4 Physiology: Biomechanics

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Contents

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4.1 Introduction

The menisci are two crescent-shaped fibrocartilagenous structures found in the medial and lateral compartments of the tibiofemoral joint of the knee. Once thought of as useless "remnant vestiges" [3], they are now well understood to play a critical role in knee joint stability and load distribution, protecting the smooth hyaline cartilage on both the distal femur and proximal tibia. These functional attributes are achieved via a combination of geometry, material properties, and ligamentous attachments of the menisci to the bones. They are also thought to play roles in knee joint lubrication and nutrient distribution [33] as well as proprioception [22]. With very poor self-healing capabilities and with injuries shown to speed up the progression of osteoarthritis, achieving effective repair or replacement of the menisci is an ongoing and important research aim.

4.2 Morphology

The lateral and medial menisci are both "c" shaped when viewed from above, although the medial meniscus is larger and more like a capital letter "C" (Fig. 4.1). They are wedge shaped in cross section when cut radially and are attached to the joint capsule via their peripheral rim and also to the tibia anteriorly and posteriorly by insertional ligaments. They partially cover the tibiofemoral joint surface (Fig. 4.2). In the sagittal

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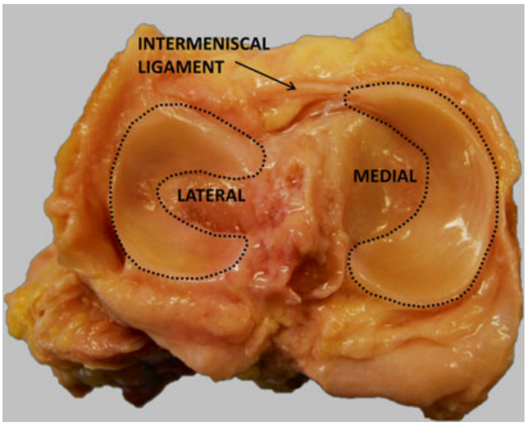

Fig. 4.1 A tibial plateau viewed from above. The donor was a 65-year-old female with moderate patellofemoral joint (PFJ) osteoarthritis (OA) and mild tibiofemoral joint (TFJ) OA

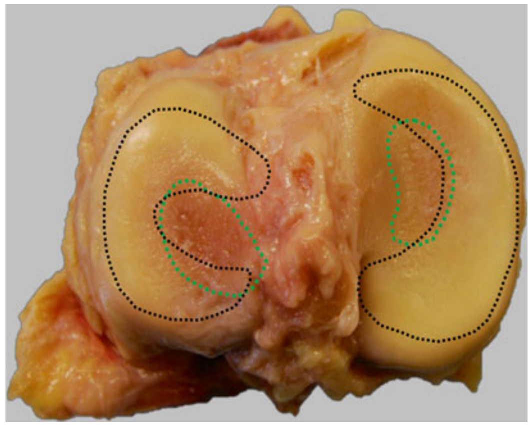

Fig. 4.2 The same tibial plateau as shown in Fig. 4.1, with the menisci removed. The outlines of where the menisci were shown, along with the areas of cartilage damage, where the menisci were not protecting the medial and lateral compartments (*dotted green lines*)

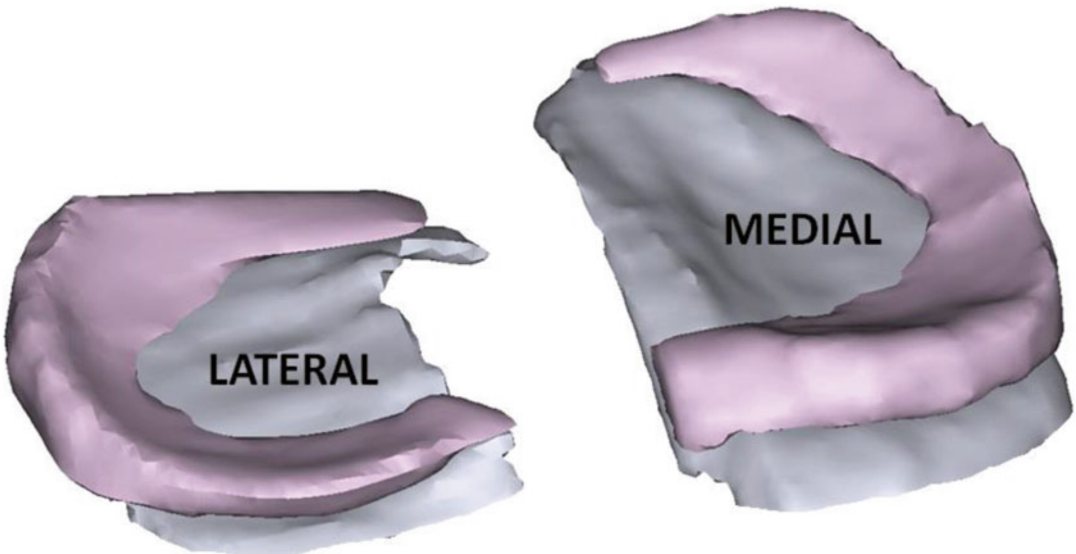

Fig. 4.3 3-dimensional reconstructions of the menisci (*pink*) and articular cartilage on the tibial plateau (*grey*), created from a magnetic resonance image. The convex lateral and concave medial compartments are clear

plane, the lateral compartment has a more convex tibial plateau than the concave medial compartment and the menisci conform to the tibial and femoral bony geometry (Figs. 4.3 and 4.4).

The various meniscal dimensions were measured as part of a study on meniscal allograft sizing [30]. Eighty-eight menisci (medial and lateral) were examined from 22 pairs of dissected cadaveric knees, and the dimensions described in Fig. 4.5 were determined using digital Vernier callipers. The results are given in Table 4.1. These results are of interest, as they demonstrate the wide variation in meniscal sizes that exists across different knees and are relevant because of the critical importance of accurate meniscal allograft and synthetic graft sizing [23, 41].

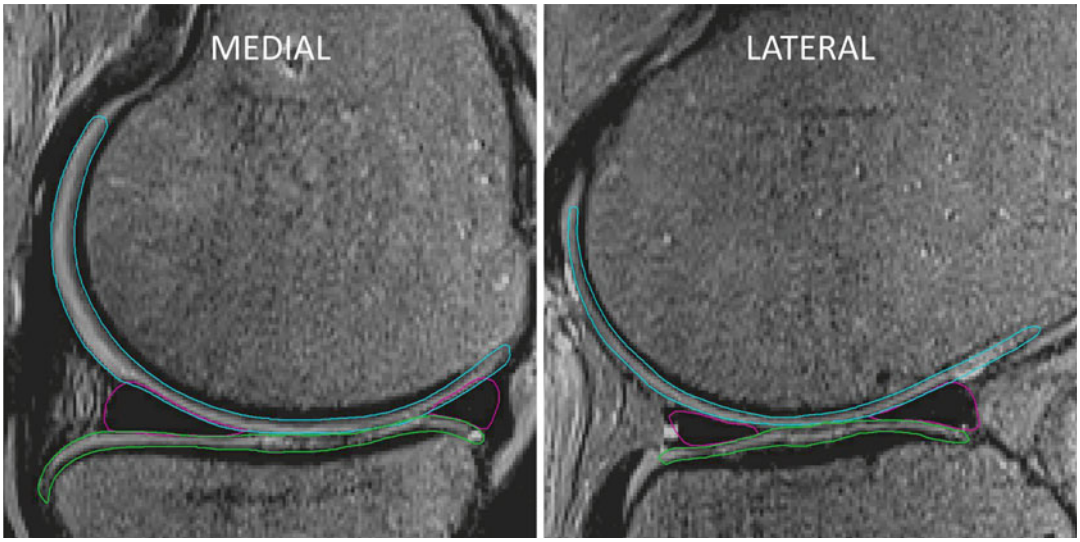

Fig. 4.4 Outlines of articular cartilage (*blue and green*) and menisci (*pink*), constructed using sagittal MRI slices and segmentation

Fig. 4.5 Left-sided menisci showing meniscus sizing notation. *MMC* medial meniscus circumference, *MMW* medial meniscal width, *MML* medial meniscal length, *LMC* lateral meniscus circumference, *LMW* lateral meniscal width, *LML* lateral meniscal length

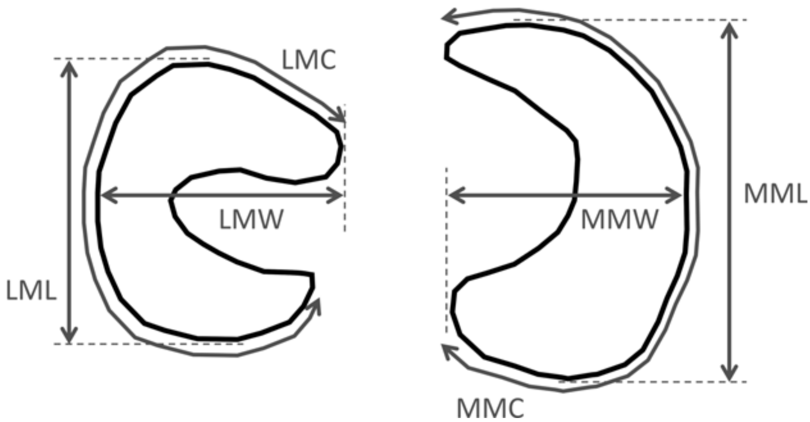

Table 4.1 Meniscal dimensions measured from 44 cadaver knees

	Mean ± SD (mm)	Smallest (mm)	Largest (mm)
Medial meniscus circumference (MMC)	99.0 ± 9.3	84.0	119.0
Medial meniscal width (MMW)	27.4 ± 2.5	23.3	32.7
Medial meniscal length (MML)	45.7 ± 5.0	30.1	56.1
Lateral meniscus circumference (LMC)	91.7 ± 9.6	78.0	112.0
Lateral meniscal width (LMW)	29.3 ± 3.0	24.0	36.3
Lateral meniscal length (LML)	35.7 ± 3.7	29.5	51.2

Data taken from McDermott et al. [30]

4.3 Material Properties of Meniscal Tissue

The microstructure (discussed in Chap. 3) of the meniscal tissue, as in all materials, principally defines the material properties and thus the mechanical behaviour of the tissue. The meniscal behaviour in both tension and compression is directly related to the predominantly circumferential orientation of the meniscal collagen fibres [4, 37, 38].

4.3.1 Tensile Material Properties

There are quite a few studies in the literature that have tested meniscal tissue in tension [13, 14, 26, 27, 45]. Because of the non-uniform nature of the shape of the menisci and their microstructure, uniformly shaped (rectangular or "dumbbell") specimens are harvested from whole menisci to be tested in tension. These samples are either taken in the radial or circumferential direction and can be cut either parallel or perpendicular to the bottom surface of the meniscus (Fig. 4.6). As well as this, the specimens are often classified by their location in the meniscus, in the horizontal plane: either anterior, central or posterior third (Fig. 4.6). It has been shown that circumferentially, the meniscus is about ten times stronger than it is radially (around 100 MPa compared to 10 MPa; Table 4.2), in keeping with the microstructure of the tissue, which may explain why the meniscus is more prone to circumferential tears, rather than radial ones. A corollary of the difference between radial and circumferential strength is that a radial tear is relatively uncommon and must break the collagen fibres, and so it defunctions the meniscus and is also hard to repair (due to sutures pulling out along the fibre direction and the tissue working at a high stress in the circumferential direction, across the radial tear). The opposite is true for circumferential tears, which occur easily because the tissue is weak when pulled apart radially, yet that also implies low stresses across the tear and hence it is relatively easy for sutures to hold it together. Lechner et al. [26] found that the cross-sectional area of their tensile testing specimens had an inverse effect on the tensile modulus, possibly a result of the thicker specimens having a greater water to collagen ratio than the thinner ones (Table 4.2). The results from these studies also suggest that the posterior third of the meniscus is less strong in tension in the circumferential direction, although there is no histological data explaining this difference.

4.3.2 Compressive Material Properties

There are three different types of compression tests that have been performed on the human meniscus: unconfined compression, confined compression, and indentation [8, 21, 32, 42, 44]. A combination of these test methods can give us knowledge about the non-linear and viscoelastic behaviour of the meniscus via the aggregate modulus (how stiff the material is under compression; H_A), the equilibrium modulus (how stiff the material is when fluid

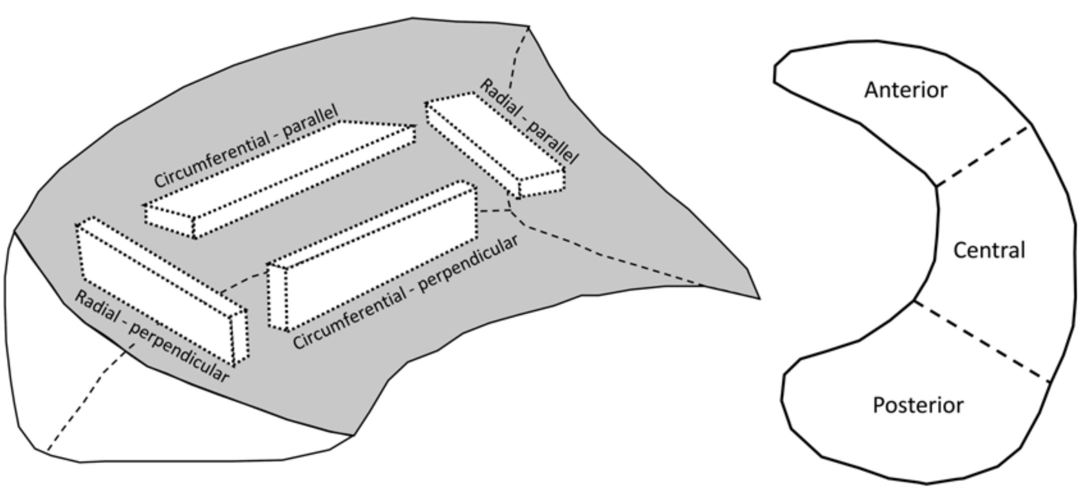

Fig. 4.6 Tensile testing specimens' harvesting locations

Table 4.2 Tensile properties of the human meniscus

Type of specimen	Study	Cross-sectional area of specimen (mm^2)	Tensile elastic modulus (MPa)			
			Anterior	Central	Posterior	Mean
Circumferential	Fithian et al. [14]	0.4	159	161	159	160
	Tissakht and Ahmed [45]	2.6–6.0	91	77	81	83
	Lechner et al. [26]	0.5	141	116	108	122
		1.5	105	94	61	86
		3.0	72	43	67	61
	Fischenich et al. [13]	1.0	170	–	105	138
Radial	Tissakht and Ahmed [45]	1.4–6.0	8	11	13	11

Table 4.3 Compressive properties of the human meniscus

Study	Test method	H_A (MPa)	k ($\times 10^{-15}$ m^4/Ns)	E_{eq} (MPa)
Joshi et al. [21]	Confined compression	0.23	1.99	
Sweigart et al. [44]	Indentation	0.12	1.78	
Seitz et al. [42]	Confined compression	0.06	4.24	
Chia and Hull [8]	Unconfined compression			0.08
Moyer et al. [32]	Indentation			1.59

flow has ceased; E_{eq}), the hydraulic permeability (how easily fluid flows through the tissue; k), and Poisson's ratio (the ratio of transverse to axial strain; ν). Values in the literature vary considerably (Table 4.3) which may be due to differing experimental methods and interpretation of data. Nevertheless, it is clear that the meniscus is considerable less stiff in compression than it is in tension (less than 1 MPa). This allows the cross section of the meniscus to conform to the condylar geometry when the knee is moving and may go some way to explain the loss of function and extrusion of the meniscus that can be observable in the older patient, particularly in the posterior medial meniscus in deep flexion, where it is squeezed against the rim of the tibial plateau, causing large deformation of the cross section of the meniscus.

4.4 Ligaments

Investigating the biomechanical function of the menisci is complex in nature, partly due to the many ligaments that are attached to them. There are 12 ligaments connected to the medial and lateral menisci and allograft transplantation should try and consider the functional contribution of these structures; there will most likely be functional limitations post-implantation because not all of the ligaments will be adequately replaced during surgery.

4.4.1 Meniscotibial Ligaments

There are two types of ligaments that connect the menisci to the tibia: the coronary ligaments and the tibial insertional ligaments.

The coronary ligaments resemble a "skirt" connecting the peripheral circumference of the menisci to the proximal tibia. These have not been investigated much in the literature and their exact function isn't clear. From their appearance it would be sensible to assume that they do have some kind of effect on meniscal movement and possibly also on knee stability.

The tibial insertional ligaments (or meniscotibial ligaments) connect the 4 horns of the menisci to the bone beneath the tibial plateau. These ligaments are extensions of the collagen fibres that run

Table 4.4 Maximum failure loads of the tibial insertional ligaments in cadaver knees

	Mean (*N*)	Range (*N*)	Number of roots tested
Anterolateral (AL)	673	250–1100	23
Anteromedial (AM)	532	200–824	24
Posterolateral (PL)	579	300–875	25
Posteromedial (PM)	596	388–850	19

Data taken from Kopf et al. [24] and Ellman et al. [11]

circumferentially through the bulk of the menisci. Data in the literature suggest that the pullout strength of these insertional ligaments is independent of location, though there is some variability between studies (Table 4.4). In studies that have examined the repair strength of various fixation methods used for meniscal root rupture, it has been concluded that none of the repair methods restore the pull-out strength of the insertions to the pre-injured state [12, 24], highlighting the importance of adequate fixation of allografts and implants.

4.4.2 Meniscofemoral Ligaments

There are two meniscofemoral ligaments: anterior (also known as the ligament of Humphry) and posterior (also known as the ligament of Wrisberg). Neither appear in all people, although the rate of incidence varies considerably in the literature [2, 17, 40]. If they are present, they act as a secondary restraint to posterior translation of the tibia up to 90° flexion and in deeper flexion, and they provide some resistance to external rotation [16].

4.4.3 The Deep Medial Collateral Ligament (dMCL)

As the dMCL passes from the tibia to the femur, it connects to the outer rim of the medial meniscus. It is thought to control the motion of the medial meniscus, although this has not been investigated in the literature. The ligament itself provides rotatory stability to the tibia as well as resisting valgus moments.

4.4.4 The Anterior Inter-meniscal Ligament

The anterior intermeniscal ligament (AIL; also called the transverse geniculate ligament or anterior transverse ligament) connects the medial and lateral menisci, via their anterior horns (Fig. 4.1). Its anatomy has been described [15, 34], but its exact function remains unclear. One anatomical study suggests that in a quarter of knees, the AIL acts as the primary connection between the medial meniscus and the tibial plateau, in the absence of an anterior medial horn or in cases where the horn is very fine [34]. This suggests that the AIL should not be compromised during surgical procedures, such as anterior cruciate ligament reconstruction.

4.5 Functional Biomechanics of the Menisci

4.5.1 Load Distribution

The force transmission role of the menisci is well established; during activities of daily living (ADLs), the knee joint is subject to axial compression, leading to contact stresses in the articular cartilage. The menisci help to make the contact between the femur and tibia more congruent, increasing the contact area of the tibiofemoral joint, thus reducing the contact stresses. The medial compartment is more congruent than the lateral one, because the medial side of the tibial plateau is more concave (Fig. 4.3). The lateral compartment is flatter and almost convex in some parts (Fig. 4.4). It has been shown that in meniscectomised knees, the contact area in that compartment goes down and the contact pressures therefore go up (Fig. 4.7), which is demonstrated by increased cartilage damage in meniscectomised knees (Fig. 4.8) and

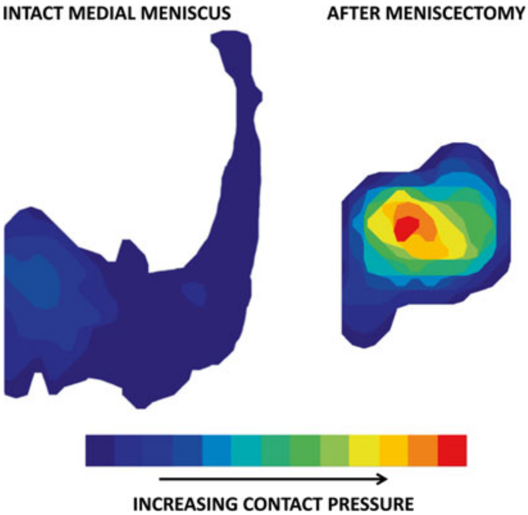

Fig. 4.7 A pressure map demonstrating the consequences of meniscectomy, using a Tekscan K-Scan 4000 pressure-sensitive film inserted underneath the medial meniscus in a human cadaver knee at 0° flexion with a 700 N axial compressive load

may partly explain the increased rate of incidence of osteoarthritis (OA) in people who have had partial or total meniscectomies [9].

Because the lateral meniscus covers a greater percentage of its compartment than its medial counterpart, combined with the fact that the lateral compartment is less congruent with its femoral condyle, it is implied that lateral meniscectomy would present a greater risk of OA development than medial. However, the clinical results are mixed, with some reporting worse outcomes with lateral meniscectomy [19, 20, 31] and others finding no difference between the two procedures [5, 28, 36]. In cadaveric experiments, contact areas and pressures change by similar amounts on the medial and lateral sides after simulated meniscal injuries (Fig. 4.9; [25, 35]). Although the lateral compartment is less congruent than the medial, the forces during gait are concentrated onto the medial aspect by the knee adduction moment which occurs during weight bearing.

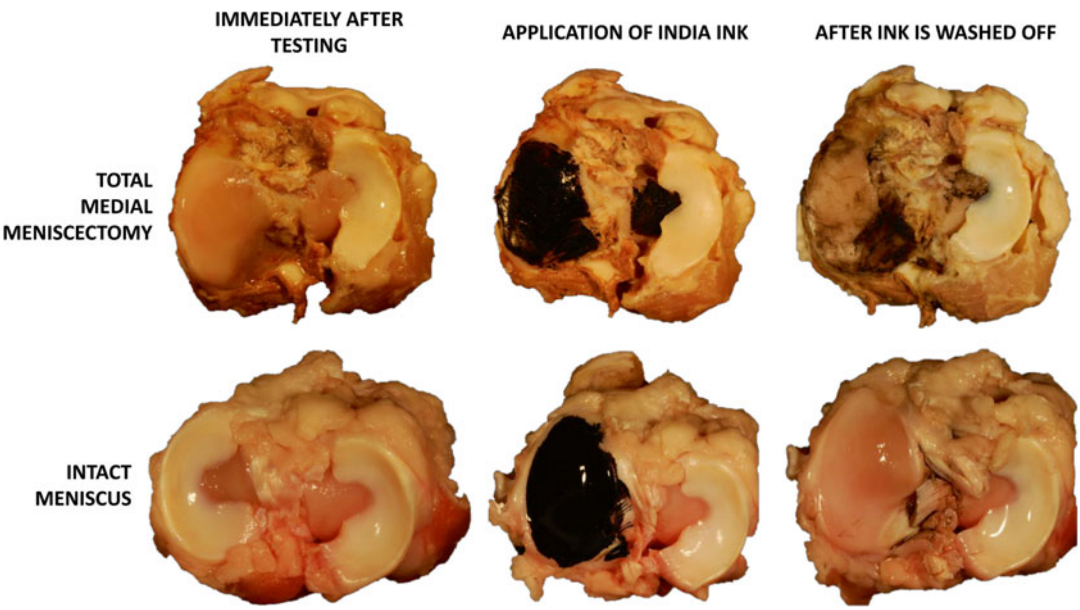

Fig. 4.8 Photographs demonstrating the consequences of meniscectomy, using an ovine stifle model. Joints were either left intact or had a total medial meniscectomy performed. They were then cycled 500,000 times in a bespoke flexion-extension rig, with a loaded stance phase. After testing, the joints were disarticulated and the medial compartment was coated with India ink. The ink was then washed off. The intact joint showed no damage while the meniscectomised joint showed significant cartilage damage, shown by the permanent staining by the ink [18]

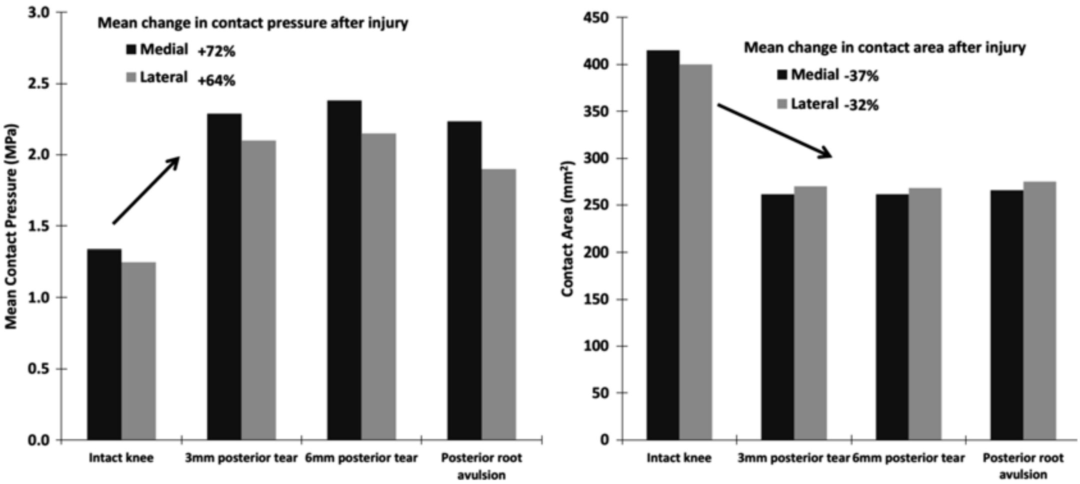

Fig. 4.9 Bar charts showing the consequences of differing amounts of meniscus injury on mean contact pressure (*left*) and contact area (*right*) for the medial and lateral compartments, pooled across flexion angles ranging from 0° to 90°. The data is taken from two separate journal articles (medial data taken from Padalecki et al. [35]; lateral data taken from LaPrade et al. [25]) but the work was done by the same research group

4.5.2 Stability

Because the menisci are attached to both the tibia and femur, they have a stabilising effect on the knee joint in certain degrees of freedom, at certain flexion angles. The medial meniscus in particular has been shown to be a secondary restraint to anterior translation of the tibia [1, 43] and the menisci also restrain tibial rotation and the pivot-shift mechanism [7, 39].

4.5.3 Meniscal Motion During Knee Flexion

The load-bearing role of the menisci is able to occur throughout the whole range of knee joint flexion (up to 160°) because the menisci are mainly attached to the tibia by insertional ligaments at their horns, which are mobile, allowing displacement in all directions. There have been several studies that have examined this movement in both cadaver and clinical settings, but only one has measured meniscal translation in vivo, under weight-bearing conditions, using open MRI.

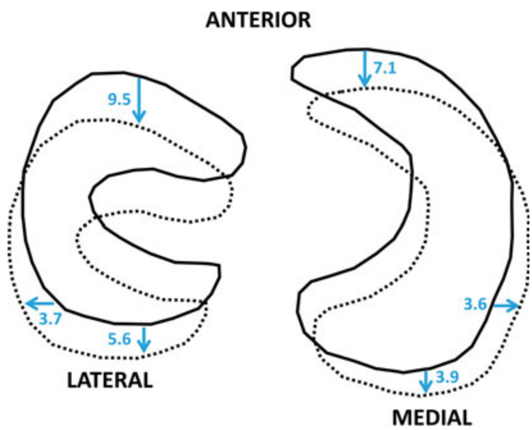

Fig. 4.10 A diagram showing the motion of the menisci during flexion measured in patients using dynamic MRI. Weight-bearing knee flexion from 0° to 90°. Both menisci move a similar amount peripherally but the lateral meniscus moves more posteriorly and the anterior horns move more than their posterior counterparts (data taken from Vedi et al. [46]. Diagram not to scale)

Vedi et al. [46] described meniscal motion in the normal knee (Fig. 4.10). They observed that both menisci moved posteriorly as the knee flexed. The anterior horns were also noted to be more mobile than the posterior horns and the lateral meniscus was noted to be more mobile than the medial. The posterior horn of the medial meniscus was found to be the least mobile. The lateral meniscus was shown to be more mobile than the medial meniscus, partly due to the dMCL's attachment to the medial side but also because the concave medial tibial plateau, with secure attachment of the capsule to its rim, does not allow the posterior horn of the medial meniscus to displace off the joint posteriorly in deep flexion, whereas the convex posterior aspect of the lateral tibial plateau does allow this to occur to the lateral meniscus.

These observations may explain the increased frequency of medial meniscal tears compared to lateral meniscal tears, which happen twice as often [6]. They may also explain the observations of medial meniscal tears being located more frequently in the posterior horn of the meniscus [10].

Conclusion

The menisci of the knee and their associated ligaments in combination are a highly complex construct. Their function is inextricably linked to their structure and morphology and the interactions between the menisci, their ligaments and the proximal tibia and distal femur. The importance of the menisci is now well understood and meniscal preservation is practised routinely during surgery, if it is possible to do so and there are many different repair options available. However, structures such as the coronary, meniscofemoral and intermeniscal ligaments are often ignored during meniscal allograft procedures, and the tibial insertional ligaments are not adequately restored. Allografts have many contraindications for use and mixed results in long-term follow-up, but it has been shown to be possible to restore intact joint contact stresses at time zero in vitro [29]. There needs to be a better understanding of the relevance of the detailed anatomical features of the menisci in order to develop more accurate modelling of this tissue, in order to be able to manufacture or grow appropriate artificial scaffolds or tissue-engineered replacement tissue and to enhance the meniscal repair techniques.

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