

[Orthopaedic Surgery]

The Basic Science of Human Knee Menisci: Structure, Composition, and Function

Alice J. S. Fox, MSc,^{*†} Asheesh Bedi, MD,[‡] and Scott A. Rodeo, MD[†]

Context: Information regarding the structure, composition, and function of the knee menisci has been scattered across multiple sources and fields. This review contains a concise, detailed description of the knee menisci—including anatomy, etymology, phylogeny, ultrastructure and biochemistry, vascular anatomy and neuroanatomy, biomechanical function, maturation and aging, and imaging modalities.

Evidence Acquisition: A literature search was performed by a review of PubMed and OVID articles published from 1858 to 2011.

Results: This study highlights the structural, compositional, and functional characteristics of the menisci, which may be relevant to clinical presentations, diagnosis, and surgical repairs.

Conclusions: An understanding of the normal anatomy and biomechanics of the menisci is a necessary prerequisite to understanding the pathogenesis of disorders involving the knee.

Keywords: knee; meniscus; anatomy; function

Once described as a functionless embryonic remnant,¹⁶² the menisci are now known to be vital for the normal function and long-term health of the knee joint.[§] The menisci increase stability for femorotibial articulation, distribute axial load, absorb shock, and provide lubrication and nutrition to the knee joint.^{4,91,152,153}

Injuries to the menisci are recognized as a cause of significant musculoskeletal morbidity. The unique and complex structure of menisci makes treatment and repair challenging for the patient, surgeon, and physical therapist. Furthermore, long-term damage may lead to degenerative joint changes such as osteophyte formation, articular cartilage degeneration, joint space narrowing, and symptomatic osteoarthritis.^{36,45,92} Preservation of the menisci depends on maintaining their distinctive composition and organization.

ANATOMY OF MENISCI

Meniscal Etymology

The word *meniscus* comes from the Greek word *mēniskos*, meaning “crescent,” diminutive of *mēnē*, meaning “moon.”

[§]References 9, 13, 29, 45, 144, 160, 161.

Meniscal Phylogeny and Comparative Anatomy

Hominids exhibit similar anatomic and functional characteristics, including a bicondylar distal femur, intra-articular cruciate ligaments, menisci, and asymmetrical collateral.^{40,66} These similar morphologic characteristics reflect a shared genetic lineage that can be traced back more than 300 million years.^{40,66,119}

In the primate lineage leading to humans, hominids evolved to bipedal stance approximately 3 to 4 million years ago, and by 1.3 million years ago, the modern patellofemoral joint was established (with a longer lateral patellar facet and matching lateral femoral trochlea).¹⁶⁴ Tardieu investigated the transition from occasional bipedalism to permanent bipedalism and observed that primates contain a medial and lateral fibrocartilaginous meniscus, with the medial meniscus being morphologically similar in all primates (crescent shaped with 2 tibial insertions).¹⁶³ By contrast, the lateral meniscus was observed to be more variable in shape. Unique in *Homo sapiens* is the presence of 2 tibial insertions—1 anterior and 1 posterior—indicating a habitual practice of full extension movements of the knee joint during the stance and swing phases of bipedal walking.^{20,134,142,163,168}

From the [†]Hospital for Special Surgery, New York, New York, and the [‡]Department of Orthopaedic Surgery, University of Michigan, Ann Arbor, Michigan

*Address correspondence to Asheesh Bedi, MD, Department of Orthopaedic Surgery, University of Michigan, 24 Frank Lloyd Wright Drive, Ann Arbor, MI 48105 (e-mail: abedi@med.umich.edu).

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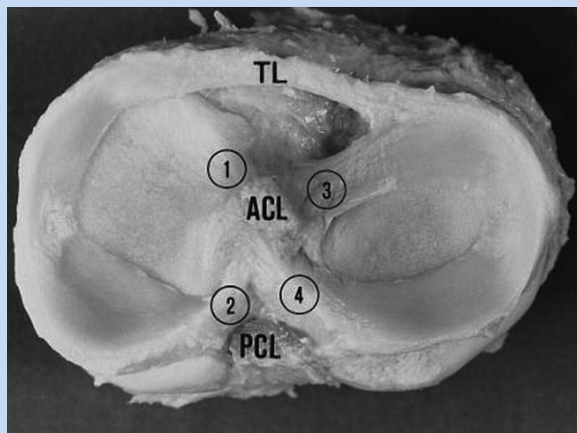


Figure 1. Gross photograph of human tibial plateau demonstrating the relative size and attachments of the medial and lateral menisci. The medial and lateral menisci (left side and right side of image, respectively) are connected by a transverse ligament (TL). 1, anterior insertional ligament of the medial meniscus; 2, posterior insertional ligament of the medial meniscus; 3, anterior insertional ligament of the lateral meniscus; 4, posterior insertional ligament of the lateral meniscus. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament. Reprinted with permission from Messner and Gao.¹¹⁵

Embryology and Development

The characteristic shape of the lateral and medial menisci is attained between the 8th and 10th week of gestation.^{53,60} They arise from a condensation of the intermediate layer of mesenchymal tissue to form attachments to the surrounding joint capsule.^{31,87,110} The developing menisci are highly cellular and vascular, with the blood supply entering from the periphery and extending through the entire width of the menisci.³¹ As the fetus continues to develop, there is a gradual decrease in the cellularity of the menisci with a concomitant increase in the collagen content in a circumferential arrangement.^{30,31} Joint motion and the postnatal stress of weightbearing are important factors in determining the orientation of collagen fibers. By adulthood, only the peripheral 10% to 30% have a blood supply.^{12,31}

Despite these histologic changes, the proportion of tibial plateau covered by the corresponding meniscus is relatively constant throughout fetal development, with the medial and lateral menisci covering approximately 60% and 80% of the surface areas, respectively.³¹

Gross Anatomy

Gross examination of the knee menisci reveals a smooth, lubricated tissue (Figure 1). They are crescent-shaped wedges of fibrocartilage located on the medial and lateral aspects of

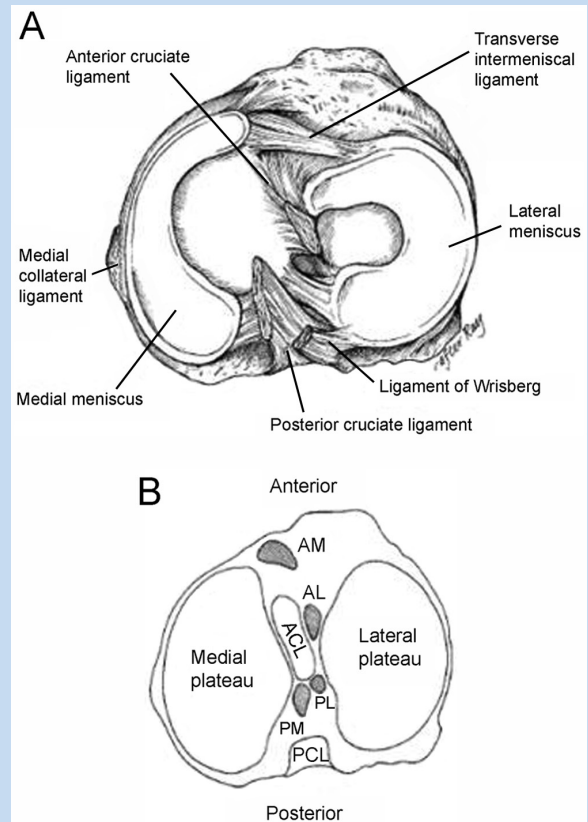


Figure 2. (A) Anatomy of the meniscus viewed from above (adapted image reprinted with permission from Greis et al⁶³; original from Pagnani et al¹²⁹). (B) Axial view of a right tibial plateau showing sections of the meniscus and their relationship to the cruciate ligaments. AL, anterior horn lateral meniscus; AM, anterior horn medial meniscus; PCL, posterior cruciate ligament; PL, posterior horn lateral meniscus; PM, posterior horn medial meniscus. Reprinted with permission from Johnson et al.⁸³

the knee joint (Figure 2A). The peripheral, vascular border (also known as the *red zone*) of each meniscus is thick, convex, and attached to the joint capsule. The innermost border (also known as the *white zone*) tapers to a thin free edge. The superior surfaces of menisci are concave, enabling effective articulation with their respective convex femoral condyles. The inferior surfaces are flat to accommodate the tibial plateau (Figure 1).^{28,175}

Medial meniscus. The semicircular medial meniscus measures approximately 35 mm in diameter (anterior to posterior) and is significantly broader posteriorly than it is anteriorly.¹⁷⁵ The anterior horn is attached to the tibia plateau near the intercondylar fossa anterior to the anterior cruciate ligament (ACL). There is significant variability in the attachment location of the anterior horn of the medial meniscus. The posterior

horn is attached to the posterior intercondylar fossa of the tibia between the lateral meniscus and the posterior cruciate ligament (PCL; Figures 1 and 2B). Johnson et al reexamined the tibial insertion sites of the menisci and their topographic relationships to surrounding anatomic landmarks of the knee.⁸² They found that the anterior and posterior horn insertion sites of the medial meniscus were larger than those of the lateral meniscus. The area of the anterior horn insertion site of the medial meniscus was the largest overall, measuring 61.4 mm², whereas the posterior horn of the lateral meniscus was the smallest, at 28.5 mm².⁸²

The tibial portion of the capsular attachment is the coronary ligament. At its midpoint, the medial meniscus is more firmly attached to the femur through a condensation in the joint capsule known as the *deep medial collateral ligament*.¹⁷⁵ The transverse, or “intermeniscal,” ligament is a fibrous band of tissue that connects the anterior horn of the medial meniscus to the anterior horn of the lateral meniscus (Figures 1 and 2A).

Lateral meniscus. The lateral meniscus is almost circular, with an approximately uniform width from anterior to posterior (Figures 1 and 2A). It occupies a larger portion (~80%) of the articular surface than the medial meniscus (~60%) and is more mobile.^{10,31,165} Both horns of the lateral meniscus are attached to the tibia. The insertion of the anterior horn of the lateral meniscus lies anterior to the intercondylar eminence and adjacent to the broad attachment site of the ACL (Figure 2B).^{9,83} The posterior horn of the lateral meniscus inserts posterior to the lateral tibial spine and just anterior to the insertion of the posterior horn of the medial meniscus (Figure 2B).⁸³ The lateral meniscus is loosely attached to the capsular ligament; however, these fibers do not attach to the lateral collateral ligament. The posterior horn of the lateral meniscus attaches to the inner aspect of the medial femoral condyle via the anterior and posterior menisofemoral ligaments of Humphrey and Wrisberg, respectively, which originate near the origin of the PCL (Figures 1 and 2).⁷⁵

Menisofemoral ligaments. The literature reports significant inconsistencies in the presence and size of menisofemoral ligaments of the lateral meniscus. There may be none, 1, 2, or 4.¹¹ When present, these accessory ligaments transverse from the posterior horn of the lateral meniscus to the lateral aspect of the medial femoral condyle. They insert immediately adjacent to the femoral attachment of the PCL (Figures 1 and 2).

In a series of studies, Harner et al measured the cross-sectional area of the ligaments and found that the menisofemoral ligament averaged 20% of the size of the PCL (range, 7%-35%).^{69,70} However, the size of the insertional area alone without knowledge of the insertional angle or collagen density does not indicate their relative strength.¹¹⁵ The function of these ligaments remains unknown; they may pull the posterior horn of the lateral meniscus in an anterior direction

¹¹⁵References 11, 75, 79, 93, 98, 133, 173, 185.

to increase the congruity of the meniscotibial fossa and the lateral femoral condyle.⁷⁵

ULTRASTRUCTURE AND BIOCHEMISTRY

Extracellular Matrix

The meniscus is a dense extracellular matrix (ECM) composed primarily of water (72%) and collagen (22%), interposed with cells.^{9,55,56,77} Proteoglycans, noncollagenous proteins, and glycoproteins account for the remaining dry weight.⁹ Meniscal cells synthesize and maintain the ECM, which determines the material properties of the tissue.

The cells of the menisci are referred to as *fibrochondrocytes* because they appear to be a mixture of fibroblasts and chondrocytes.^{111,177} The cells in the more superficial layer of the menisci are fusiform or spindle shaped (more fibroblastic), whereas the cells located deeper in the meniscus are ovoid or polygonal (more chondrocytic).^{55,56,178} Cell morphology does not differ between the peripheral and central locations in the menisci.⁵⁶

Both cell types contain abundant endoplasmic reticulum and Golgi complex. Mitochondria are only occasionally visualized, suggesting that the major pathway for energy production of fibrochondrocytes in their avascular milieu is probably anaerobic glycolysis.¹¹²

Water

In normal, healthy menisci, tissue fluid represents 65% to 70% of the total weight. Most of the water is retained within the tissue in the solvent domains of proteoglycans. The water content of meniscal tissue is higher in the posterior areas than in the central or anterior areas; tissue samples from surface and deeper layers had similar contents.¹³⁵

Large hydraulic pressures are required to overcome the drag of frictional resistance of forcing fluid flow through meniscal tissue. Thus, interactions between water and the matrix macromolecular framework significantly influence the viscoelastic properties of the tissue.

Collagens

Collagens are primarily responsible for the tensile strength of menisci; they contribute up to 75% of the dry weight of the ECM.⁷⁷ The ECM is composed primarily of type I collagen (90% dry weight) with variable amounts of types II, III, V, and VI.^{43,44,80,112,181} The predominance of type I collagen distinguishes the fibrocartilage of menisci from articular (hyaline) cartilage. The collagens are heavily cross-linked by hydroxylpyridinium aldehydes.⁴⁴

The collagen fiber arrangement is ideal for transferring a vertical compressive load into circumferential “hoop” stresses (Figure 3).⁵⁷ Type I collagen fibers are oriented circumferentially in the deeper layers of the meniscus, parallel

¹¹²References 8, 16, 49, 77, 80, 112, 131, 166, 180.

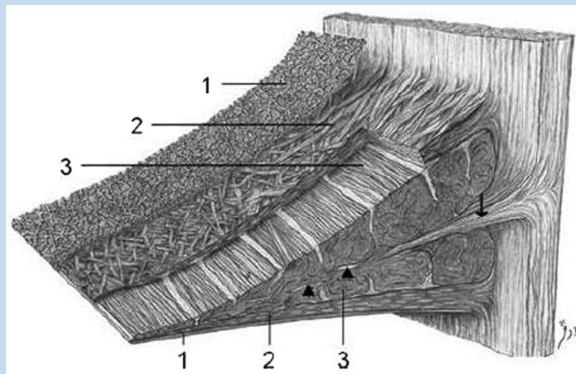


Figure 3. Schematic diagram demonstrating the collagen fiber ultrastructure and orientation within the meniscus: 1, superficial network; 2, lamellar layer; 3, central main layer. Arrowheads, radial interwoven fibers; arrow, loose connective tissue. Reprinted with permission from Petersen and Tillmann.¹³²

to the peripheral border. These fibers blend the ligamentous connections of the meniscal horns to the tibial articular surface (Figure 3).^{10,27,49,156} In the most superficial region of the menisci, the type I fibers are oriented in a more radial direction. Radially oriented “tie” fibers are also present in the deep zone and are interspersed or woven between the circumferential fibers to provide structural integrity (Figure 3).[†] There is lipid debris and calcified bodies in the ECM of human menisci.⁵⁴ The calcified bodies contain long, slender crystals of phosphorous, calcium, and magnesium on electron-probe roentgenographic analysis.⁵⁴ The function of these crystals is not completely understood, but it is believed that they may play a role in acute joint inflammation and destructive arthropathies.

Noncollagenous matrix proteins, such as fibronectin, contribute 8% to 13% of the organic dry weight. Fibronectin is involved in many cellular processes, including tissue repair, embryogenesis, blood clotting, and cell migration/adhesion. Elastin forms less than 0.6% of the meniscus dry weight; its ultrastructural localization is not clear. It likely interacts directly with collagen to provide resiliency to the tissue.”

Proteoglycans

Located within a fine meshwork of collagen fibrils, proteoglycans are large, negatively charged hydrophilic molecules, contributing 1% to 2% of dry weight.⁵⁸ They are formed by a core protein with 1 or more covalently attached glycosaminoglycan chains (Figure 4).¹²² The size of these molecules is further increased by specific interaction with

[†]References 13, 14, 21, 27, 49, 59, 114, 156, 171, 182.

^{**}References 13, 49, 73, 78, 80, 112, 131.

hyaluronic acid.^{67,72} The amount of proteoglycans in the meniscus is one-eighth that of articular cartilage,^{2,3} and there may be considerable variation depending on the site of the sample and the age of the patient.⁴⁹

By virtue of their specialized structure, high fixed-charge density, and charge-charge repulsion forces, proteoglycans in the ECM are responsible for hydration and provide the tissue with a high capacity to resist compressive loads.[‡] The glycosaminoglycan profile of the normal adult human meniscus consists of chondroitin-6-sulfate (40%), chondroitin-4-sulfate (10% to 20%), dermatan sulfate (20% to 30%), and keratin sulfate (15%; Figure 4).^{65,77,99,159} The highest glycosaminoglycan concentrations are found in the meniscal horns and the inner half of the menisci in the primary weightbearing areas.^{58,77}

Aggrecan is the major proteoglycan found in the human menisci and is largely responsible for their viscoelastic compressive properties (Figure 5). Smaller proteoglycans, such as decorin, biglycan, and fibromodulin, are found in smaller amounts.^{124,151} Hexosamine contributes 1% to the dry weight of ECM.^{57,74} The precise functions of each of these small proteoglycans on the meniscus have yet to be fully elucidated.

Matrix Glycoproteins

Meniscal cartilage contains a range of matrix glycoproteins, the identities and functions of which have yet to be determined. Electrophoresis and subsequent staining of the polyacrylamide gels reveals bands with molecular weights varying from a few kilodaltons to more than 200 kDa.¹¹² These matrix molecules include the link proteins that stabilize proteoglycan-hyaluronic acid aggregates and a 116-kDa protein of unknown function.⁴⁶ This protein resides in the matrix in the form of disulfide-bonded complex of high molecular weight.⁴⁶ Immunolocalization studies suggest that it is predominantly located around the collagen bundles in the interterritorial matrix.⁴⁷

The adhesive glycoproteins constitute a subgroup of the matrix glycoproteins. These macromolecules are partly responsible for binding with other matrix molecules and/or cells. Such intermolecular adhesion molecules are therefore important components in the supramolecular organization of the extracellular molecules of the meniscus.¹⁵⁰ Three molecules have been identified within the meniscus: type VI collagen, fibronectin, and thrombospondin.^{112,118,181}

VASCULAR ANATOMY

The meniscus is a relatively avascular structure with a limited peripheral blood supply. The medial, lateral, and middle geniculate arteries (which branch off the popliteal artery) provide the major vascularization to the inferior and superior aspects of each meniscus (Figure 5).^{9,12,33-35,148} The middle geniculate artery is a small posterior branch that perforates the oblique popliteal ligament at the posteromedial corner of

[‡]References 1, 10, 71, 89, 116, 121, 145.

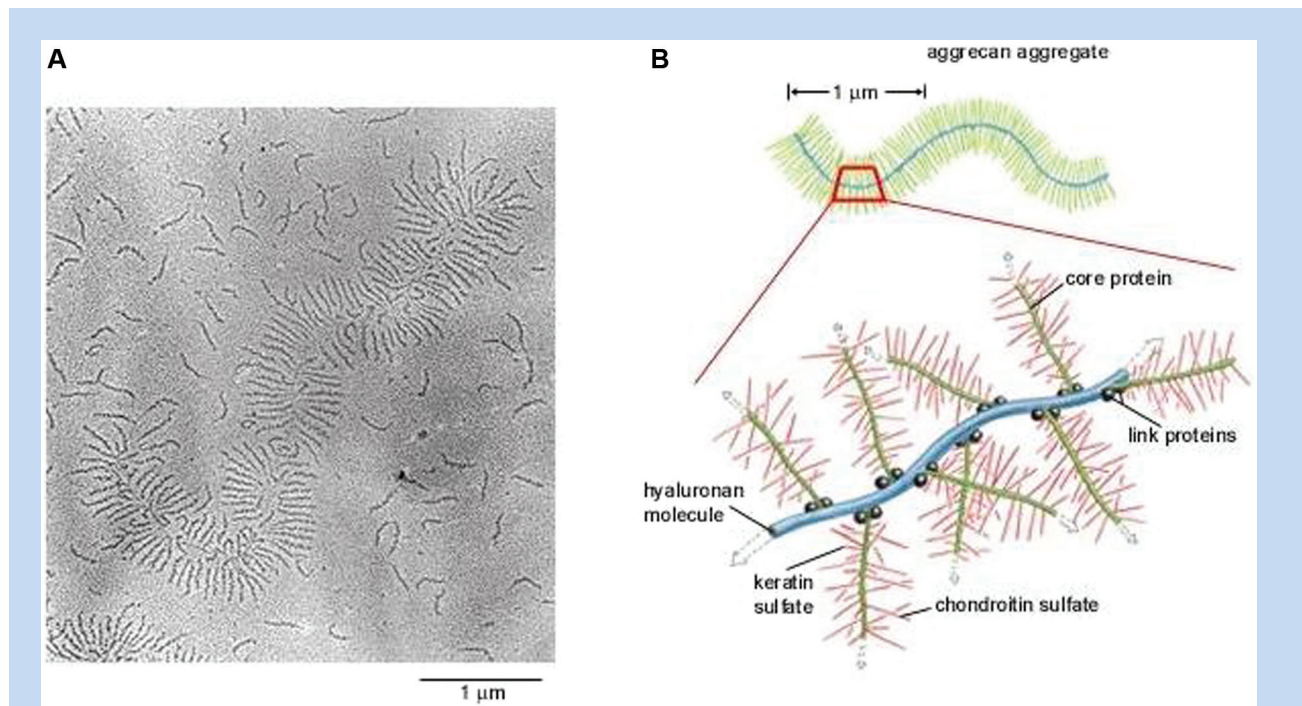


Figure 4. Extracellular matrix. (A) Electron micrograph of an aggrecan aggregate shadowed by platinum. Many free aggrecan molecules are also seen. (B) Schematic drawing of an aggrecan aggregate shown in part A. Reprinted with permission from Alberts et al.⁶

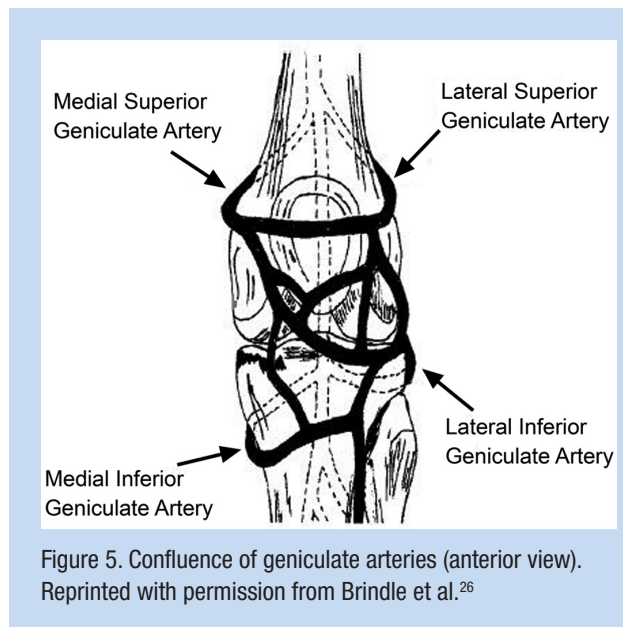


Figure 5. Confluence of geniculate arteries (anterior view). Reprinted with permission from Brindle et al.²⁶

the tibiofemoral joint. A premeniscal capillary network arising from the branches of these arteries originates within the synovial and capsular tissues of the knee along the periphery of the menisci. The peripheral 10% to 30% of the medial meniscus border and 10% to 25% of the lateral meniscus are relatively well vascularized, which has important implications

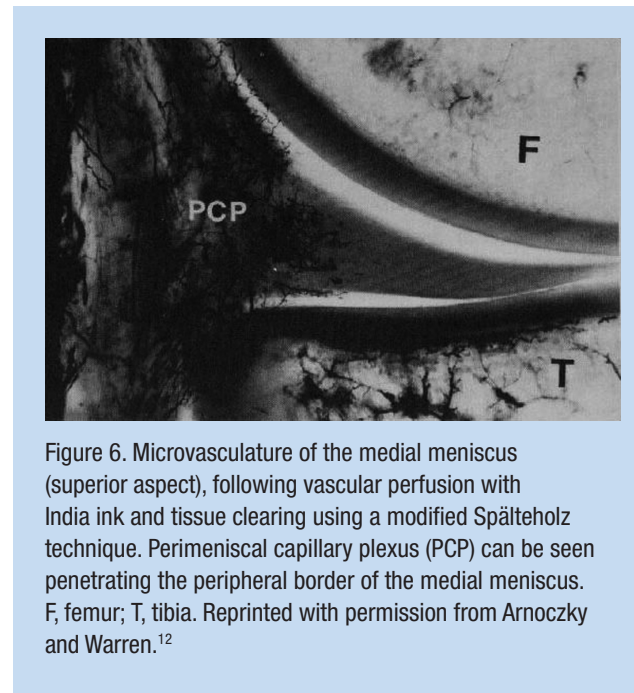


Figure 6. Microvasculature of the medial meniscus (superior aspect), following vascular perfusion with India ink and tissue clearing using a modified Spalteholz technique. Perimeniscal capillary plexus (PCP) can be seen penetrating the peripheral border of the medial meniscus. F, femur; T, tibia. Reprinted with permission from Arnoczky and Warren.¹²

for meniscus healing (Figure 6).^{12,33,68} Endoligamentous vessels from the anterior and posterior horns travel a short distance into the substance of the menisci and form terminal loops, providing a direct route for nourishment.³³ The remaining

portion of each meniscus (65% to 75%) receives nourishment from synovial fluid via diffusion or mechanical pumping (ie, joint motion).^{116,120}

Bird and Sweet examined the menisci of animals and humans using scanning electron and light microscopy.^{23,24} They observed canal-like structures opening deep into the surface of the menisci. These canals may play a role in the transport of fluid within the meniscus and may carry nutrients from the synovial fluid and blood vessels to the avascular sections of the meniscus.^{23,24} However, further study is needed to elucidate the exact mechanism by which mechanical motion supplies nutrition to the avascular portion of the menisci.

NEUROANATOMY

The knee joint is innervated by the posterior articular branch of the posterior tibial nerve and the terminal branches of the obturator and femoral nerves. The lateral portion of the capsule is innervated by the recurrent peroneal branch of the common peroneal nerve. These nerve fibers penetrate the capsule and follow the vascular supply to the peripheral portion of the menisci and the anterior and posterior horns, where most of the nerve fibers are concentrated.^{52,90} The outer third of the body of the meniscus is more densely innervated than the middle third.^{183,184} During extremes of flexion and extension of the knee, the meniscal horns are stressed, and the afferent input is likely greatest at these extreme positions.^{183,184}

The mechanoreceptors within the menisci function as transducers, converting the physical stimulus of tension and compression into a specific electrical nerve impulse. Studies of human menisci have identified 3 morphologically distinct mechanoreceptors: Ruffini endings, Pacinian corpuscles, and Golgi tendon organs.^{##} Type I (Ruffini) mechanoreceptors are low threshold and slowly adapting to the changes in joint deformation and pressure. Type II (Pacinian) mechanoreceptors are low threshold and fast adapting to tension changes.^{##} Type III (Golgi) are high-threshold mechanoreceptors, which signal when the knee joint approaches the terminal range of motion and are associated with neuromuscular inhibition. These neural elements were found in greater concentration in the meniscal horns, particularly the posterior horn.

The asymmetrical components of the knee act in concert as a type of biological transmission that accepts, transfers, and dissipates loads along the femur, tibia, patella, and femur.⁴¹ Ligaments act as an adaptive linkage, with the menisci representing mobile bearings. Several studies have reported that various intra-articular components of the knee are sensate, capable of generating neurosensory signals that reach spinal, cerebellar, and higher central nervous system levels.^{|||} It is believed that these neurosensory signals result in conscious perception and are important for normal knee joint function and maintenance of tissue homeostasis.⁴²

^{##}References 15, 35, 52, 64, 90, 126, 127, 149, 183.

^{##}References 15, 52, 90, 126, 127, 149, 183.

^{|||}References 19,32,42,125,136,157,174.

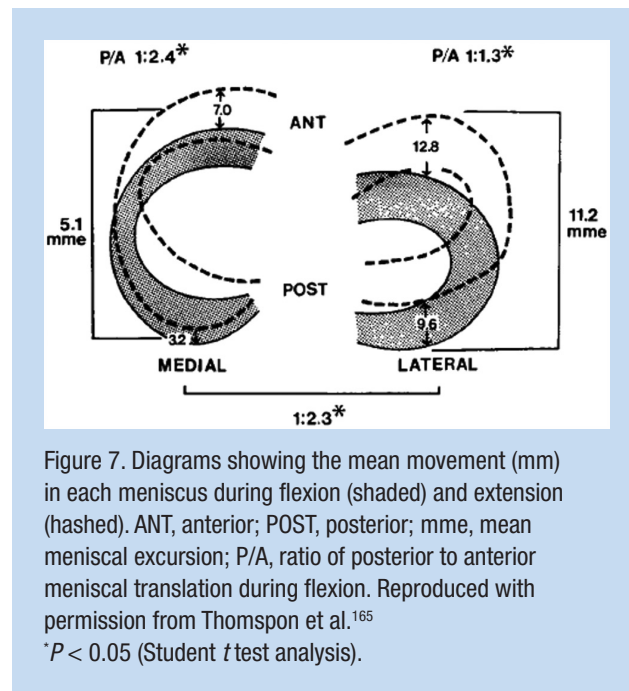


Figure 7. Diagrams showing the mean movement (mm) in each meniscus during flexion (shaded) and extension (hashed). ANT, anterior; POST, posterior; mme, mean meniscal excursion; P/A, ratio of posterior to anterior meniscal translation during flexion. Reproduced with permission from Thomsson et al.¹⁶⁵

* $P < 0.05$ (Student t test analysis).

BIOMECHANICAL FUNCTION

The biomechanical function of the meniscus is a reflection of the gross and ultrastructural anatomy and of its relationship to the surrounding intra-articular and extra-articular structures. The menisci serve many important biomechanical functions. They contribute to load transmission,⁹⁹ shock absorption,^{10,49,94,96,170} stability,^{51,100,101,109,155} nutrition,^{23,24,84,141} joint lubrication,^{102,104,141} and proprioception.^{5,15,81,88,115,147} They also serve to decrease contact stresses and increase contact area and congruity of the knee.^{91,172}

Meniscal Kinematics

In a study on ligamentous function, Brantigan and Voshell reported the medial meniscus to move an average 2 mm, while the lateral meniscus was markedly more mobile with approximately 10 mm of anterior-posterior displacement during flexion.²⁵ Similarly, DePalma reported that the medial meniscus undergoes 3 mm of anterior-posterior displacement, while the lateral meniscus moves 9 mm during flexion.³⁷ In a study using 5 cadaveric knees, Thompson et al reported the mean medial excursion to be 5.1 mm (average of anterior and posterior horns) and the mean lateral excursion, 11.2 mm, along the tibial articular surface (Figure 7).¹⁶⁵ The findings from these studies confirm a significant difference in segmental motion between the medial and lateral menisci. The anterior and posterior horn lateral meniscus ratio is smaller and indicates that the meniscus moves more as a single unit.¹⁶⁵ Alternatively, the medial meniscus (as a whole) moves less than the lateral meniscus, displaying a greater anterior to posterior horn

^{|||}References 4, 10, 45, 50, 152, 153, 172.

differential excursion. Thompson et al found that the area of least meniscal motion is the posterior medial corner, where the meniscus is constrained by its attachment to the tibial plateau by the meniscotibial portion of the posterior oblique ligament, which has been reported to be more prone to injury.^{143,165} A reduction in the motion of the posterior horn of the medial meniscus is a potential mechanism for meniscal tears, with a resultant “trapping” of the fibrocartilage between the femoral condyle and the tibial plateau during full flexion. The greater differential between anterior and posterior horn excursion may place the medial meniscus at a greater risk of injury.¹⁶⁵

The differential of anterior horn to posterior horn motion allows the menisci to assume a decreasing radius with flexion, which correlates to the decreased radius of curvature of the posterior femoral condyles.¹⁶⁵ This change of radius allows the meniscus to maintain contact with the articulating surface of both the femur and the tibia throughout flexion.

Load Transmission

The function of the menisci has been clinically inferred by the degenerative changes that accompany its removal. Fairbank described the increased incidence and predictable degenerative changes of the articular surfaces in completely meniscectomized knees.⁴⁵ Since this early work, numerous studies have confirmed these findings and have further established the important role of the meniscus as a protective, load-bearing structure.

Weightbearing produces axial forces across the knee, which compress the menisci, resulting in “hoop” (circumferential) stresses.¹⁷⁰ Hoop stresses are generated as axial forces and converted to tensile stresses along the circumferential collagen fibers of the meniscus (Figure 8). Firm attachments by the anterior and posterior insertional ligaments prevent the meniscus from extruding peripherally during load bearing.⁹⁴ Studies by Seedhom and Hargreaves reported that 70% of the load in the lateral compartment and 50% of the load in the medial compartment is transmitted through the menisci.¹⁵³ The menisci transmit 50% of compressive load through the posterior horns in extension, with 85% transmission at 90° flexion.¹⁷² Radin et al demonstrated that these loads are well distributed when the menisci are intact.¹³⁷ However, removal of the medial meniscus results in a 50% to 70% reduction in femoral condyle contact area and a 100% increase in contact stress.^{4,50,91} Total lateral meniscectomy results in a 40% to 50% decrease in contact area and increases contact stress in the lateral component to 200% to 300% of normal.^{18,50,76,91} This significantly increases the load per unit area and may contribute to accelerated articular cartilage damage and degeneration.^{45,85}

Shock Absorption

The menisci play a vital role in attenuating the intermittent shock waves generated by impulse loading of the knee with normal gait.^{94,96,153} Voloshin and Wosk showed that the normal knee has a shock-absorbing capacity about 20% higher than

knees that have undergone meniscectomy.¹⁷⁰ As the inability of a joint system to absorb shock has been implicated in the development of osteoarthritis, the meniscus would appear to play an important role in maintaining the health of the knee joint.¹³⁸

Joint Stability

The geometric structure of the menisci provides an important role in maintaining joint congruity and stability.²² The superior surface of each meniscus is concave, enabling effective articulation between the convex femoral condyles and flat tibial plateau. When the meniscus is intact, axial loading of the knee has a multidirectional stabilizing function, limiting excess motion in all directions.⁹

Markolf and colleagues have addressed the effect of meniscectomy on anterior-posterior and rotational knee laxity. Medial meniscectomy in the ACL-intact knee has little effect on anterior-posterior motion, but in the ACL-deficient knee, it results in an increase in anterior-posterior tibial translation of up to 58% at 90° of flexion.¹⁰⁹ Shoemaker and Markolf demonstrated that the posterior horn of the medial meniscus is the most important structure resisting an anterior tibial force in the ACL-deficient knee.¹⁵⁵ Allen et al showed that the resultant force in the medial meniscus of the ACL-deficient knee increased by 52% in full extension and by 197% at 60° of flexion under a 134-N anterior tibial load.⁷ The large changes in kinematics due to medial meniscectomy in the ACL-deficient knee confirm the important role of the medial meniscus in knee stability. Recently, Musahl et al reported that the lateral meniscus plays a role in anterior tibial translation during the pivot-shift maneuver.¹²³

Joint Nutrition and Lubrication

The menisci may also play a role in the nutrition and lubrication of the knee joint. The mechanics of this lubrication remains unknown; the menisci may compress synovial fluid into the articular cartilage, which reduces frictional forces during weightbearing.¹³

There is a system of microcanals within the meniscus located close to the blood vessels, which communicates with the synovial cavity; these may provide fluid transport for nutrition and joint lubrication.^{23,24}

Proprioception

The perception of joint motion and position (proprioception) is mediated by mechanoreceptors that transduce mechanical deformation into electric neural signals. Mechanoreceptors have been identified in the anterior and posterior horns of the menisci.²⁰⁰ Quick-adapting mechanoreceptors, such as Pacinian corpuscles, are thought to mediate the sensation of joint motion, and slow-adapting receptors, such as Ruffini

^{##}References 7, 25, 51, 101, 108, 109, 128, 155.

^{***}References 5, 15, 81, 88, 147, 179, 184.

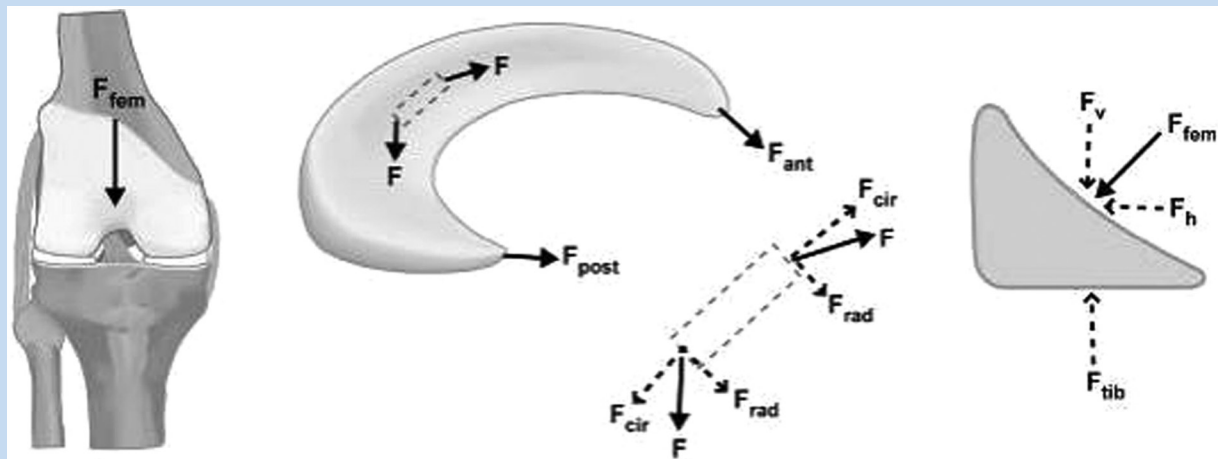


Figure 8. Free body diagram of forces acting on the meniscus during loading. As the femur presses down on the meniscus during normal loading, the meniscus deforms radially but is anchored by its anterior and posterior horns (F_{ant} and F_{post}). During loading, tensile, compressive, and shear forces are generated. A tensile hoop stress (F_{cir}) results from the radial deformation, while vertical and horizontal forces (F_v and F_h) result from the femur pressing on the curved superior surface of the tissue. A radial reaction force (F_{rad}) balances the femoral horizontal force (F_h). Reprinted with permission from Athanasiou and Sanchez-Adams.¹⁷

endings and Golgi tendon organs, are believed to mediate the sensation of joint position.¹⁴⁰ The identification of these neural elements (located mostly in the middle and outer third of the meniscus) indicates that the menisci are capable of detecting proprioceptive information in the knee joint, thus playing an important afferent role in the sensory feedback mechanism of the knee.^{61,88,90,158,169}

MATURATION AND AGING OF THE MENISCUS

The microanatomy of the meniscus is complex and certainly demonstrates senescent changes. With advancing age, the meniscus becomes stiffer, loses elasticity, and becomes yellow.^{78,95} Microscopically, there is a gradual loss of cellular elements with empty spaces and an increase in fibrous tissue in comparison with elastic tissue.⁷⁴ These cystic areas can initiate a tear, and with a torsional force by the femoral condyle, the superficial layers of the meniscus may shear off from the deep layer at the interface of the cystic degenerative change, producing a horizontal cleavage tear. Shear between these layers may cause pain. The torn meniscus may directly injure the overlying articular cartilage.^{74,95}

Ghosh and Taylor found that collagen concentration increased from birth to 30 years and remained constant until 80 years of age, after which a decline occurred.⁵⁸ The noncollagenous matrix proteins showed the most profound changes, decreasing from $21.9\% \pm 1.0\%$ (dry weight) in neonates to $8.1\% \pm 0.8\%$ between the ages of 30 to 70 years.⁸⁰ After 70 years of age, the noncollagenous matrix protein levels increased to $11.6\% \pm 1.3\%$. Peters and Smillie observed an increase in hexosamine and uronic acid with age.¹³¹

McNicol and Roughley studied the variation of meniscal proteoglycans in aging¹¹³; small differences in extractability and hydrodynamic size were observed. The proportions of keratin sulfate relative to chondroitin-6-sulfate increased with aging.¹⁴⁶

Petersen and Tillmann immunohistochemically investigated human menisci (ranging from 22 weeks of gestation to 80 years), observing the differentiation of blood vessels and lymphatics in 20 human cadavers. At the time of birth, nearly the entire meniscus was vascularized. In the second year of life, an avascular area developed in the inner circumference. In the second decade, blood vessels were present in the peripheral third. After 50 years of age, only the peripheral quarter of the meniscal base was vascularized. The dense connective tissue of the insertion was vascularized but not the fibrocartilage of the insertion. Blood vessels were accompanied by lymphatics in all areas.¹¹¹

Arnoczky suggested that body weight and knee joint motion may eliminate blood vessels in the inner and middle aspects of the menisci.⁹ Nutrition of meniscal tissue occurs via perfusion from blood vessels and via diffusion from synovial fluid. A requirement for nutrition via diffusion is the intermittent loading and release on the articular surfaces, stressed by body weight and muscle forces.¹³⁰ The mechanism is comparable with the nutrition of articular cartilage.²²

MAGNETIC RESONANCE IMAGING OF THE MENISCUS

Magnetic resonance imaging (MRI) is a noninvasive diagnostic tool used in the evaluation, diagnosis, and monitoring of

¹¹¹References 9, 12, 31, 33, 35, 61, 132, 139, 140, 148, 167.

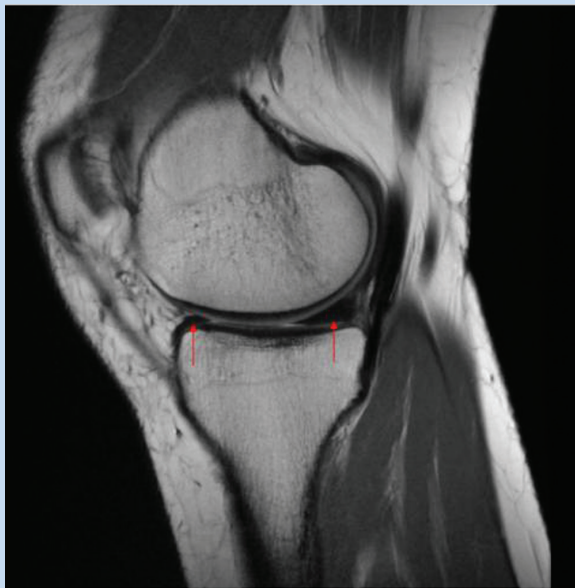


Figure 9. A sagittal magnetic resonance (proton-density) image of a healthy knee depicting the medial menisci (arrows). The concave superior meniscal surface improves contact with the femoral epicondyles, and a flat undersurface improves contact with the tibial plateau. The periphery is thicker than the central portion, allowing for firm attachment to the joint capsule.

the menisci. MRI is widely accepted as the optimal imaging modality because of superior soft tissue contrast.

On cross-sectional MRI, the normal meniscus appears as a uniform low-signal (dark) triangular structure (Figure 9). A meniscal tear is identified by the presence of an increased intrameniscal signal that extends to the surface of this structure.

Several studies have evaluated the clinical utility of MRI for meniscal tears. In general, MRI is highly sensitive and specific for tears of the meniscus. The sensitivity of MRI in detecting meniscal tears ranges from 70% to 98%, and the specificity, from 74% to 98%.^{48,62,105,107,117} The MRI of 1014 patients before an arthroscopic examination had an accuracy of 89% for pathology of the medial meniscus and 88% for the lateral meniscus.⁴⁸ A meta-analysis of 2000 patients with an MRI and arthroscopic examination found 88% sensitivity and 94% accuracy for meniscal tears.^{105,107}

There have been discrepancies between MRI diagnoses and the pathology identified during arthroscopic examination.^{†††} Justice and Quinn reported discrepancies in the diagnosis of 66 of the 561 patients (12%).⁸⁶ In a study of 92 patients, discrepancies between the MRI and arthroscopic diagnoses were noted in 22 of the 349 (6%) cases.¹⁰⁶ Miller conducted a

single-blind prospective study comparing clinical examinations and MRI in 57 knee examinations.¹¹⁷ He found no significant difference in sensitivity between the clinical examination and MRI (80.7% and 73.7%, respectively). Shepard et al assessed the accuracy of MRI in detecting clinically significant lesions of the anterior horn of the meniscus in 947 consecutive knee MRI¹⁵⁴ and found a 74% false-positive rate. Increased signal intensity in the anterior horn does not necessarily indicate a clinically significant lesion.¹⁵⁴

CONCLUSIONS

The menisci of the knee joint are crescent-shaped wedges of fibrocartilage that provide increased stability to the femorotibial articulation, distribute axial load, absorb shock, and provide lubrication to the knee joint. Injuries to the menisci are recognized as a cause of significant musculoskeletal morbidity. Preservation of the menisci is highly dependent on maintaining its distinctive composition and organization.

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