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Review of Meniscus Anatomy and Biomechanics

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Abstract

Purpose of Review Anatomic repair of meniscal pathology is critical for restoring native joint biomechanics and kinematics for patients who suffer from meniscal tears. The purpose of this review was to summarize the pertinent anatomy, biomechanics, and kinematics of the meniscus to guide surgeons during meniscal repair procedures.

Recent Findings Over the past decade, there has been a growing trend to save the meniscus whenever possible. The goal of repair should be to recreate native anatomy as close as possible to recapitulate normal mechanics. Studies describing the quantitative and qualitative relationship of the meniscus roots, ligaments, and attachments are key in guiding any meniscus repair. This review summarizes these relationships, with particular emphasis on meniscal roots and other key attachments to the meniscus. The composition, embryology, vascularization, biomechanics, in vivo kinetics, and in vivo kinematics of the meniscus are also discussed in this review.

Summary Meniscal tears can cause profound functional, biomechanical, and kinematic derangements within the knee joint leading to accelerated degeneration of the articular cartilage. A strong understanding of the quantitative and qualitative relationships of the meniscus and its attachments with key arthroscopic landmarks will allow a surgeon to anatomically repair meniscal pathology in order to restore native joint biomechanics.

Keywords Meniscus · Anatomy · Knee

Introduction

The menisci are crescent-shaped, fibrocartilaginous structures with wedge-like cross sections that function to deepen the tibial plateau, transmit load through the joint, provide shock absorption, and increase knee joint stability [1–3]. In order to improve congruence between the rounded femoral condyle and the flat tibial plateau, the menisci have a concave superior surface to accommodate the femoral condyle's convex surface as well as a flat inferior surface to match the relatively flat tibial plateau [4]. The wedge shape of the meniscus allows it to optimize the transmission of axial loads through the joint and minimize peak contact pressures on articular cartilage surfaces by improving the joint contact area between the flat tibial plateau and rounded femoral condyle [4]. Additionally, its elasticity allows it to function as a shock absorber within the joint [4]. As a result, any deficiency of the meniscus can lead to accelerated degenerative changes and resection of as little as 10% of the meniscus can contribute to the development of chondral lesions as well as decreased subjective and objective clinical outcome measures [4, 5]. In addition to its role in minimizing articular cartilage contact pressures, the menisci also function as secondary stabilizers of the knee. The medial meniscus mainly contributes to anteroposterior translation, while the lateral meniscus helps resist rotary motion [4]. The purpose of this review was to summarize the key

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clinically relevant anatomy and biomechanical principles of the medial and lateral meniscus to guide surgeons in evaluating and managing meniscal pathology.

Meniscus Anatomy

The medial meniscus measures approximately 45.7 mm in length and 27.4 mm in width [1, 6]. Its width decreases from posterior to anterior and has been reported to range from 12.6 to 17.4 mm in the posterior third, 9.3 to 12.2 mm in the middle third, and 7.6 to 9.0 mm in the anterior third of the medial meniscus [7, 8, 9••, 10]. The thickness of the medial meniscus is relatively consistent from anterior to posterior and ranges from 5.2 to 6.9 mm in thickness over the entire meniscus [4, 7, 10]. The medial meniscus can also be divided into five anteroposterior zones (Fig. 1) [11–13]. This includes the anterior root attachment (zone 1), the anteromedial zone between the posterior border of the anterior root and the anterior border of the superficial medial collateral ligament (zone 2A and 2B), the portion of the meniscus that is adjacent to the superficial medial collateral ligament (zone 3), the posterior horn (zone 4), and the posterior root (zone 5). Of clinical note, zone 4 is the most common location for meniscal tears and is the location where meniscal repair is most commonly performed [4, 9••, 14, 15]. Anatomic studies have demonstrated that the medial meniscus covers between 51 and 74% of the medial tibial plateau surface area [2, 16, 17]. A study by Bloecker et al. attempted to examine this property using MRI and found that the medial meniscus covered 50% of the medial tibial plateau [18].

The lateral meniscus measures approximately 35.7 mm in length and 29.3 mm in width [6]. Unlike the medial meniscus, the width of the lateral meniscus is relatively consistent across the entire structure for a given specimen [4]. It has been reported to range from 9.8 to 12.0 mm in the posterior third, 10.0 to 12.5 mm in the middle third, and 10.0 to 11.9 mm in the anterior third of the meniscus [7, 10, 19]. The lateral meniscus is thinner on the anterior third, where it ranges from 3.8 to 4.73 mm in thickness [7, 10, 19]. The thicker middle third and posterior third range from 5.9 to 6.5 mm and 5.3 to 6.2 mm in thickness, respectively [7, 10, 19]. The lateral meniscus can be classified into six zones based on anteroposterior location (Fig. 1) [13]. These include the anterior root (zone 1), the anterolateral zone between the anterior root and the anterior border of the popliteal hiatus (zones 2A and 2B), the popliteal hiatus (zone 3), the posteroinferior popliteomeniscal fascicle (zone 4), the ligamentous zone (zone 5), and the posterior root (zone 6). Anatomic studies have demonstrated that the lateral meniscus covers between 75 and 93% of the lateral tibial plateau surface area [2, 16, 17]. The MRI study by Bloecker et al. found that the lateral meniscus covered 59% of the lateral tibial plateau [18].

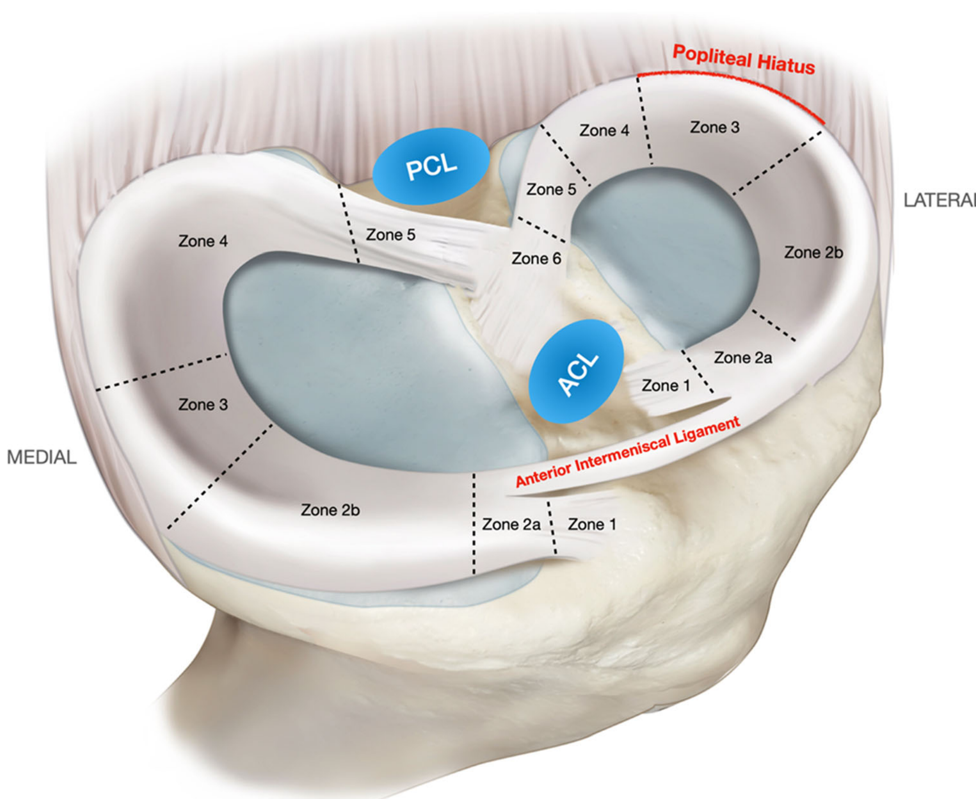

Fig. 1 Medial and lateral meniscus zones and relevant anatomical relations. ACL, anterior cruciate ligament; PCL, posterior cruciate ligament

The menisci are attached to the tibial plateau via their anterior and posterior roots and are stabilized by the medial collateral ligament, the transverse ligament, the meniscotibial ligaments, and the meniscofemoral ligaments [2, 20]. The roots of the meniscus are ligamentous-like structures with fibrocartilaginous entheses [20]. They are essential to function as they anchor the meniscus to convert axial loads into hoop stresses and prevent extrusion during joint loading [21]. The meniscotibial ligament anchors the entire outer margin of the medial meniscus to the medial tibial plateau [4]. The medial meniscus also has attachments to the posterior oblique ligament and the posteromedial capsule [4]. The majority of the outer border of the lateral meniscus is attached to the lateral tibial plateau by the meniscotibial ligament [4]. The lateral meniscotibial ligament is thinner and more elastic than the medial meniscotibial ligament [4]. Additionally, the crossing of the popliteus tendon partially disrupts this circumferential attachment [4]. Together, these properties allow the lateral meniscus to have increased translation and mobility relative to the more static medial meniscus [22].

Roots of the Meniscus

An understanding of the anatomy of the roots is critical to clinical practice as non-anatomic repairs can compromise meniscal function (Fig. 3) [23]. Structurally intact meniscal roots preserve the meniscus' biomechanical ability to convert axial loads to hoop stresses, prevent extrusion, and decrease the load placed on the articular cartilage [24••]. An avulsed meniscal root leads to an inability to convert compressive loads into hoop stresses and also leads to extensive extrusion from the joint (Fig. 2) [25]. Biomechanically, this leads to increased contact pressures on the articular cartilage that is comparable to the forces in a knee after a total meniscectomy [26••, 27, 28••]. Clinically, this presents as a rapid progression of osteoarthritis [24••, 28••]. Additionally, these previously underdiagnosed tears have been implicated as pathologic contributors to subchondral insufficiency fractures of the knee [29].

Subsequent studies have demonstrated the clinical benefit to an anatomic meniscal root repair. For example, a recent meta-analysis by Perry et al. demonstrated that anatomic repair of medial meniscal posterior root tears leads to significantly improved biomechanical and clinical outcomes [30•]. Furthermore, the results from a separate study by Krivicich et al. suggested that root repair significantly delays the progression of osteoarthritis and conversion to subsequent total knee arthroplasty at 5-year follow-up [31]. Taken together, these findings underscore the clinical importance of an anatomic root repair and a strong understanding of the relevant surrounding arthroscopic anatomy.

A 2012 study by Johannsen et al. attempted to quantify the anatomic relationships between the posterior root of the medial meniscus and the key arthroscopic anatomic landmarks within the knee [28••]. They found this structure to have an average surface area of 30.4 ± 2.9 mm^2. The posterior root was 9.6 ± 0.8 mm posterior to the medial tibial eminence apex, 0.7 ± 0.4 mm lateral to the medial tibial eminence apex, and 6.0 ± 0.6 mm inferior to the medial tibial eminence apex. Its direct distance was 11.5 mm from the medial tibial eminence apex. The root was 3.5 ± 0.4 mm lateral to the medial articular edge inflection point and 8.2 ± 0.7 mm from the nearest border of the PCL tibial insertion site. The shiny white fibers of the posterior horn of the medial meniscus had an average surface area of 47.3 ± 4.4 mm^2. These fibers constitute a large portion of the overall footprint of the posterior root, ranging from 38.8 to 60.8% of the attachment, and are in close proximity to the PCL attachment, raising the issue of potential iatrogenic damage during PCL tibial tunnel drilling (Fig. 3) [4, 28••].

This study by Johannsen et al. also quantified the anatomic relationships between the posterior root of the lateral meniscus and the surrounding key anatomic structures within the knee [28••]. This root was found to have an average surface area of 39.2 ± 2.4 mm^2. The posterior root was 5.3 ± 0.3 mm from the lateral tibial eminence apex. More specifically, it was 4.2 ± 0.4 mm medial, 1.5 ± 0.7 mm posterior, and 1.4 ± 0.2 mm inferior to this landmark. The posterior root was reported to be 4.3 ± 0.5 mm medial to the lateral articular cartilage border, 12.7 ± 1.1 mm anterior to the posterior cruciate ligament proximal border, and 10.1 ± 0.8 mm from the posterior border of the anterior root of the lateral meniscus.

A 2014 cadaveric study by LaPrade et al. attempted to quantify the anatomical relationships of the anterior medial and lateral roots relative to the critical open and arthroscopic landmarks of the knee [24••]. The authors noted that the anterior medial meniscal root was composed of central, dense fibers as well as supplemental fiber extensions. For the medial meniscus, the central anterior root attachment was 56.3 ± 14.9 mm^2, and it was 140.7 ± 30.0 mm^2, when including the central, dense root along with the supplemental fiber extensions. Relative to open anatomic landmarks, LaPrade et al. demonstrated that the anterior meniscal root was 29.8 ± 2.7 mm proximal to the medial aspect of the tibial tuberosity and 27.0 ± 1.9 mm proximal to the center of the superior edge of the tibial tuberosity. Relative to crucial arthroscopic landmarks, the anterior medial meniscal root was 18.2 ± 2.9 mm anteromedial to the center of the ACL, 9.2 ± 2.7 mm anteromedial to the nearest edge of the ACL, 7.6 ± 2.3 mm anterolateral from the closest edge of the medial tibial plateau articular cartilage, and 32.8 ± 4.1 mm anterior to the nearest edge of the posterior medial meniscal root insertion.

LaPrade et al. also quantified the relationships of the anterior lateral meniscal root relative to the surrounding relevant open and arthroscopic knee anatomy [24••]. The authors noted

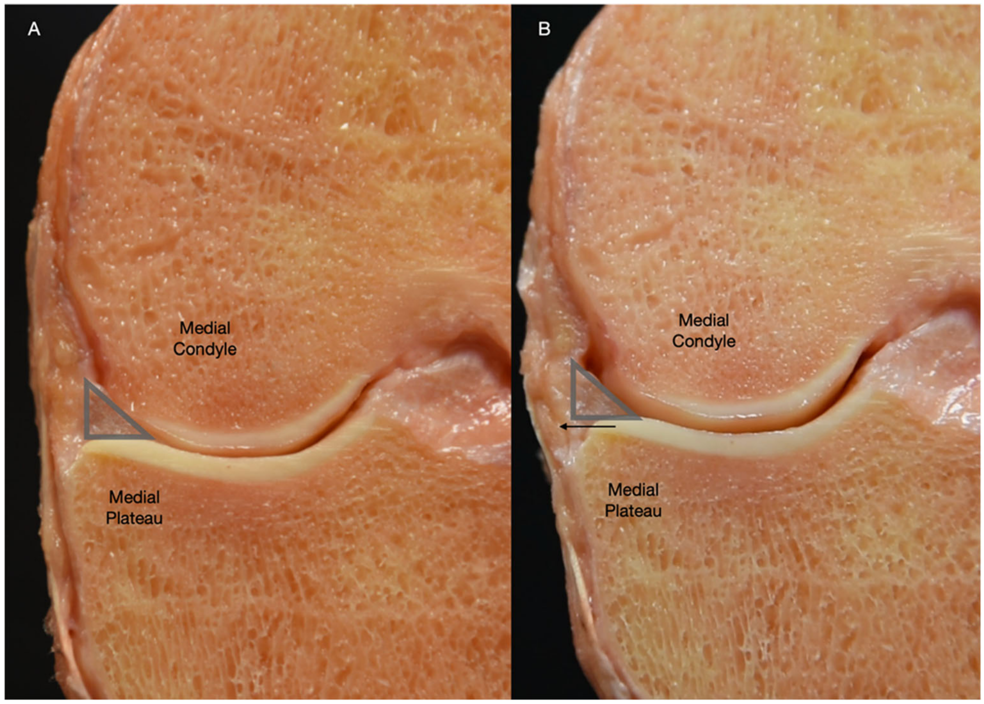

Fig. 2 Cadaveric representation of intact medial meniscus posterior root (**A**) and root tear (**B**), with significant medial extrusion (black arrow) of the meniscus (gray triangle) in the root tear state

that in all twelve specimens that they examined, this root contained fibers that inserted deep beneath the tibial insertion site of the ACL. Additionally, they noted that the anterior lateral root was completely composed of fibers that had the same density, meaning the entire root was composed only of central fibers. The anterolateral root tibial insertion had an area of 140.7 ± 30.0 mm^2, shared a common insertion with the ACL tibial attachment site, and overlapped with the ACL insertion by an average of 88.9 ± 40.8 mm^2. This overlap is approximately 63.2% of the entire anterior lateral meniscal

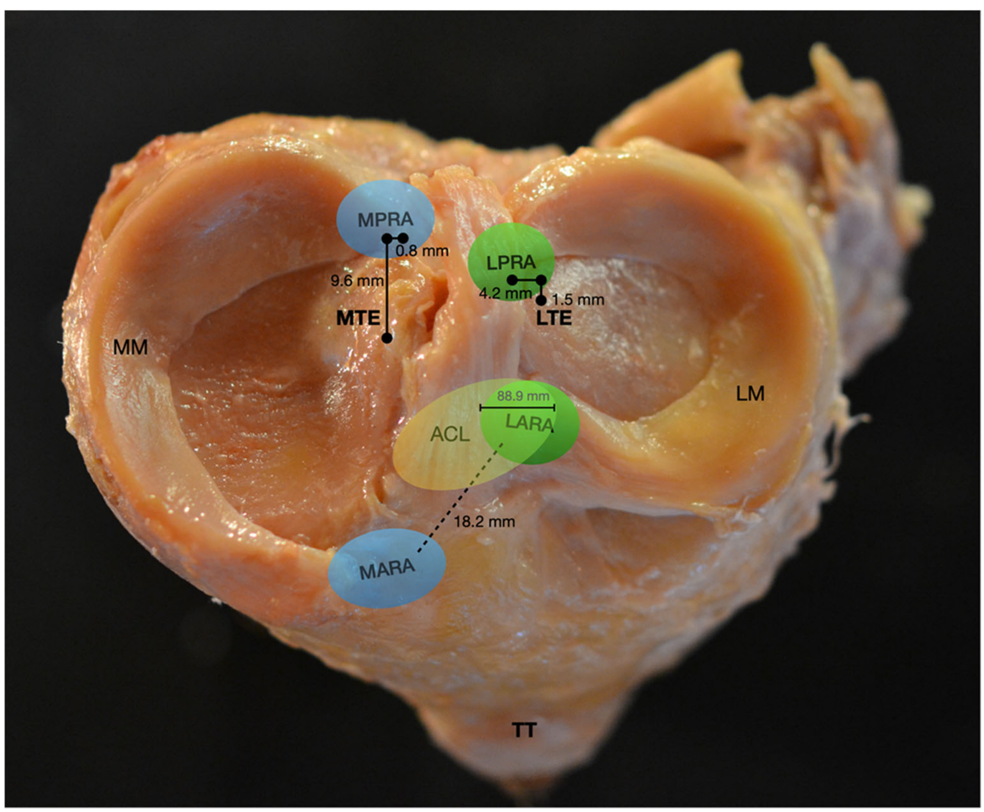

Fig. 3 Anatomical relations of medial and lateral meniscal roots. MARA, medial anterior root attachment; LARA, lateral anterior root attachment; MPRA, medial posterior root attachment; LPRA, lateral posterior root attachment; MM, medial meniscus; LM, lateral meniscus; MTE, medial tibial eminence; LTE, lateral tibial eminence; ACL, anterior cruciate ligament; TT, tibial tuberosity

root and 40.7% of the ACL tibial insertion site, suggesting that anterior lateral meniscal root damage during anatomic ACL reconstruction may be unavoidable during tibial tunnel drilling. Quantitatively, the anterior lateral meniscal root was 14.4 ± 2.2 mm anteromedial to the apex of the lateral tibial eminence, 5.0 ± 1.8 mm anterolateral to the center of the ACL tibial insertion, 7.1 ± 1.3 mm anterior medial to the nearest articular cartilage edge of the lateral tibial plateau, and 13.4 ± 2.1 mm anterior to the closest edge of the posterior lateral root. The anterior lateral and medial meniscal roots were found to be 18.0 ± 3.3 mm apart from each other.

Anterior Intermeniscal Ligament

The anterior intermeniscal ligament connects the anterior horns of the medial and lateral menisci (Fig. 1) [4]. It is on average 33 mm long and 3 mm in width [4]. LaPrade et al. noted that the anterior intermeniscal ligament was only present in six of the twelve included knees for their cadaveric study [24••]. For these six knees, the authors reported that the center of the anterior medial meniscal root was 11.4 ± 1.9 mm from the center of the medial attachment of the anterior intermeniscal ligament. Additionally, the anterior intermeniscal ligament was attached to the posteromedial aspect of the anterior medial meniscal horn in all included specimens. Relative to the center of the anterior lateral meniscal root, the center of the lateral attachment of the anterior meniscal ligament was 19.2 ± 4.4 mm apart. The anterior meniscal ligament was also found to be attached to the anterolateral aspect of the anterior root of the lateral meniscus in all six specimens with this ligament.

While the function of this ligament is not clear, several theories have been proposed. Some have theorized that the ligament has a potential role as a stabilizer of meniscal translation through knee motion and a neurologic role in sensorimotor function of the knee [32, 33]. Additionally, sectioning of this ligament has led to an increase in tibiofemoral contact pressures in a prior biomechanical study [33]. Beyond the anterior intermeniscal ligament, three other ligaments can connect the menisci together: these are the medial oblique ligament, lateral oblique intermeniscal ligament, and posterior intermeniscal ligament [4].

Attachments to the Posterior Horn of the Medial Meniscus

When examining posterior medial meniscal attachments, key anatomic structures include the posterior meniscocapsular attachment, posterior meniscotibial ligament, the posterior oblique ligament, the deep medial collateral ligament, and the semimembranosus. An anatomic study by DePhillipo et al. attempted to quantify the relative attachments of the posterior medial meniscus anatomy [9••]. The authors noted that the posterior horn of the medial meniscus has an average length of 21.3 ± 2.0 mm and the posterior meniscocapsular attachment had an average length of 20.2 ± 6.0 mm.

The meniscotibial ligaments circumferentially anchor the peripheral margin of the medial and lateral meniscus to the edge of the tibial condyle [4]. The medial meniscotibial ligament is a relatively thicker and stronger structure and restricts the relative mobility of the medial meniscus. The study by DePhillipo et al. described the anatomic attachments of the medial meniscotibial ligament [9••]. The authors noted that the ligament in the middle third has a length of 17.7 mm and attaches 6.4 mm inferior to the articular cartilage margin. At the region of the posterior horn, DePhillipo et al. reported the ligament has a length of 14 mm and attached 5.9 mm inferior to the articular margin. Finally, adjacent to the posterior oblique ligament, they noted that the ligament had a length of 9 mm and attached 6.7 mm inferior to the margin of articular cartilage. The medial meniscotibial ligament joins the posterior capsule to form a conjoined attachment onto the posterior horn of the meniscus [4]. Disruption of the medial meniscotibial ligament is called a ramp lesion when it is adjacent to the posterior horn of the medial meniscus (Fig. 4) and can lead to translation of the medial meniscus with varus/valgus stress and anteromedial rotatory instability [4, 34–36].

The posterior oblique ligament (POL) consists of two structures. The POL meniscofemoral ligament attaches the meniscus to the femur, has a length of 8.2 ± 2.1 mm, and attaches 34.1 ± 6.7 mm from the posterior medial meniscal root [9••]. The POL meniscotibial ligament attaches the medial meniscus to the tibia, has a length of 9.0 ± 2.3 mm, and attaches 6.7 ± 1.7 mm inferior to the medial plateau articular cartilage margin [9••]. The midbody of the medial meniscus is firmly attached to the deep medial collateral ligament (dMCL). The dMCL blends with the POL meniscofemoral ligament and the anteromedial capsule. It has a meniscofemoral component and a meniscotibial component. Its meniscofemoral attachment has a mean length of 14.8 ± 3.8 mm and a center that is 45.9 ± 7.0 mm medial to the center of the posterior medial meniscal root [9••]. The meniscotibial component of the dMCL was 17.7 ± 3.4 mm long and inserted 6.4 ± 1.9 mm inferior to the lateral tibial plateau articular cartilage margin [9••]. Finally, the anterior arm of the semimembranosus tendon had a fascial attachment to the medial meniscus that is 9.2 ± 2.1 mm in length [9••]. It was located between the posterior meniscotibial ligament and the POL meniscotibial ligament, and it inserts onto the posterior inferior margin of the medial meniscus [9••].

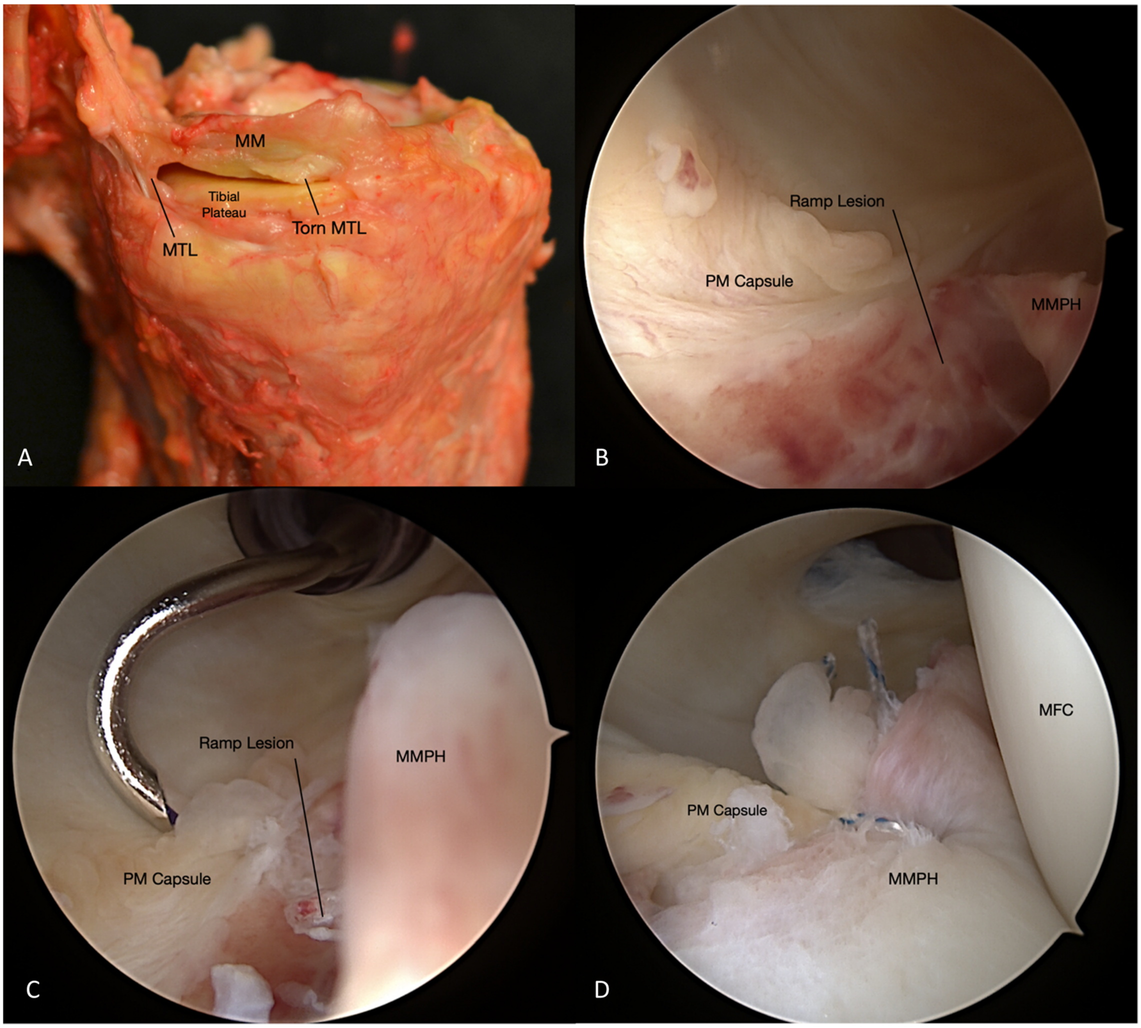

Fig. 4 Cadaveric right knee specimen with a representation of a disrupted meniscotibial ligament at the posterior horn of the medial meniscus—or ramp lesion (**A**). Modified Guilquist arthroscopic view of a left knee ramp lesion (**B**), sutured with an all-inside all-suture technique via instrumentation through the posteromedial portal (**C** and **D**). MM, medial meniscus; MTL, meniscotibial ligament; MMPH, medial meniscus posterior horn; MFC, medial femoral condyle; PM, posteromedial

Attachments to the Posterior Horn of the Lateral Meniscus

An understanding of the anatomy of the lateral meniscal attachments is critical as tears to the posterior horn of the lateral meniscus are challenging to manage due to its inherent increased mobility [37•]. The lateral meniscotibial ligament has a length of 12.8 ± 3.9 mm [37•]. It is thinner and more elastic relative to the medial side, and it also lacks the discrete thickenings seen on the medial meniscotibial ligament [4]. It is also absent throughout the popliteal hiatus [37•, 38, 39]. These properties make the lateral meniscus inherently more mobile than the medial meniscus. The posterolateral capsule attachment attaches to 11% of the total height of the posterior horn of the lateral meniscus and is 7.6 ± 2.5 mm superior to the tibial articular cartilage margin [37•]. The superior aspect of the popliteal hiatus has an average length of 12.1 ± 2.5 mm with its center beginning 33.6 ± 3.7 mm from the center of the lateral meniscal posterior root [37•]. The inferior aspect of the popliteal hiatus has a curved length of 36.9 ± 6.0 mm and begins 22.8 ± 4.2 mm from the center of the lateral meniscal posterior root [37•].

Additional attachments to the lateral meniscus include the popliteomeniscal fascicles, the meniscofibular ligament, and the meniscofemoral ligament. The popliteomeniscal fascicles are stout attachments from the popliteal tendon that insert onto the lateral meniscus [37•]. There are three popliteomeniscal fascicles: anteroinferior, posterosuperior, and posteroinferior [37•, 38–42]. The anteroinferior fascicle was 8.0 ± 1.9 mm long and attaches 4.6 ± 2.3 mm superior to the tibial articular cartilage margin [37•]. The posterosuperior fascicle was 6.5 ± 1.5 mm long and attaches 6.2 ± 1.9 mm superior to the tibial articular cartilage margin [37•]. The posteroinferior fascicle courses from the inferior margin of the lateral meniscus to the popliteal fascia in a posterior and distal direction, although it is not visualized during arthroscopy and its existence is disputed by some authors. The anteroinferior fascicle forms the floor of the popliteal hiatus, while the posterosuperior fascicle forms the roof of the popliteal hiatus [4]. Together, these fascicles work to prevent medial translation of the lateral meniscus, and injuries to these structures will lead to medial subluxation of the meniscus, lateral sided knee pain, and mechanical symptoms like locking [22, 43]. Injuries to these structures often occur with concomitant anterior cruciate ligament (ACL) and posterolateral corner (PLC) injuries [37•].

The meniscofibular ligament originates from the lateral meniscus and inserts into the fibular head, just anterior to the popliteus muscle origin [4]. It has been reported to have a width that ranges from 8 to 13 mm, a length that ranges from 13 to 22 mm, and a mean thickness of 3.84 mm [44, 45]. It has an unclear function and is believed to help the lateral meniscotibial ligament control anteroposterior translation and external rotation of the lateral meniscus [4]. It may also have a role as a secondary restraint to varus and external rotation of the knee joint [4].

Finally, there are two meniscofemoral ligaments: the ligament of Humphrey, which is the anterior meniscofemoral ligament, and the ligament of Wrisberg, which is the posterior meniscofemoral ligament [13, 46–49]. The ligament of Humphrey passes anterior to the posterior cruciate ligament, and the ligament of Wrisberg passes posterior to the posterior cruciate ligament [4]. The anterior meniscofemoral ligament attaches 5.5 ± 2.9 mm from the center of the posterior root of the lateral meniscus, and the posterior meniscofemoral ligament attaches 11.5 ± 4.4 mm from the center of the posterior root of the lateral meniscus [37•]. The meniscofemoral ligaments function to connect the lateral meniscal posterior horn to the lateral border of the medial femoral condyle [4]. Biomechanically, they contribute to preventing lateral meniscus extrusion as well as provide a secondary restraint to posterior tibial translation [48, 49].

Microstructure

The menisci are composed of roughly 70% water and 30% organic material [50]. More specifically, water comprises approximately 65–72%, collagen 20–25%, and proteoglycans <1% of the total menisci [51]. The composition of water is highest in the posterior horns of the menisci as compared to the central or anterior portions, which is thought to generate a drag force during compressive loads [52]. Furthermore, water is attracted to the negatively charged meniscal extracellular matrix (ECM), which is a dense network of cross-linked collagen and intermixed proteoglycans [51].

Overall, collagen composes 75% of the dry weight of the menisci [51, 52]. Type I collagen predominates (with variable amounts of types II, III, V, and VI) and provides the primary structural framework of the meniscus [52, 53•]. The surface of the meniscus is comprised of randomly oriented collagen fibers to minimize friction and exhibit a smooth articulating surface [51]. While the superficial layer of the meniscus is comprised of radially oriented type I collagen fibers, the deep layer is made up of circumferentially oriented type I collagen fibers [50, 51]. This specific arrangement of fibers acts to convert compressive loads into circumferential stresses during weight bearing [50]. Additionally, there are "tie" fibers occasionally oriented radially throughout the deep layer that weave through the circumferential fibers and prevent longitudinal splitting [52, 53•].

Proteoglycans comprise less than 1% of the ECM but serve an important role. These large hydrophilic molecules attract water for fluid transmission, thus reducing compressive strain and injury to the meniscus [51]. The most common proteoglycan is aggrecan, which is responsible for the viscoelastic compressive property of the menisci [53•]. Other smaller proteoglycans known to exist include decorin, biglycan, and fibromodulin, but the exact function of these molecules are still unclear [53•]. These proteoglycans are made up of a core protein that is attached to one or more glycosaminoglycans [51]. The concentration of glycosaminoglycans is higher in the horns and periphery of the meniscus due to their weight-bearing nature [53•].

Embryology

During gestation, the menisci form from the intermediate layer of the mesenchymal tissue and differentiate within the limb bud [51, 54]. The normal menisci can be defined by week 8 of gestation and form its mature anatomic shape by week 14 [16]. Throughout prenatal development, the menisci are highly vascularized and receive vessels from the capsular and tibial attachments to the inner third of the menisci. During this time, the meniscus remains highly cellular with a large nuclear/cytoplasmic ratio [16, 55, 56].

After birth, the vascularity and cellularity of the menisci gradually recedes as the collagen content continues to increase [51]. By 9 months of life, the central third of the meniscus is avascular, and by 10 years of age, the vascularity and structure resemble that of an adult knee [16, 57]. While this transition is gradual over the first decade of life, the lateral meniscus demonstrates more variability throughout development [16]. Occasionally, this variability leads to alternations in the organization of the collagen fibers and can result in a hypertrophic, discoid, or unstable lateral meniscus. However, in most cases, as the menisci grow, the ratio of the area of each meniscus to the area of the corresponding tibial plateau, as well as the ratio of the area of the medial meniscus to the lateral meniscus, remain fairly consistent and uniform [16].

Vascularization

The blood supply to the menisci is supplied by branches of the medial inferior, lateral inferior, and middle geniculate arteries that penetrate the knee joint capsule [51]. These branches constitute a surrounding perimeniscal capillary plexus that penetrate to a depth of 2–3 mm within the menisci, roughly 20–30% of the periphery of the medial meniscus, and 10–25% of the periphery of the lateral meniscus [1, 3, 58]. Consequently, the remainder of the avascular central meniscus receives nutrition through the diffusion of the synovial fluid [51, 59]. Contrarily, the anterior and posterior meniscal roots are supplied through endoligamentous vessels formed through capillary loops [52, 56, 60••].

Two distinct vascular distributions supply the menisci. Firstly, branches from the perimeniscal vascular plexus penetrate the meniscal stroma in a radial fashion. Penetration of the substance of the medial meniscus by these radial branches ranges from 10 to 30% of the meniscal width and is greater in the anterior horn and midbody than in the posterior horn [60••, 61]. For the lateral meniscus, radial vessels penetrate 10 to 25% of the width of the stroma and show no significant difference when comparing the anterior horn, midbody, and posterior horn regions (Fig. 5) [60••, 61]. A second, distinct vascular synovial fringe extends on both the femoral and tibial surfaces of the menisci [60••, 61, 62]. This fringe is predominantly in the anterior horns of the medial and lateral menisci, where it covers up to 100% of the femoral surface and up to 50% of the tibial surface [60••]. The vascular fringe is also present in the posterior horns of the medial and lateral menisci, albeit, to a lesser degree. It covers up to 40% of both surfaces of the posterior horn of the lateral meniscus and 25% of both surfaces of the posterior horn of the medial meniscus [60••]. On the femoral and tibial surfaces of the midbody of both medial and lateral menisci, a 1 to 2 mm vascular fringe is present [60••]. Of note, the region of the popliteal hiatus is devoid of both penetrating radial vessels and devoid of a vascular fringe [52, 60••, 61].

The relatively avascular nature of the meniscus has led to the categorization of the red-red, red-white, and white-white zone. The red-red zone represents the vascular peripheral region supplied directly by the perimeniscal capillary plexus and includes thick ligamentous structures with attachments to the joint capsule [1, 20]. The white-white central zone is avascular and represents the thin, concave cartilaginous region of the central menisci with unattached free edges. The red-white intermediate zone is located between the red-red periphery and white-white central region and has characteristics of these other two zones [1]. This arrangement translates to the central two-thirds to three quarters of the meniscus being essentially avascular and receiving nutrition through diffusion from the synovial fluid [60••, 63].

It has been reported that meniscal tears will have different healing potential according to the involved vascular zone [52, 61, 64]. Tears in the red-red and, to some extent, the red-white zones are recognized as having an acceptable healing potential, so repair is frequently indicated. In contrast, tears in the white-white zone were traditionally thought to have poor healing potential and thus were not normally considered amenable to being repaired

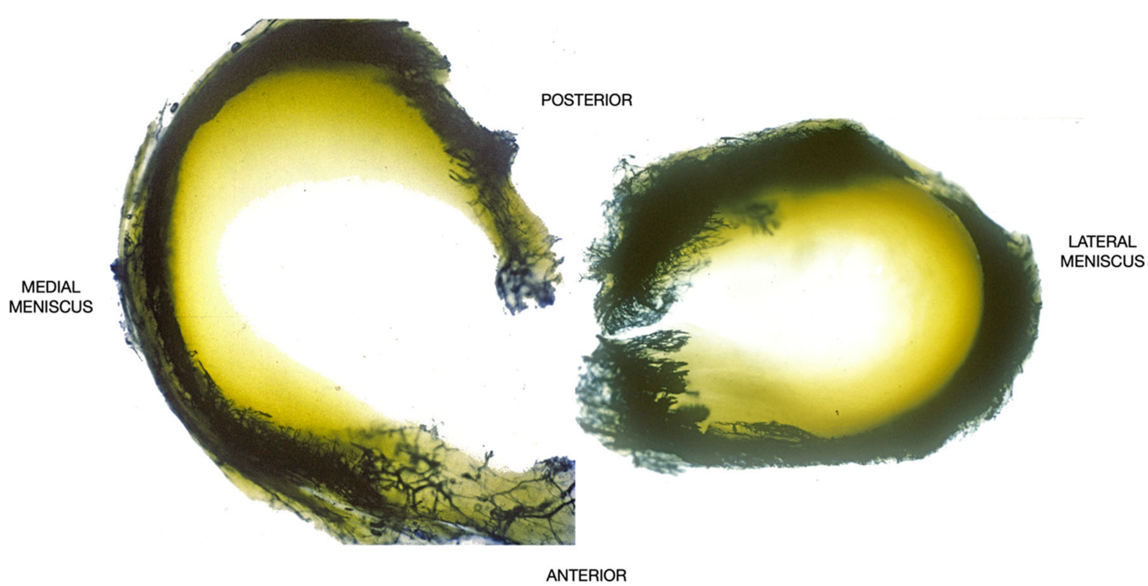

Fig. 5 Superior view of microvascular anatomy of the menisci on India ink vascular injection. The peripheral 10 to 30% of the medial meniscus and the peripheral 10–25% of the lateral meniscus are perfused—with interrupted perfusion on the popliteal hiatus. Figure adapted from Evidence Based Management of Complex Knee Injuries [4]

successfully, so a partial meniscectomy tended to have been indicated for these tears [61]. Current treatment algorithms heavily rely on these concepts; nevertheless, a recent study by Chahla et al. demonstrated the presence of multipotent mesenchymal stromal progenitor cells and vascularization in the white-white zone of the meniscus, which may indicate that tears in this region could have a better healing potential than previously thought [65]. The results of this study would suggest a potential benefit in pursuing repair with biologic augmentation for tears in the white-white zone of the meniscus in young, healthy, and active patient cohorts. Furthermore, the results of another recent study by Cinque et al. supported this notion and demonstrated a significant subjective clinical benefit to repairing meniscal tears in the white-white zone [66].

Biomechanics

The load distribution properties of the meniscus allow for greater contact area and decreased contact pressures within the tibiofemoral joint [67]. This is particularly important in the lateral compartment, where 70% of the load is transmitted to the lateral meniscus, compared to 50% in the medial compartment, due to the larger role of the lateral meniscus in joint congruity [67]. In addition to Ahmed and Burke's study, which demonstrated a 50–70% decrease in contact area and subsequent increase in contact pressures following medial meniscectomy, numerous recent laboratory studies have further demonstrated the effects of various meniscal pathologies on knee joint biomechanics, kinetics, and kinematics [68].

Biomechanical Effect of Meniscus Pathology

Vertical meniscal tears run parallel to the circumferential ECM fibers and are less likely to disrupt the meniscus' biomechanical function as these tears typically do not compromise the meniscus' ability to convert axial loads into hoop stresses. For example, a cadaveric study from Goyal et al. found no difference in contact pressures between specimens with an intact lateral meniscus compared to specimens with an artificially created vertical tear [69]. While this may be true in the body of the meniscus, vertical tears in the horns of the meniscus may be more problematic. A recent finite element analysis study by Zhang et al. demonstrated that vertical tears at the horns of the menisci increase peak compressive and shear stresses on the menisci, cartilage, and subchondral bone in both static and dynamic-flexion simulations [70]. The authors reported more meaningful biomechanical alterations following tears in the medial meniscus and tears in the posterior horn. This is further corroborated by Chen et al.'s cadaveric study, which demonstrated impaired contact pressure after longitudinal tearing of the medial meniscus [71].

Like vertical tears, horizontal cleavage tears do not disrupt the circumferential collagen fibers. However, horizontal cleavage tears do have a higher correlation with altered biomechanics. In a 2017 cadaveric study, Beamer et al. reported a 70% increase in contact pressures across all flexion angles [72]. Furthermore, when managing this tear pattern with partial meniscectomy, prior studies have demonstrated that resection of one medial meniscal leaflet increased contact pressures by 33–46%, while resection of both leaflets increased pressure by 75–79% [73, 74].

Radial tears are tears that extend perpendicularly across the circumferential collagen fibers and can disrupt the meniscus ability to convert loads into hoop stresses. Large radial tears and root tears can be functionally equivalent to a total meniscectomy because they fully disrupt the meniscus' circumferential collagen fibers leading to functional failure of the meniscus [75]. In the setting of partial radial tears, the meniscus retains a degree of its inherent biomechanical function. Cadaveric studies have demonstrated that partial tears up to 60–66% of the meniscal width have little/no impact on the meniscus load dissipating properties [76, 77].

Like radial tears, meniscal root tears are also functionally equivalent to a total meniscectomy. The meniscal roots anchor the menisci to the tibia in order to prevent extrusion and facilitate meniscal function [4]. Similar to radial tears, root tears also leave the meniscus unable to convert axial loads into hoop stresses [75]. This tear pattern leads to total functional failure of the meniscus and places the knee joint at high risk for accelerated degenerative changes and impaired biomechanics/kinematics. A controlled cadaveric study by Allaire et al. demonstrated that meniscal root tears allow for increased lateral tibial translation (LTT) and increased knee adduction angles (KAA) [26••]. These findings appear to translate to in vivo kinematics. A study by Marsh et al. demonstrated that medial meniscus root dysfunction significantly increased LTT during level walking, decline walking, and squatting [78]. Additionally, a study by Ishii et al. used inertial motion sensors to assess gait in patients with meniscal root dysfunction, reporting a positive correlation between the magnitude of increment in meniscal extrusion during weight-bearing and increased knee lateral thrust [79]. Varus thrust has long been recognized as risk factor for progression of medial compartment cartilage lesions and progression of knee osteoarthritis [80, 81]. A varus thrust gait pattern is the prime feature of one of four distinct gait patterns for severe knee osteoarthritis as described by Leporace et al., which the authors deem as a more significant feature than peak joint angles [82].

Impact on In Vivo Knee Kinetics

The knee adduction moment (KAM) is a well-established kinetics measure that correlates with medial compartment loading of the knee during weight-bearing activities [83, 84]. KAM is a product of both the ground force acting on the knee joint during the stance phase and the perpendicular distance that this force acts from the center of the joint. A larger KAM leads to increased varus thrust and results in increased medial joint loads, which are directly correlated with medial compartment articular cartilage thickness and progression of knee osteoarthritis [85].

The meniscus plays an important role in normalizing the KAM experienced within the knee joint. Thorlund et al. assessed 3-D gait analysis of 23 patients with a medial meniscus tear without radiographic knee osteoarthritis, before and 1 year after partial meniscectomy. Despite a significant improvement in Knee Injury and Osteoarthritis Outcome Scores (KOOS), there was a consistent increase in peak KAM after meniscectomy in comparison to the contralateral limb [86•]. Furthermore, Hall et al. reported an increase in the peak knee flexion moment (KFM) in a 2-year follow-up of partial meniscectomies [87]. The combination of these studies further implicates meniscectomies in the progression of osteoarthritis, as an increased KFM has been linked to cartilage wear in early osteoarthritis, while an increased KAM is strongly associated with more severe osteoarthritis [85].

The same pattern of abnormal kinetics was reported in different studies comparing partial meniscectomy and meniscal repair in the setting of an ACL reconstruction. Capin et al. assessed an athletic cohort of patients after completing full rehabilitation of an ACL reconstruction [88•]. The authors used a validated electromyography-driven musculoskeletal model and classified groups according to concomitant medial meniscus treatment. Subjects in the partial meniscectomy group demonstrated a higher peak KAM in the surgical limb relative to the contralateral limb; however, this increased KAM was not observed in the surgical limb of the intact meniscus and the meniscal repair groups. Estimated medial tibiofemoral compartment contact forces were also increased in the meniscectomy group in comparison with the other two groups at 2 years of follow-up [89].

Impact on In Vivo Knee Kinematics

The meniscus plays a critical role in physiologic in vivo knee kinematics. There is ample evidence demonstrating the alteration in knee kinematics when there is suboptimal meniscal function. A study by Zhang et al. examined gait kinematics in ACL deficient patients with or without meniscal injures [90]. The authors demonstrated that meniscal injuries impaired physiological kinematics and this alteration of normal knee function was dependent on location of the meniscal tear. Patients with concomitant medial and lateral meniscus tears had abnormal sagittal excursion, particularly anterior tibial translation (ATT), while patients with an isolated medial meniscus tear showed a significant increase in lateral tibial translation (LTT). Hosseini et al. reported similar findings during stair-climbing through a dynamic fluoroscopy-based assessment [91]. A subsequent study examining 3-D gait analysis demonstrated significantly increased axial plane rotation angles during the entire gait cycle in patients with concomitant unstable meniscus tears versus isolated ACL tears [92]. Similarly, a separate study by Ren et al. demonstrated significantly increased external tibial rotation during the pre-swing phase in ACL-deficient patients with concomitant medial meniscus posterior horn tears [93].

There is already convincing data indicating that the benefits of meniscus repair also translate to the in vivo setting and mitigate abnormal kinematics following a knee injury [89, 94]. For example, Wang et al. assessed the kinematics of a total of 32 patients who underwent ACL reconstruction and concomitant medial meniscus treatment at 2 years of follow-up [94]. The authors divided their patient cohort into repair and partial meniscectomy groups and compared these groups to a control group composed of 20 healthy participants. Patients in the partial medial meniscectomy group walked with an increased knee adduction angle (KAA) during early and mid-stance phases of gait and had an increased tibial external rotation during early stance. This difference was not observed between meniscus repair and healthy control groups.

Discoid lateral menisci have also been shown to result in altered kinematics. Gait analyses by Li et al. demonstrate significantly lower peak knee flexion angles (KFA) during stance and swing phases and reduced adduction-abduction angles during gait in patients with a discoid meniscus [95]. A similar pattern of limited knee excursion has been further reported in the literature when comparing discoid meniscus groups versus healthy controls as well as when comparing symptomatic discoid menisci versus asymptomatic discoid menisci [92, 96]. Healthy knees experience external rotation during stance and internal rotation during the swing phase, while the discoid meniscus groups demonstrated decreased internal rotation during the swing phase. Lin et al. hypothesized that the resulting non-physiological horizontal shear stress initiated the destruction of the meniscus [96].

Conclusion

Meniscal tears can cause profound functional, biomechanical, and kinematic derangements within the knee joint leading to accelerated degeneration of the articular cartilage. A strong understanding of the quantitative and qualitative relationships of the meniscus and its attachments with key arthroscopic landmarks will allow a surgeon to anatomically repair meniscal pathology in order to restore native joint biomechanics.

Declarations

Conflict of Interest Dr. Jorge Chahla is a board member for AOSSM, Arthroscopy AANA, and ISAKOS and a paid consultant for Smith and Nephew, Arthrex, Conmed, and Ossur.

Dr. Adam Yanke is a paid consultant for Allosource, Conmed, JRF Ortho, and Olympus; an unpaid consultant for Smith and Nephew, Patient IQ, and Sparta Biomedical; and does research support for Arthrex, Organogenesis, and Vericel.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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• Of importance
•• Of major importance

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