Chapter 2

Meniscus: Biomechanics and Biology

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Introduction

In the United States, a meniscal tear is the most common diagnosis among patients undergoing knee arthroscopy [1, 2]. Clinically, patients with meniscal deficiency or tears have been shown to progress to early joint degeneration and osteoarthritis [1, 2], revealing the essential chondroprotective role of this structure in the knee joint. The meniscus optimizes load transmission across the knee by increasing joint congruency, thereby increasing contact area and decreasing point loading. Further, the menisci serve as important shock absorbers in the knee, as meniscal tissue is more elastic than articular cartilage and absorbs stress caused by impact loading [3]. The menisci also help to stabilize the knee joint [1], as the medial and lateral menisci function as secondary stabilizers for anterior-posterior translation and rotatory motion, respectively.

While early treatment of meniscal tears focused primarily on the removal of the injured tissue, recent attention on detrimental long-term consequences following partial or total meniscectomy has led to increased attempts at meniscus

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repair whenever possible. Although meniscal repairs have a higher reoperation rate than meniscectomy, repairs have been reported to result in better long-term patient-reported outcomes, improved activity levels, and slower progression to osteoarthritis [4–6]. Therefore, understanding and preserving meniscal integrity are crucial to maintain the long-term health of the knee joint.

The purpose of this chapter is to describe the (i) anatomy of the menisci with an emphasis on anatomic root attachments, (ii) microstructure and biology of meniscal tissue, and (iii) biomechanical properties of meniscal tissue and their clinical relevance following meniscal injury.

Anatomy

The medial meniscus is a semilunar sheet of fibrocartilage localized between the medial femoral and medial tibial condyle (Fig. 2.1). It covers up to 60% of the articular surface of the medial tibial condyle, with an average width of 9–10 mm and average thickness of 3–5 mm [7]. The medial meniscus has a strong attachment to the surrounding structures (medial collateral ligament (MCL), posteromedial capsule) and therefore is less mobile than the lateral meniscus.

The lateral meniscus is more circular and covers a larger portion of the articular surface than the medial meniscus (up to 70%) (Fig. 2.1). The average width of the lateral meniscus is 10–12 mm, with an average thickness of 4–5 mm. The meniscus itself is grooved laterally for the popliteus tendon, which separates the meniscus from the fibular collateral ligament (FCL).

There are several supplemental attachments to the menisci that may play a role in stabilization of meniscal tissue. The transverse intermeniscal ligament connects the medial and lateral menisci anteriorly. The coronary ligaments connect the menisci to the capsule posteriorly and are stronger on the medial side than the lateral side, helping to explain the increased rigidity of the medial meniscus compared with the

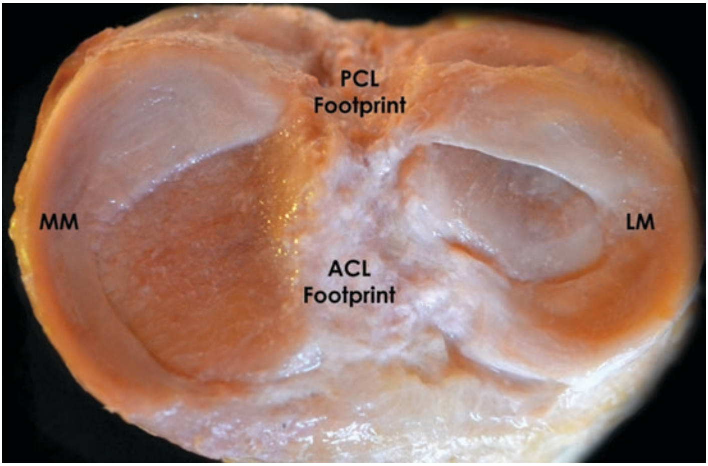

Figure 2.1 Axial view of cadaveric right knee demonstrating the anatomy of the medial meniscus (MM) and lateral meniscus (LM) in relation to the ACL and PCL footprint. The medial meniscus is semilunar in shape, while the lateral meniscus is more circular and covers a larger portion of the articular surface

lateral meniscus. Finally, the meniscofemoral ligaments originate from the posterior horn of the lateral meniscus (Fig. 2.2a, b). They are composed of two distinct ligamentous structures, the ligament of Humphrey, which lies anterior to the PCL (Fig. 2.2a), and the ligament of Wrisberg, posterior to the PCL (Fig. 2.2a, b). These structures help to stabilize the posterior horn of the lateral meniscus.

The menisci are anchored to the bone anteriorly and posteriorly by their strong root attachments. The clinical importance of maintaining meniscal root integrity has been well-documented in the literature. In a biomechanical study, Allaire et al. reported a significant 25% increase in medial compartment contact pressure following a PMMR tear [8]. Several other studies have corroborated these findings [9, 10], as a complete root tear biomechanically simulates a meniscectomized knee, thereby increasing the risk for (often rapid) progression of osteoarthritis. A thorough knowledge of the

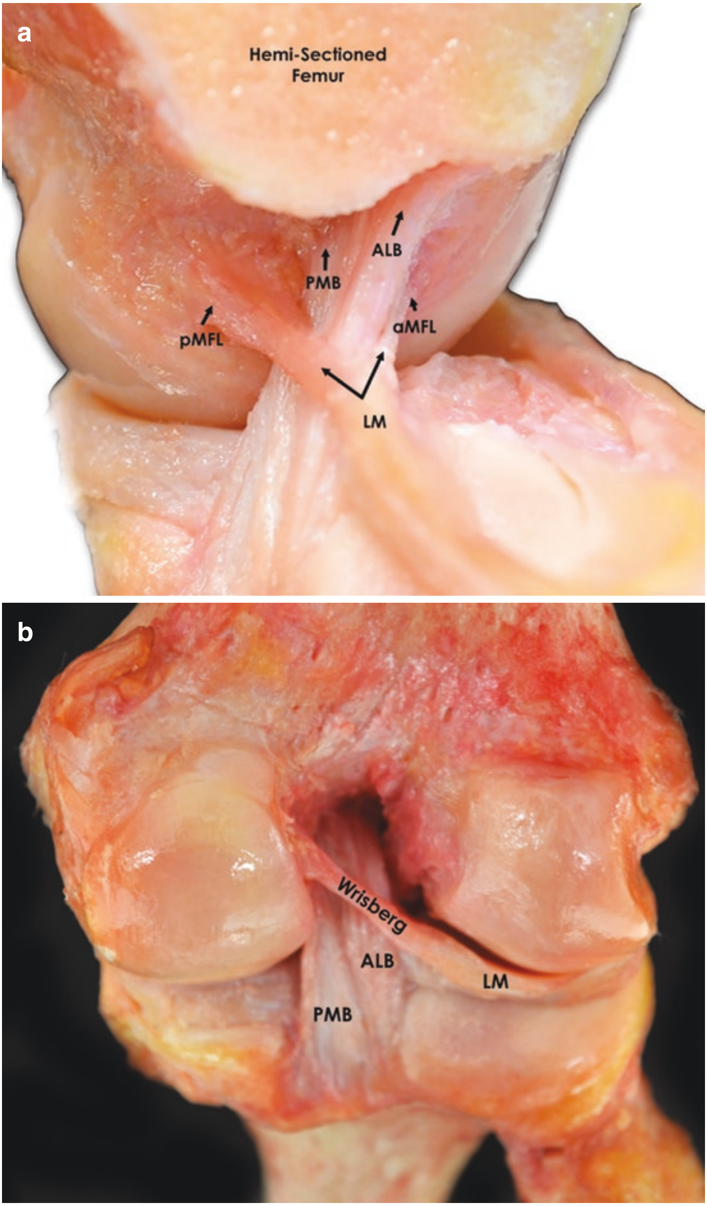
a
Hemi-Sectioned Femur
ALB
PMB
pMFL
aMFL
LM
b
Wrisberg
ALB
LM
PMB

FIGURE 2.2 (**a**) Cadaveric sagittal hemisection of the right knee demonstrating anatomy of anterior meniscofemoral ligament (aMFL, aka ligament of Humphrey) and posterior meniscofemoral ligament (pMFL, aka ligament of Wrisberg) arising from posterior horn of lateral meniscus (LM). The PCL is present with a clear distinction between the anterolateral bundle (ALB) fibers and posteromedial bundle (PMB) fibers. (**b**) Posterior view of cadaveric right knee demonstrating ligament of Wrisberg originating from posterior horn of lateral meniscus (LM), traversing posterior to the two bundles of the PCL (anterolateral bundle (ALB) and posteromedial bundle (PMB), and attaching the posterolateral aspect of the medial femoral condyle

precise anatomical location and area of each root is vital for the surgeon to successfully perform anatomic meniscal root repairs.

The structural properties of the four meniscal roots have also been described in the literature [11], with each root containing strong, central fibers as well as peripheral, supplemental fibers that increase the surface area, strength, and stiffness of each root (Table 2.1). Anatomically, the medial tibial eminence (MTE) apex is the most reproducible osseous landmark for identification of the posterior medial meniscal root (PMMR) attachment (Fig. 2.3a). The center of the PMMR is approximately 10 mm posterior and 1 mm lateral to the MTE [12]. The most proximal PCL tibial attachment fibers (located 8 mm lateral from the center of the PMMR) and the medial tibial plateau articular cartilage inflection point (4 mm lateral to the root) are two other consistent landmarks to identify the root attachment (Fig. 2.3a).

The posterior lateral meniscal root (PLMR) attachment can also be identified using the apex of the lateral tibial eminence (LTE), which is the most consistent landmark (Fig. 2.3b). The center of the PLMR is consistently found to be 4 mm medial and 1.5 mm posterior to the LTE. According to Johannsen et al. [12], the center of the PLMR is located 4 mm medial to the lateral tibial plateau articular cartilage edge and 13 mm anterior to the most proximal edge of the posterior cruciate ligament (PCL) tibial attachment (Fig. 2.3b).

Table 2.1 Structural properties of the meniscal roots with and without sectioning of the supplemental root attachment fibers

Root	Native	Sectioned
Attachment area, mm^2		
AM	101.7 (82.4–120.9)	57.0 (49.4–64.5)
PM	68.0 (59.1–76.9)	41.6 (35.3–47.8)
AL	99.5 (83.1–116.0)	N/A
PL	83.1 (63.6–102.7)	57.7 (47.3–68.0)
Ultimate failure strength, *N*		
AM	655.5 (487.2–823.8)	469.1 (240.7–697.4)
PM	513.8 (388.4–639.1)	267.9 (206.6–329.2)
AL	652.8 (528.2–777.3)	608.4 (434.2–782.6)
PL	509.0 (392.0–625.9)	419.4 (288.9–549.8)
Stiffness, N/mm		
AM	124.9 (101.4–148.3)	103.7 (75.4–132.0)
PM	122.7 (95.1–150.3)	80.7 (71.1–90.2)
AL	151.1 (123.9–178.4)	136.8 (108.4–165.2)
PL	128.7 (104.1–153.3)	117.2 (89.8–144.7)

The anterior medial meniscal root has the largest native area and ultimate failure strength

AL anterior lateral, *AM* anterior medial, *PL* posterior lateral, *PM* posterior medial meniscal root; data reported as mean (95% confidence interval)

These findings help the surgeon when identifying the proper anatomic location during a meniscal root repair.

Microstructure/Biology

Understanding the microstructure of the meniscus helps to explain its complex biomechanical properties and function. The meniscus is mainly comprised of water (up to 75%) and

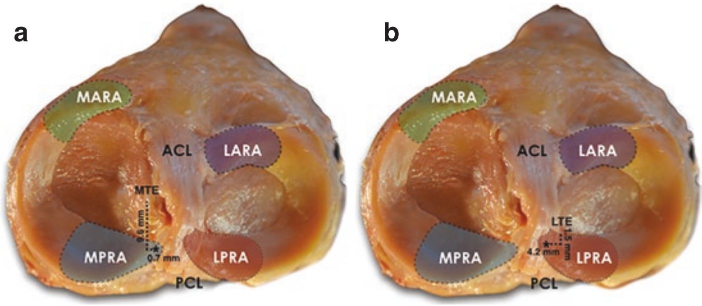

FIGURE 2.3 Cadaveric images (superior axial view) demonstrating the anatomical landmarks to identify (**a**) medial meniscus posterior root attachment and (**b**) lateral meniscus posterior root attachment in a right knee. MTE medial tibial eminence, LTE lateral tibial eminence, MARA medial meniscus anterior root attachment, LARA lateral meniscus anterior root attachment, MPRA medial meniscus posterior root attachment, LPRA lateral meniscus posterior root attachment

collagen (20–25%, 90% type I) and a minority of other elements including proteoglycans, matrix glycoproteins, and elastin [13–17].

Each meniscus is composed of three layers (Fig. 2.4). A more superficial layer is in direct contact with the articular surface and is composed of randomly oriented collagen fibers mixed with a lubricating layer of proteoglycans, allowing for a low frictional surface [18, 19]. Deep to this layer is the middle stratum, which is composed of a lamellar layer containing collagen fibers extending radially (externally), with internal fibers intersecting at various angles, creating a mesh to provide rigidity to the tissue [19]. Finally, the inner layer is composed of large circumferential fibers, with the majority located in the internal and external circumference of the menisci because the middle portion experiences more uniform compressive stress and minimal radial stress (Fig. 2.4) [20, 21]. These circumferential fibers undergo significant tensile or "hoop" stresses when axially loaded [20, 22–25].

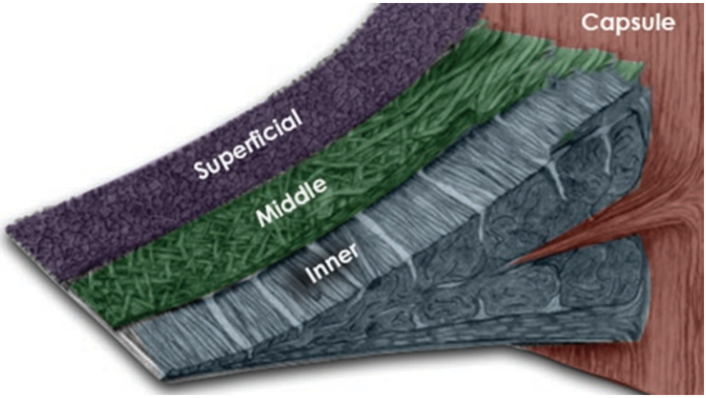

FIGURE 2.4 Schematic illustration showing the different layers of the menisci. The superficial layer contains disorganized fibers, the lamellar layer contains peripherally oriented radial fibers with an internal interconnecting meshwork, and the deep/inner layer contains large circumferential oriented bundles intermingling with radial tie fibers

FIGURE 2.5 Illustration demonstrating application of load, including compression, tension, and shear stress to meniscal tissue

Biomechanical Properties

Several unique biomechanical principles contribute to the complex function of the menisci. These include viscoelasticity, permeability, creep, stress relaxation, ultimate tensile load, and shear stiffness, with each principle playing a vital role in the biomechanical response of meniscal tissue to compression, tension, and shear stresses (Fig. 2.5).

- *Viscoelasticity*: Due to the unique three-layered anatomy described above, the tissue properties of the menisci change throughout an applied load; i.e., they exhibit both viscous and elastic properties. This transition occurs in a time-dependent fashion, beginning in the elastic phase and shifting to the viscous phase during loading. The elastic phase is due to the meniscus collagenous-proteoglycan structure. Conversely, the viscous phase is due to its permeability and water content [20, 26, 27]. When a compressive load is applied to the menisci, the elastic phase initiates, with the meniscal tissue exhibiting an elastic response and compressing the menisci. Simultaneously, fluid extrudes slowly, which accommodates the compressive load without excess deformation, hence beginning the viscous phase [28, 29]. Under compression, meniscal permeability determines the rate at which fluid is extruded. Meniscal permeability is much lower than articular cartilage, allowing for slow extrusion and helping to maintain meniscal shape and integrity during axial loads [27, 28, 30]. Thus, menisci maintain their load-bearing capacity during gait by resisting fluid loss [17, 31, 32], which inhibits compression and helps to maintain their shape.
- *Response to Compression*: Creep and stress relaxation are two related characteristics of viscoelastic behavior [28]. After the initial load is applied and fluid is extruded from the menisci, the compressive load is resisted, known as "creep." [20, 28] This results in a diminished rate of compression over time. When the menisci are compressed and held, the tissue relaxes, and the load required to maintain the given compression decreases. This is referred to as "stress relaxation." Further, when a compressive load is applied to the menisci, an axial load redistributes "hoop stresses" to the circumferential fibers of the menisci, extending to their attachments on the tibia and femur [20, 23–25]. As the femur compresses down, the menisci extrude peripherally due to their wedge shape, causing a radially oriented tangential force [33]. This peripheral extrusion is prevented by the anterior and posterior meniscal root attachments, as

described above. When a root tear occurs clinically, these forces are unopposed, resulting in a functionally meniscectomized state with a significant increase in contract stress occurring in the respective compartment [8] and thereby increasing the risk of progression to osteoarthritis.

- *Response to Tension*: When menisci undergo tensile forces (stretching forces), elongation occurs relatively fast because collagen fibers are relaxed [34]. After the initial phase, there is a linear relationship between elongation and the load applied, followed by a drastic decrease in elongation as fibers begin to fail and tear [35]. The maximum load the menisci can maintain in tension before failure is referred to as the ultimate tensile load. The tensile properties can change depending on the location of the menisci.
- *Response to Shear*: Shear stiffness is defined as the capacity of the meniscus to resist a change of its shape. In this regard, menisci have a lower shear stiffness compared to the articular cartilage and bone, thereby allowing the menisci to maintain optimal congruency between the tibia and the femur through a full range of motion, ensuring equal load distribution [20].

In Vivo Biomechanics

Synchronized motion of the menisci during knee range of motion allows for a maximum congruency over the articulating surfaces, thereby decreasing contact stress within the joint and optimizing congruency and stability [36]. For example, the translation of the lateral meniscus is twice that of the medial meniscus [37], with greater translation of the anterior horns compared to the posterior horns. This is critical because the femoral condyles' articulating shape with the menisci changes during flexion and extension, causing the anterior and posterior horns to drift apart during full extension and closer together during flexion [27]. The anterior horns allow movement to accommodate this, while the posterior horns are more secure and stable, restricting excess movement [36]. Approximately 85% of the weight-bearing load is transmitted in knee flexion with the horns closer together, while 50% is transmitted in extension with the horns further apart [3]. Further, during internal rotation of the tibia, the lateral meniscus translates posteriorly, while the medial meniscus translates anteriorly [38]. These reciprocal functions allow the menisci to maximize contact area with the articular surfaces, reduce point stresses, and avoid chondral damage or injury over time [27].

Clinically, patients with lateral meniscal deficiency demonstrate worse outcomes compared to patients with medial meniscal deficiency [1, 2]. This may be a consequence of the less congruent, more convex articular surfaces of the lateral femoral condyle and lateral tibial plateau, as well as the greater degree of translation of the lateral meniscus, suggesting a crucial role of the lateral meniscus in maintaining lateral joint integrity [24, 37]. Further, the lateral meniscus absorbs 70% of load while the medial meniscus only 50% [3], again helping to elucidate the clinical significance of the lateral meniscus.

The aforementioned differences in translation of each meniscus may also help to explain the role of the menisci as secondary stabilizers within the knee joint. The medial meniscus is an important secondary restraint to anterior tibial translation [28, 39, 40]. This can be explained by the decreased mobility of the medial meniscus, as the medial meniscus is less mobile with approximately 50% translation compared to the lateral meniscus and therefore is more stable in an anterior-posterior direction. The medial meniscus is also postulated to have a "wedge" effect created by compression on the posterior horn during loading, further preventing anterior displacement [41]. The joint stabilizing capability of the medial meniscus is most apparent in ACL-deficient knees. Following medial meniscectomy in the ACL-deficient knee, there is a significant increase in anterior tibial translation after an anterior tibial load is applied, compared to ACL-deficient knees with an intact medial meniscus [41, 42]. These findings corroborate the vital role of the medial meniscus as a secondary stabilizer of anterior-posterior translation of the knee.

In contrast, due to its increased mobility and translation, the lateral meniscus is thought to play a lesser role in anterior-posterior stabilization [41, 43, 44], but it has been found to play a greater role in anterolateral rotatory stability [45]. The lateral meniscus has also been suggested to play an important secondary role in restraining combined axial and rotatory loads [45].

Conclusion

The meniscus plays an integral role in the knee with several chondroprotective and stabilizing functions. A thorough understanding of meniscal anatomy, biology, and biomechanics is vital to understand the complex structure and function of the medial and lateral menisci.

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