locations and structural contributions to medial knee stability enable better placement of graft reconstructions and improve anatomic reconstruction techniques.[5] The structures making up the medial knee serve as important static stabilizers protecting from abnormal rotation and translation of knee stabilization.[5–7] The 3 most important ligaments that provide the most stability of the medial knee are the superficial medial collateral ligament (sMCL), posterior oblique ligament (POL), and deep medial collateral ligament (dMCL).[2,5–7] Other important structures include the adductor magnus tendon (AMT), the medial patellofemoral ligament (MPFL), the medial hamstring tendons, the medial gastrocnemius tendon (MGT), and the vastus medialis obliquus muscle.[2] The stabilizing function of these structures relies heavily on their attachment sites to the medial femoral condyle, medial tibial plateau, and the medial meniscus.[2,5,6]

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ANATOMY OF THE MEDIAL KNEE

Bony Landmarks

The medial epicondyle has been previously described as the most anterior and distal osseous prominence over the medial aspect of the medial femoral condyle (Figs. 1A, B).[2] Just proximal and posterior to the medial epicondyle,[2] the distal part of the femur has a thin ridge of bone termed the medial supracondylar line, whereas the adductor tubercle is located along the distal edge of this ridge.[2] Quantitatively, the medial epicondyle has been reported to be 12.6 mm distal and 8.3 mm anterior to the adductor tubercle.[2] Located slightly distal and posterior to the adductor tubercle and close to a small depression, a third osseous prominence has been defined as the gastrocnemius tubercle.[2] This osseous prominence has been reported to be adjacent to the femoral attachment of the medial head of the gastrocnemius tendon.[2] This location is 6.0 mm proximal and 13.7 mm posterior to the medial epicondyle, and 9.4 mm distal and 8.7 mm posterior to the adductor tubercle.[2] Identification of these osseous prominences is key for proper reconstructions of medial knee injuries, especially as the difficulty in locating the gastrocnemius tubercle may confuse attachment sites of structures with similar locations.[2]

Superficial Medial (Tibial) Collateral Ligament (sMCL)

The sMCL, or tibial collateral ligament, has 1 femoral and 2 tibial attachment sites, proximal and distal (Figs. 2A, B).[2,5] The femoral attachment site has been described as being round shaped and located in a small depression, which is located 3.2 mm proximal and 4.8 mm posterior to the center of the medial epicondyle.[2] The center of the distal tibial attachment site was reported to be 6 cm distal to the joint line and directly attached to bone.[2] Wijdicks and colleagues reported that the proximal tibial attachment was 11.2 mm distal to the tibial joint line on anteroposterior radiographic views, and LaPrade and colleagues reported that the proximal tibial attachment site was attached to the soft tissues directly located over the anterior arm of the semimembranosus.[2,8–10] In addition, the sMCL was reported to be the largest structure of the medial aspect of the knee, at approximately 10 to 12 cm in total length.[2,11,12]

POL

In the past, the POL was commonly referred to as the posterior expansion of the sMCL.[10,13,14] However, more

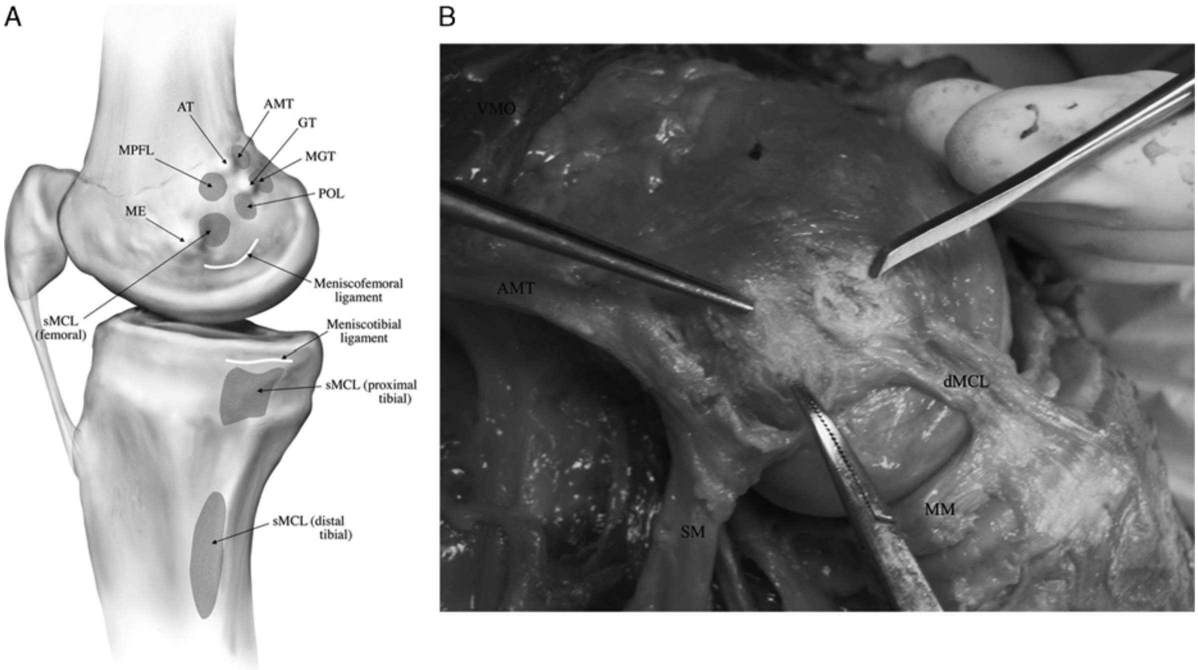

FIGURE 1. A, Illustration of femoral osseous landmarks and attachment sites of main medial knee structures. B, Photograph showing the exposure of the deep medial collateral ligament (dMCL) and its attachment to the medial femoral condyle and the MM (medial meniscus). The sMCL attachment to the femur has been removed just above the dMCL (medial view, left knee). AMT indicates adductor magnus tendon; AT, adductor tubercle; GT, gastrocnemius tubercle; ME, medial epicondyle; MGT, medial gastrocnemius tendon; MPFL, medial patellofemoral ligament; POL, posterior oblique ligament; SM, semimembranosus tendon; VMO, vastus medialis obliquus muscle. Reproduced with permission from LaPrade et al.[2]

recent studies have described that the POL is anatomically and functionally distinct from the sMCL.[15] The POL consists of 3 fascial attachments that extend off of the distal aspect of the semimembranosus tendon, merging with and reinforcing the posteromedial aspect of the joint capsule (Fig. 2A).[2,16,17] The 3 attachments have been termed the capsular, superficial, and the central (tibial) arms.[2,16,17] The central arm of the POL attaches to the femur 1.4 mm distal and 2.9 mm anterior to the gastrocnemius tubercle and 7.7 mm distal and 6.4 mm posterior to the adductor tubercle.[2]

The capsular arm of the POL is a thin fascial expansion that extends from the anterior and distal aspects of the semimembranosus tendon.[2,17] The capsular arm attaches to soft tissue coursing over the MGT, AMT femoral attachment, and AMT expansion to the medial gastrocnemius.[2,18] The superficial arm of the POL is a thin fascial expression that proximally courses medial to the anterior arm of the semimembranosus, and distally follows the posterior border of the sMCL.[2] The superficial arm proximally blends into the central arm of the POL, while it runs distally and parallel to the posterior border of the sMCL until it blends into the distal tibial expansion of the semimembranosus and its tibial attachment.[2,18] Hughston and Eilers[15] proposed that the central arm of the POL is the most crucial of the 3 attachments, because it is the largest and thickest of the 3 attachments. It extends from the distal aspect of the semimembranosus tendon, attaches to and blends into the posterior joint capsule and the posterior medial meniscus, and reinforces the dMCL.[2,17] The central arm fibers are fan-like and follow a proximal course, allowing them to be differentiated from the sMCL.[2]

dMCL

The dMCL, or mid-third medial capsular ligament, is a distinct thickening of the anterior aspect of the medial joint capsule and is located deep to the sMCL (Fig. 1B).[2,5] The dMCL is roughly parallel to the anterior aspect of the sMCL and is comprised of meniscotibial and meniscofemoral components.[2,16] The meniscotibial component is shorter and thicker than the meniscofemoral component, and attaches on average 3.2 mm distal to the tibial joint line.[2] The meniscofemoral component is longer and thinner than the meniscotibial component, and is located approximately 15.7 mm proximal to the femoral joint line.[2]

AMT

The AMT inserts in a small depression 3.0 mm posterior and 2.7 mm proximal to the adductor tubercle, and does not attach directly to the apex of the tubercle.[2] A thick posteromedial fascial expansion from the distal aspect of the AMT has attachment sites coursing proximal to the MGT and the posteromedial joint capsule (Fig. 3).[2] The vastus medialis obliquus muscle has 2 attachments along a thick tendinous sheath of the AMT and along the lateral aspect of the AMT.[2] This thick tendinous sheath resides in the distal-lateral aspect of the AMT, which attaches to the medial supracondylar line.[2] The AMT is rarely injured and serves as an important surgical landmark for medial knee injuries.[2]

MPFL

The MPFL is an important stabilizer of the knee which assists with sustaining the patella in the trochlear groove.[19] A study by LaPrade et al[2] identified its attachment sites

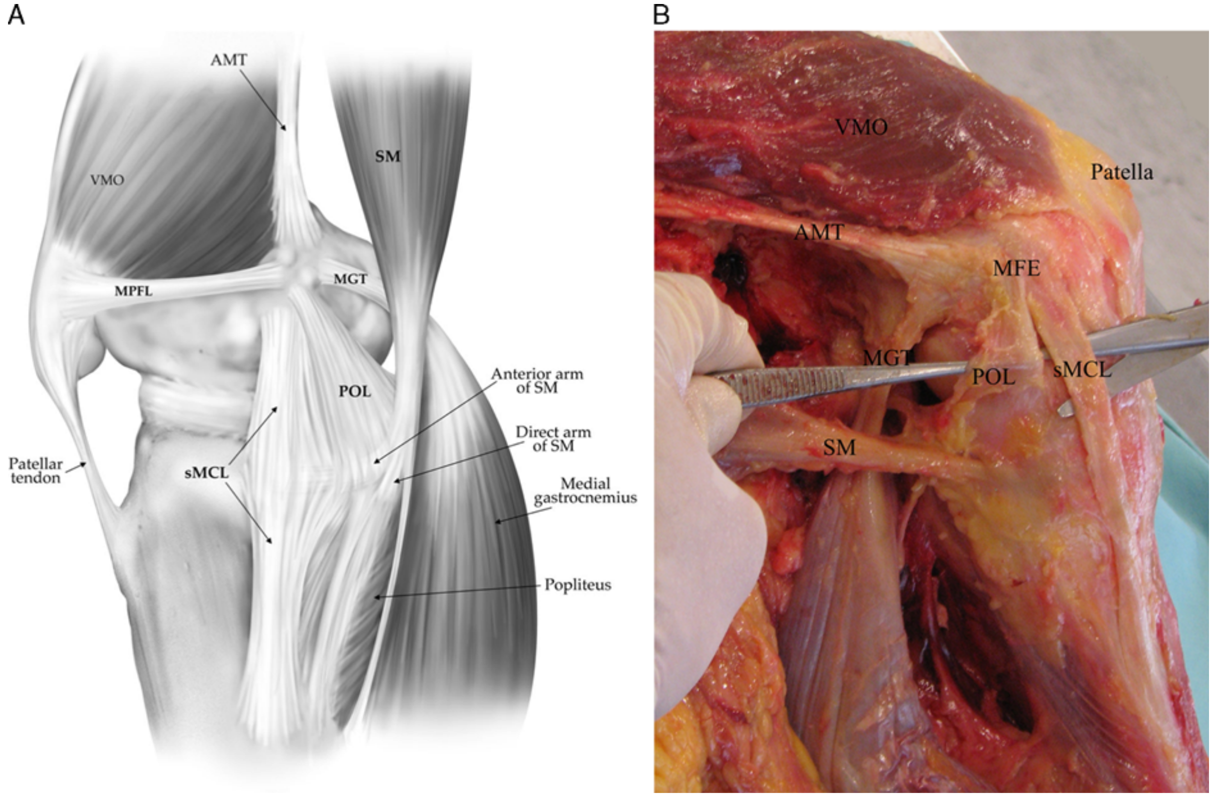

FIGURE 2. A, Illustration of the main structures of the medial knee. B, Photograph of the ligamentous attachments to the medial femoral epicondyle (MFE) by the superficial medial collateral ligament (sMCL), posterior oblique ligament (POL), medial gastrocnemius tendon (MGT), and adductor magnus tendon (AMT) (medial view, left knee). AMT indicates adductor magnus tendon; MGT, medial gastrocnemius tubercle; MPFL, medial patellofemoral ligament; SM, semimembranosus muscle; sMCL, superficial medial collateral ligament; POL, posterior oblique ligament; VMO, vastus medialis obliquus muscle. Reproduced with permission from LaPrade et al.[2]

as coursing distal-proximal, from the adductor tubercle to the medial patella. The MPFL femoral attachment has reported to be located 1.9 mm anterior and 3.8 mm distal to the adductor tubercle, where the femoral attachments of the sMCL and the AMT are also located (Fig. 4).[2] From this femoral attachment the tendon is said to "fan out," and form a wider attachment to the medial patella, likewise it is said that a gradual thickening occurs in the ligament from the patella to its femoral attachment.[20,21] The MPFL also has fibers that merge into the deep aspect of the vastus medialis obliquus.[2] The association between merging MPFL fibers into the vastus medialis obliquus infers the relationship of these 2 structures in preserving a transverse orientation, which helps maintain patellar stability.[20]

Pes Anserinus (Gracilis, Sartorius, and Semitendinosus) Tendons

The pes anserinus, or hamstring tendons, attach at the anteromedial aspect of the proximal part of the tibia.[2] The pes anserinus tendons, which form the roof of the pes anserine bursa, are most commonly described in the following order from proximal to distal: sartorius, gracilis, and semitendinosus (Fig. 5).[2,23,24] Grassi et al[23] reported that the gracilis and semitendinosus were covered by a thin fibrotic cap formed by the sartorius tendon, which makes access to the gracilis and semitendinosus more restricted than the sartorius. The gracilis and semitendinosus tendons are most commonly used as autografts for knee reconstructions.[23,25]

Medial Meniscus

The medial meniscus is a C-shaped fibrocartilaginous bumper and shock absorber that is situated between the medial femoral condyle and medial tibial plateau.[26,27] On average, the medial meniscus is approximately 40.5 to 45.5 mm long and 27 mm wide; however, the sizes can differ significantly depending on the height, weight, and sex of the patient.[26,27] There are 2 main attachment sites of the medial meniscus, the anteromedial and posteromedial roots.[28]

MGT

The tendon attachment of the MGT is located in a depression over the posteromedial edge of the medial femoral condyle, just proximal and posterior to a third osseous prominence (gastrocnemius tubercle) (Fig. 2A).[2] LaPrade et al[2] found that the average proximal and posterior distances to the gastrocnemius tubercle were 2.6 and 3.1 mm, respectively. The MGT has 2 other fascial attachments, thick and thin, along its lateral aspect to the AMT, and along its posterior-medial aspect to the capsular arm of the POL.[2] The combination of foot plantar flexion and knee extension has been shown by Patterson et al[29] to cause eccentric contraction of the MGT, which results in stressing of the medial head of the gastrocnemius at its femoral origin.

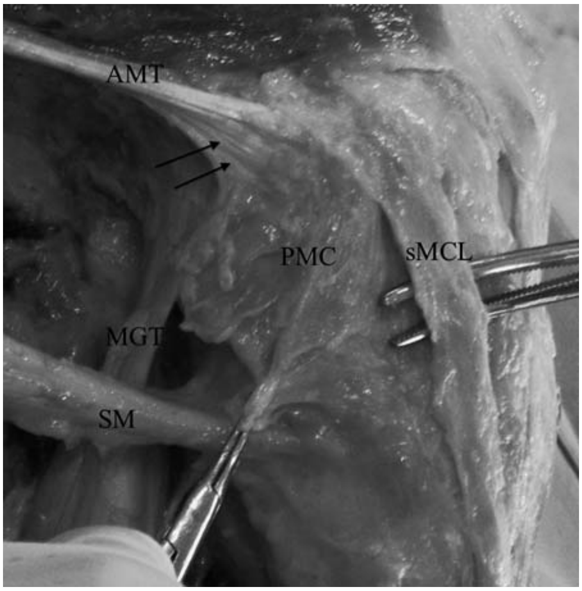

FIGURE 3. Photograph of the fascial expansion of the adductor magnus tendon (AMT) to the medial gastrocnemius tendon (MGT) and the posteromedial capsule (PMC) (in grasp of the forceps). The forceps on the right is exposing the superficial medial collateral ligament (sMCL) (medial view, left knee). SM indicates semimembranosus.

Vastus Medialis Obliquus Muscle

The vastus medialis obliquus muscle was identified by Bose and Kanagasuntheram[30] with a main origin from the AMT, along with origins from the adductor longus tendon and medial intermuscular septum. A study by LaPrade et al[2] found the distal border of the vastus medialis obliquus muscle to attach along the proximal edge of the MPFL, and the main attachment to the AMT to be a medial attachment of the vastus medialis obliquus muscle both along the thick tendinous sheath and the lateral aspect of the AMT. This location, with respect to the patella, explains how the vastus medialis obliquus muscle applies a medially directed force that when torn, disrupts medial stabilization of the patella.[31]

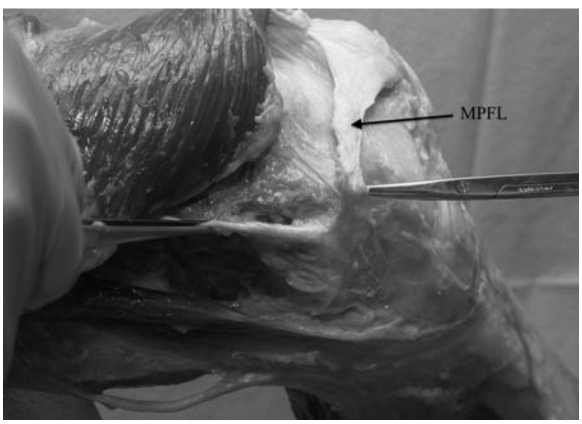

FIGURE 4. Photograph of the medial patellofemoral ligament (MPFL), demonstrating its attachment to the patella and vastus medialis obliquus (VMO) muscle (medial view, left knee).

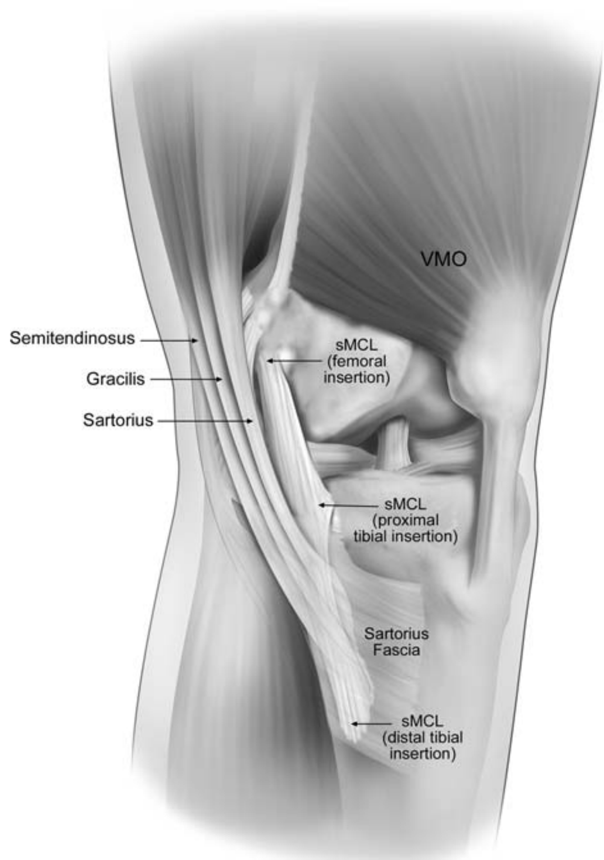

FIGURE 5. Illustration of the lateral edge of the pes anserine bursa, demonstrating the attachment of the hamstring tendons (sartorius, gracilis, and semitendinosus) to the tibia (medial view, left knee), just underneath the sMCL between its proximal and distal attachments. Reproduced with permission from Wijdicks et al.[22]

NEUROVASCULAR STRUCTURES

Saphenous Nerve

Between the gracilis and semitendinosus tendons, a division of the femoral nerve becomes the saphenous nerve, further dividing into the main saphenous branch and the infrapatellar branch.[32] The sensory nerve that innervates the anterolateral aspect of the proximal part of the lower leg and anterior aspect of the knee has been consistently identified as the infrapatellar branch of the saphenous nerve.[33–35] This branch follows a course by means of piercing the sartorius muscle, followed by a distal anterior trajectory that curves into a close to horizontal path medial of the patellar tendon. From this trajectory, a high variation has resulted in number of branches that course over the patellar tendon. The quantity of branches has been found to vary within a range of 1 to 3, with 2 branches being most common.[33,36,37] The infrapatellar branch has a few variations of branching, which either course posterior to, anterior to, or through the saphenous nerve, creating complications in surgical procedures for variant safe zones of incision.[36] Anatomic understanding of the branching patterns followed by the infrapatellar nerve is vital due to the high variation and discrepancy in textbooks.[36]

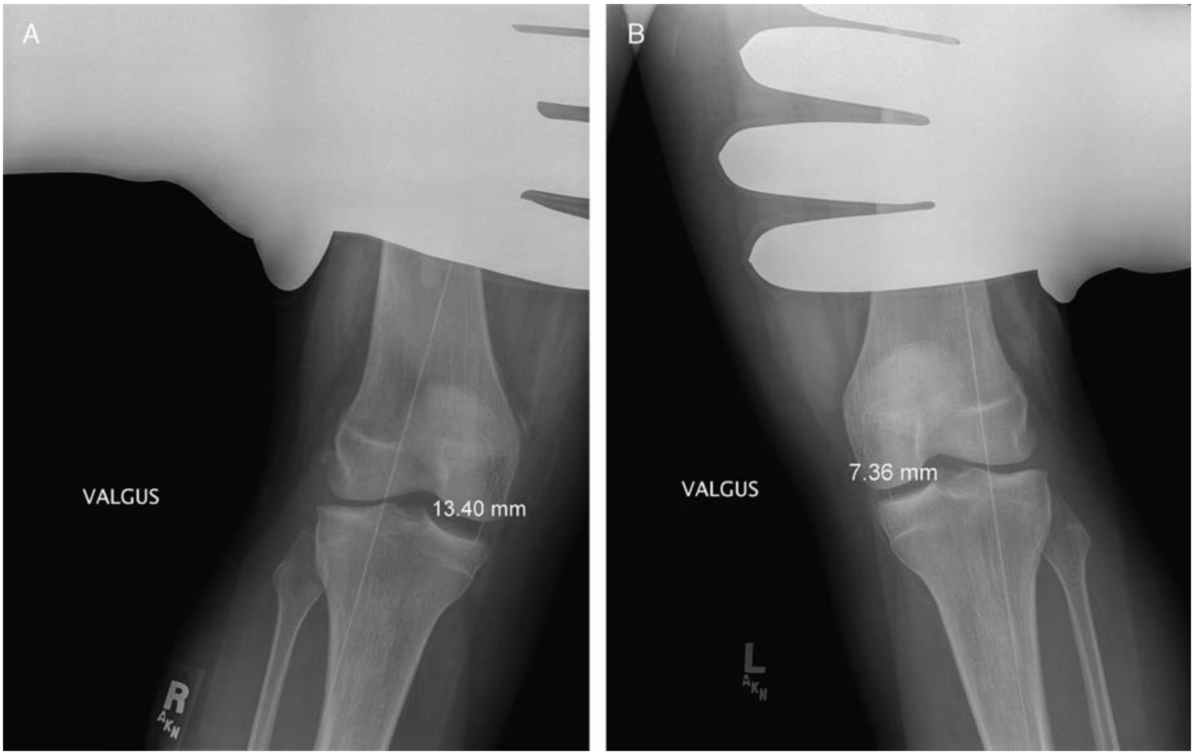

FIGURE 6. Valgus stress radiographs of the left knee (B) and the right knee (A) at 20 degrees of knee flexion. The right knee displays 6 mm of increased medial compartment gapping compared with the contralateral left knee, indicating a complete injury to medial structures of the right knee.

Superior and Inferior Medial Genicular Arteries

The superior medial genicular artery joins with the superior lateral genicular artery slightly superior to the patella and anterior to the quadriceps tendon.[38] A cadaveric study by Lazaro et al[39] described the superior medial genicular artery as originating from either the superficial femoral artery or the popliteal artery.

The inferior medial genicular artery anastomoses with the inferior lateral genicular artery posterior to the patellar ligament in the fat pad to form the transverse infrapatellar artery.[38] Recent studies concerning the vascular anatomy of knees have suggested that the inferior medial genicular artery originates from the popliteal artery.[39] The inferior medial genicular artery then runs deep to the MCL between its 2 tibial attachment sites, below the medial tibial plateau, and rises on the anterior aspect of the plateau to anastomose with the peripatellar anastomotic ring.[39]

Biomechanics of the Medial Knee

Although there are many structures in the medial aspect of the knee, 3 important structures have been identified as the key static stabilizers: the sMCL, dMCL, and the POL.[6] These structures have primary and secondary roles in providing stabilizing support against abnormal valgus motion, external/internal rotation, anterior/posterior translation in the knee, and combined force vectors in sports requiring knee flexion.[6,16] Understanding the hierarchy of structures in restraining abnormal knee motion and functional biomechanics of the medial knee improves anatomic repairs and reconstructions.[6,7,16]

Varying implications of load distribution, much like the assumption of the sMCL being 1 continuous structure instead being proven to function as conjoined but distinct structures, can affect the efficacy of surgical procedures.[16] Griffith et al[6] found that the POL and both divisions of the sMCL share differing loading responses at all tested knee flexion angles. It is important to understand the intricate load-sharing relationships of the medial knee to consistently identify the idiosyncratic properties of ligaments and the separate or concurrent occurrence of injury resulting from abnormalities of knee motion. A review of individual and communal functionality will be covered in this section, focusing primarily on the stabilizing function of the sMCL, dMCL, and the POL.

sMCL

The sMCL consists of 2 functional divisions, proximal and distal, that serve various purposes in aspects of medial knee stability.[2,5] Results from a study conducted by Griffith et al[6] on proximal-distal comparisons, further defined individual functionality.

The proximal division of the sMCL serves as the primary static stabilizer to valgus motion at all tested flexion angles (0, 20, 30, 60, and 90 degrees), a secondary external rotation stabilizer at 90 degrees of knee flexion, and a secondary stabilizer for internal rotation at 0, 30, and 90 degrees of flexion.[6] The distal division of the sMCL serves as a primary external rotation stabilizer at 30 degrees of knee flexion, a primary stabilizer for internal rotation at all tested knee flexion angles, and a secondary external rotation stabilizer at 0, 20, and 60 degrees of flexion.[6]

The largest load response difference between applied external rotation and internal rotation torques occurs at 90 degrees of knee flexion.[6] Results have demonstrated that the load response for the distal division of the sMCL was dependent on varying knee flexion angles, whereas no significant difference in load response of the proximal division was dependent on knee flexion angles.[6]

In a study determining reciprocal load response to internal torque by Wijdicks et al,[5] a complementary relationship between the POL and the sMCL was seen. Resistance to internal rotation torque varied as the degree of knee flexion increased, with the sMCL having a higher load response approaching 90 degrees of knee flexion.[5] In a sectioning study by Griffith et al,[6] individual dissection of a proximal versus distal method determined a tensile load response of the distal sMCL division reacting from valgus forces, likely explained by more medial sMCL fibers bypassing the proximal tibial attachment. It can inferred from these results that the distal division of the sMCL has an indirect role in preventing abnormal valgus motion.

A study by Coobs et al[40] utilized an anatomic medial knee reconstruction technique by placing reconstruction grafts at their anatomic attachment sites, and found that both divisions of the sMCL had specific functions in creating native load distributions. Many studies have determined that a surgical reconstruction or repair of both divisions of the sMCL is necessary to reproduce primary valgus and rotatory functions in restoring medial knee stability.[5,6,40]

POL

The POL is a primary restraint to internal rotation and is a secondary restraint to valgus translation and external rotation.[40] Tibor et al[17] discussed how the POL helps stabilize internal rotation at all knee flexion angles; however, the most load occurs at full extension. A mean load at failure was determined as 256.2 N with a mean stiffness of 38.6 N/mm in a study by Wijdicks et al.[5] More recent works have studied the forces on intact knees, which have led to a better understanding of the biomechanical properties of the POL, and its relationship to other medial structures in the knee.[6,17,40]

The POL and sMCL were recently described as having a complementary relationship in resisting internal rotation torque.[6] Griffith et al[6] helped display that the POL shares the load response against posterior and anterior tibial translation in an intact knee. The POL is an important secondary stabilizer for rotation and valgus stress after an isolated MCL injury.[17] Combined sMCL and POL ligament tears produce severe acute or chronic valgus instability, indicating the role of the POL in static stabilization for the medial knee.[41] Therefore, it has been suggested that an anatomic reconstruction of the POL, at 0 degrees of knee flexion at which the POL has its greatest role in primary restraint of internal rotation, after injury can restore near-native stability to the knee.[6,40]

dMCL

The components of the dMCL, the meniscotibial and meniscofemoral portions, serve various stabilizing functions similar to the sMCL.[5] The meniscotibial portion of the dMCL functions as a secondary valgus stabilizer at 60 degrees of knee flexion and as a secondary internal rotation stabilizer at 0, 30, and 90 degrees of knee flexion.[6] The meniscofemoral portion of the dMCL functions similar to the meniscotibial division in providing secondary valgus stability at all tested flexion angles (0, 20, 30, 60, and 90 degrees) and secondary internal rotation stability at 0 and 30 degrees of knee flexion, but also functioned in more aspects of knee stability than the meniscotibial portion.[6] These aspects include primary stability of internal rotation at 20, 60, and 90 degrees of knee flexion and secondary external rotation at 30 and 90 degrees of knee flexion.[6] A study by Robinson et al[42] similarly showed the function of the dMCL as a secondary restraint to valgus loads and restraint against external rotational torques at 30 degrees, whereas results from Griffith et al[6] found that the dMCL was additionally found to resist internal rotation. Overall, the dMCL has been recorded as having the significantly lowest load-at-failure, stiffness, and displacement-at-failure of the 3 most important ligaments of stability (sMCL, POL, and dMCL).[5]

For structural properties of the dMCL, a maximum strain was determined in full extension near the femoral attachment.[43] Robinson et al's[42] results determined a maximum load to be 194 N, whereas a study by Wijdicks et al[5] found the mean load at failure to be 100.5 N with a mean displacement at failure to be 2.1 mm. Findings by Sims and Jacobson[44] and O'Donoghue[45] are in accordance with these data showing the femoral attachment as the most common injury site for the dMCL; however, another study reported interstitial failure as more common.[4,43] In a related study by LaPrade et al[46] comparing valgus stress tests and medial knee injuries, the data developed a pattern pointing out that meniscofemoral and meniscotibial ligament tears are more common, compared with intrasubstance injuries. Of these 2 midsubstance tears, meniscofemoral base tears showed a higher rate of healing compared with meniscotibial-based tears.[46]

Valgus Stress Radiographs

When diagnosing medial knee injuries, valgus stress radiographs have been proven to be the most reliable and objective approach as opposed to subjective physical examinations.[46] Medial compartment gapping distinguishes isolated from concurrent injuries of the damaged knee.[46] Displacement of side-to-side gapping relating to the associated intact knee has a normal gapping variability of 2 mm at 20 degrees.[47–51] Valgus forces applied to a knee in flexion of full extension (0 degrees) and 20 to 30 degrees demonstrate differing relationships between neighboring medial knee ligaments and with cruciate ligaments, resulting in unique compartmental gapping specific to the injury.[46]

For isolated medial knee injuries, knee flexion between 20 and 30 degrees accounted for the majority of medial knee compartment gapping.[46] A study by LaPrade et al[46] found that with a clinician-applied load, 3.2 mm of increased medial compartmental gapping compared with that of the intact knee is needed for a grade III MCL tear (Fig. 6). In that study, an isolated sMCL tear was simulated by proximal sectioning, respectively, increasing gapping by 1.5 mm at full extension and 3.2 mm at 20 degrees.[46] A complete medial knee injury increased gapping by 6.8 mm at 0 degrees and 9.8 mm at 20 degrees, with no significant difference from initial sectioning between distal and proximal MCL injuries.[46] An additional ACL tear creates a gapping of 8.0 mm at full extension and 13.8 mm at 20 degrees, whereas an additional PCL tear, rather than ACL, creates gapping of 11.8 and 12.6 mm, respectively.[46] Furthermore, a complete medial knee injury along with damage to both cruciate ligaments creates a gapping of 21.6 mm at 0 degrees and 27.6 mm at 20 degrees.[46] In full extension, isolated medial knee injuries can be discerned by a mild amount of increased medial compartmental gapping, but the historically reported large amount of valgus instability is derived from one or both cruciate ligaments being torn concurrent with a medial knee structure.[41]

Valgus stress radiographs are important not only from its cost-efficiency and ease of acquisition in the initial diagnostic and patient follow-up, but also by providing a progression from previous qualitative physical examinations, which fail to reproduce consistent applied valgus forces for gapping measurement.[46] Compartmental gapping, quantified at full extension and 20 to 30 degrees of flexion, differentiates isolated medial knee tears from concurrent injuries involving the cruciate ligaments.[46] This radiographic research helped set a baseline for compartment gapping that is considered normal, from which a measurable deviation can define an injury.[46]

CONCLUSIONS

It is crucial to understand both the anatomic and biomechanical properties of the medial knee to be able to diagnose and treat medial knee injuries. Unlike some other structures in the knee, some complete medial knee tears do not always require surgical treatment. The complex anatomic arrangement of the medial structures makes it imperative to understand its anatomic positioning for when surgery is required. Furthermore, valgus stress radiographs can provide objective data to diagnose and establish medial compartmental gapping compared with the associated intact knee, which better identifies injuries undergone by ligaments that when endured in isolation or concurrent of a neighboring structure, produce a characteristic change in medial compartment gapping.

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