ANNUAL REVIEWS

Annual Review of Biomedical Engineering

The Meniscus in Normal and Osteoarthritic Tissues: Facing the Structure Property Challenges and Current Treatment Trends

Caroline A. Murphy,[1] Atul K. Garg,[2] Joana Silva-Correia,[3,4] Rui L. Reis,[3,4,5] Joaquim M. Oliveira,[3,4,5] and Maurice N. Collins[1,6]

[1]Stokes Laboratories, Bernal Institute, School of Engineering, University of Limerick, Limerick V94 PC82, Ireland; email: maurice.collins@ul.ie

[2]Manufacturing Technology and Innovation Global Supply Chain, Johnson & Johnson, Bridgewater, New Jersey 08807, USA

[3]3B's Research Group, I3B's: Research Institute on Biomaterials, Biodegradables and Biomimetics, University of Minho and Headquarters of the European Institute of Excellence on Tissue Engineering and Regenerative Medicine, 4805-017 Barco, Guimarães, Portugal

[4]ICVS/3B's: PT Government Associate Laboratory, 4710-057 Braga, Guimarães, Portugal

[5]The Discoveries Centre for Regenerative and Precision Medicine, University of Minho, 4805-017 Barco, Guimarães, Portugal

[6]Health Research Institute, University of Limerick, Limerick V94 T9PX, Ireland

Annu. Rev. Biomed. Eng. 2019. 21:495–521

First published as a Review in Advance on April 8, 2019

The *Annual Review of Biomedical Engineering* is online at bioeng.annualreviews.org

https://doi.org/10.1146/annurev-bioeng-060418-052547

Keywords

meniscus, repair, biomechanics, osteoarthritis, cartilage

Abstract

The treatment of meniscus injuries has recently been facing a paradigm shift toward the field of tissue engineering, with the aim of regenerating damaged and diseased menisci as opposed to current treatment techniques. This review focuses on the structure and mechanics associated with the meniscus. The meniscus is defined in terms of its biological structure and composition. Biomechanics of the meniscus are discussed in detail, as an understanding of the mechanics is fundamental for the development of new meniscal treatment strategies. Key meniscal characteristics such as biological function, damage (tears), and disease are critically analyzed. The latest technologies behind meniscal repair and regeneration are assessed.

Contents

1. INTRODUCTION

The knee menisci are crescent wedge–shaped pads of fibrocartilage. They are found in pairs, laterally and medially, between the tibial plateaus and the femoral condyles (**Figure 1**). The main ligaments that attach the menisci to the tibia are the insertional ligaments and the deep medial

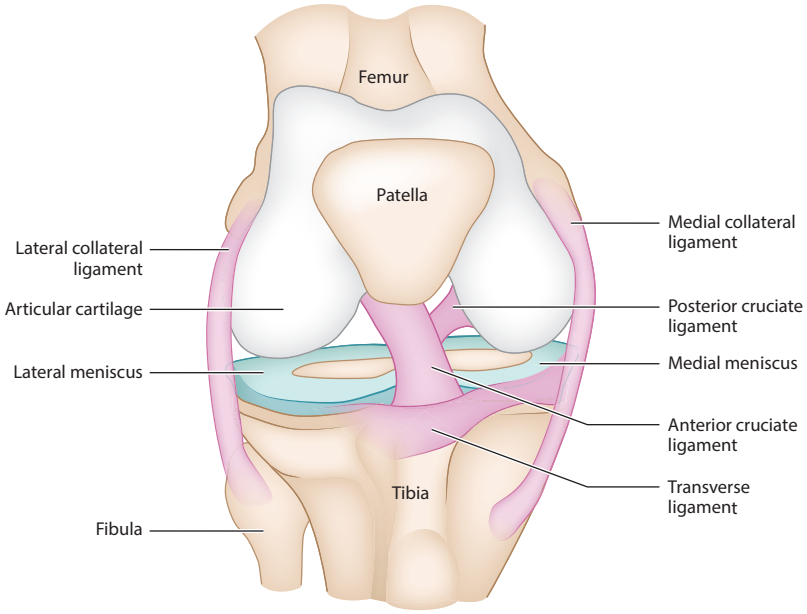

Figure 1

Drawing of the knee joint, depicting menisci and major ligaments.

collateral ligament, and they are attached to the femur via meniscofemoral ligaments (MFLs) and the deep medial collateral ligament.

After birth, the meniscus is a fully vascularized tissue; however, vascularization decreases as the meniscus matures (1). As a result of the limited vascularization, the meniscus contains two distinct regions: the peripheral red zone and the inner avascular white zone. Due to this vascularization structure and the direct relation between the healing capacity of the meniscus and its blood supply, the central white zone is susceptible to irreparable degenerative and posttraumatic injuries (2–5).

The intrinsic limited healing capacity of the meniscus is accentuated by the fact that tears, partial and total removal by surgery (i.e., meniscectomy), and degeneration play a role in the development or advancement of knee osteoarthritis (OA) (6). For instance, patients who present clinical and radiographic evidence of OA have a prevalence of meniscal lesions of 68–90% (7). Also, knee menisci undergo several changes in OA patients (6). Macroscopic and histopathologic observations revealed severe fibrocartilaginous separation of the matrix, significant wear, tears, calcification, and atypical cell arrangements in menisci from OA joints.

The menisci play a key role in joint biomechanics (6, 8), especially in transferring loads across the knee joint. The meniscus transfers forces between the femoral and tibial joint surfaces through the development of hoop stress within the meniscus tissue (9). As the femoral bone bears down on the meniscal tissue, the meniscus undergoes deformation and protrudes peripherally (10). This protrusion is halted by the anterior and posterior insertional ligaments. The hoop stress is then generated as the axial forces are converted to tensile stresses along the circumferential collagen fibers of the meniscus. However, this hoop stress is compromised when radial tears occur or a partial meniscectomy is performed (11).

2. BIOLOGICAL COMPOSITION

The meniscus is a highly hydrated structure, with 72% of its wet weight consisting of water and remaining 28% consisting primarily of an interlacing network of collagen fibers, interposed with cells and an extracellular matrix (ECM) (12, 13). The collagen content of the meniscus increases with joint motion and weight bearing until the age of 30, when it stabilizes until beginning to decrease again around the age of 80 (14). Collagen type I is found throughout the meniscus, whereas collagen type II is found only within the inner two-thirds. Collagen type I is most abundant in the peripheral third of the meniscus and represents 90% of its composition by dry weight, with other collagens present in quantities less than 1% (15–17). In the inner region collagen makes up slightly less of the dry weight at 70%, of which 60% is collagen type II and 40% is collagen type I (2).

The orientation and structure of the collagen also differ between the surface layer and the deeper tissue of the meniscus (18–20). Collagen fibers within the deep tissue are predominantly circumferentially orientated. The collagen fibers covering the surface of the tissue of the meniscus are randomly oriented and have a meshlike structure (**Figure 2**).

Radial tie fibers arborize from the outer region of the meniscus toward the inner tip (21). The tensile modulus of the meniscus is influenced by the presence of tie fibers. Interestingly, a study by Skaggs et al. (22) found that failure never occurred through or immediately adjacent to the tie fiber during uniaxial tensile tests, indicating excellent interfacial adhesion between the fiber and the matrix. A recent hypothesis is that the function of radial tie fibers is to transmit load to severed circumferential fibers near a radial tear, thereby maintaining the mechanical functionality of the meniscus (23).

Proteoglycans are found within the meshwork of collagen fibrils and account for 1–2% of the composition of the meniscus by dry weight (24). Proteoglycans are composed of a core protein

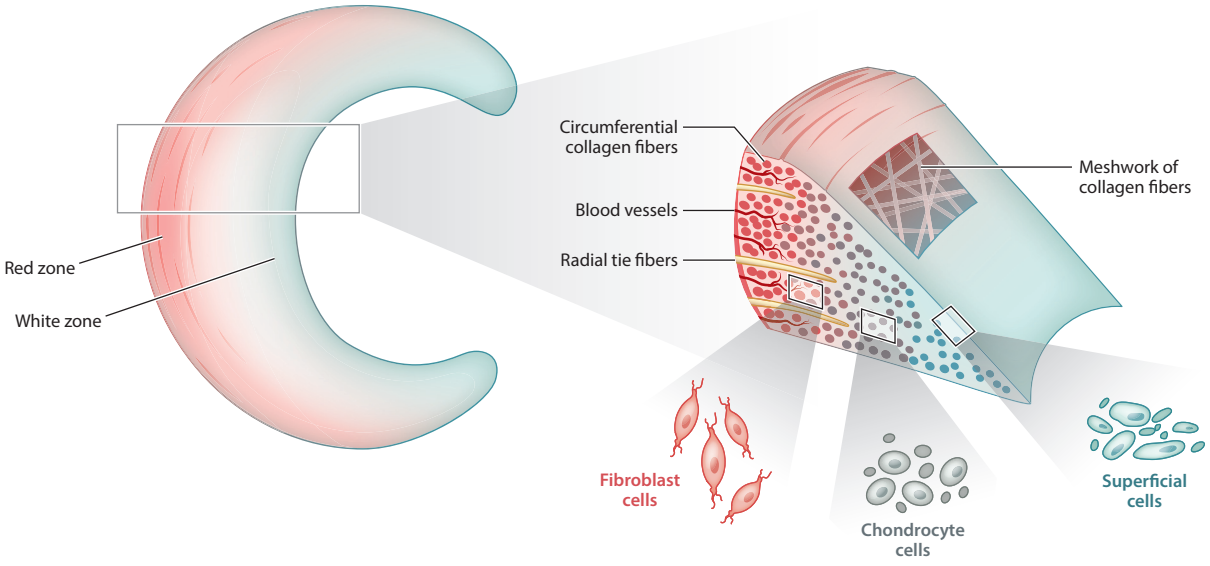

Figure 2

Illustration of the internal structure of the meniscus depicting variation in collagen orientation, vascularization, and cell population.

with glycosaminoglycans attached; the main proteoglycan found in the meniscus is known as aggrecan. The glycosaminoglycans in the meniscus typically consist of 40% chondroitin 6-sulfate, 10–20% chondroitin 4-sulfate, 20–30% dermatan sulfate, and 15% keratan sulfate (12, 25, 26). The inner third of the menisci has the highest glycosaminoglycan concentration (27). Proteoglycans in the ECM are responsible for the absorption of water and support the meniscus under compressive loads (17, 28). Nakano et al. (29) demonstrated that proteoglycans smaller than aggrecan are found in the meniscus and do not aggregate with hyaluronic acid; examples include decorin, biglycan, and fibromodulin. Nakano et al. (29) reported that biglycan and fibromodulin are present in higher concentrations in the inner zone of porcine meniscus, whereas decorin is found primarily in the peripheral zone. The precise function of each of these small proteoglycans remain unknown. Adhesion glycoproteins such as fibronectin, thrombospondin, and collagen type VI also play a key role in the meniscus and act as a link between ECM components and cells (17).

Human meniscus of the osteoarthritic knee demonstrates enhanced expression of major matrix components, namely procollagens of types I, II, and III, in the anterior horn segments in comparison to control menisci (nonarthritic knees) (30). Also, insulin-like growth factor 1 (IGF-1) is upregulated in OA menisci, which seems to be partly responsible for the increased procollagen expression. Katsuragawa et al. (30) suggest that this shift in terms of gene expression could be associated with a reparative response to OA. Although alterations in gene expression have been observed, histological analysis of matrix production and biomechanical evaluation shows only moderate changes in OA menisci, consistent with the macroscopic appearance.

Ghadially et al. (31) were among the first researchers to identify the cells found in the human meniscus. They classified cells as chondrocytes, fibroblasts, or cells of intermediate morphology on the basis of their shape and the absence or presence of territorial matrix. Although the chondrocytes found in the meniscus have morphological similarities to articular cartilage, their matrix protein expression is collagen type I, whereas in articular cartilage collagen type II is predominant. Therefore, these cells are often referred to as fibrochondrocytes (32, 33). However, various terms have been used to describe these cells (fibrocytes, meniscus cells, fibrochondrocytes, and

chondrocytes), with no consistency in the literature (34, 35). Meniscus fibrochondrocytes are surrounded by a pericellular matrix (PCM), which together with the enclosed cells has been termed the fibrochondron (36).

Regardless of the terminology used, there is consensus on the shape and behavior of the cells found in the meniscus. The meniscus contains three cell populations, each of which is found in a distinct region (**Figure 2**). Histological examination of the meniscus revealed that the inner and middle sections of the meniscus contain cells that appear similar to chondrocytes. These cells are round in appearance and found in a lacuna surrounded by the ECM (35, 37). The outer vascularized zone of the meniscus contains fibroblast-like cells. Fibroblasts are spindle shaped and reside within a dense connective tissue (37). Recently, a third population of cells was identified in the superficial zone of the meniscus. These cells are fusiform in shape and lack cell extensions, and their exact purpose has not been established. However, it has been hypothesized that these cells could contain specific progenitor cells with healing potential (32, 35).

In a study performed by Cengiz et al. (38), the three-dimensional cellular density of the human meniscus from the OA knee was quantified using a segmental and regional motion method. These authors observed that the cellular density in the vascular region was more than twice as high as in the avascular region. The cells possessed two distinct morphologies, roundish or flattened. Moreover, both fibrochondrocyte and fibroblast-like cell morphologies were observed, with the first type of cell present at much higher densities. Significantly higher cellularity was also observed in the anterior segments. Pauli et al. (6) detected atypical cell agglomeration in regions where the meniscus matrix suffered a greater degree of disruption, namely around frayed edges and tears. In terms of morphology, these cells were larger than the normal fibrochondrocytes observed in healthy menisci.

3. BIOMECHANICAL PROPERTIES

3.1. Tensile Properties

Many authors have examined the tensile modulus of animal and human meniscus. The modulus has been measured with collagen fibers running circumferentially and radially, and the results vary with respect to sample location. The depth of the sample within the meniscus has a significant effect on the results due to structural variation in the collagen fibers in the meniscal cross section. For example, Bullough et al. (20) reported that strength is highly dependent on the orientation of the fibers to the tensile axis. Subsequent tensile testing studies confirmed this finding (39–42). However, discrepancies have arisen in the literature; for example, the posterior segment of medial meniscus has a statistically greater tensile modulus compared with the anterior region (39). However, that finding was contradicted in a study by Fithian et al. (43), and later studies reported no significant variation between the different regions (40, 44). **Table 1** shows that the tensile properties of the meniscus vary significantly between animal model and sample thickness.

3.2. Compressive Properties

Compressive properties of the meniscus are typically measured by confined compression tests, unconfined compression tests, and indentation tests. Confined compression testing enables assessment of the aggregate modulus and permeability. **Table 2** shows that the aggregate modulus differs by region in the meniscus (39, 45, 46). Joshi et al. (47) investigated the compressive properties of the medial meniscus of six different species (47) and found a significant difference in aggregate modulus for porcine and bovine meniscus. Overall, these authors observed, among

Table 1 Tensile properties of the meniscus

Reference	Number of samples	Shape	Thickness (μm)	Type	Location of meniscus	Location within meniscus	Orientation	Average tensile modulus (MPa)
Bullough et al. (20)	32 samples	Rectangular	9–20	Human	Lateral	Anterior	Average of various orientations	3.44
						Central		2.37
						Posterior		3.70
					Medial	Central		3.14
						Posterior		3.80
Proctor et al. (39)	6 menisci	Dumbbell	~400	Bovine	Medial	Not applicable	Radial	26.27
							Circumferential	128.57
						Anterior	Circumferential	91.70
						Posterior	Circumferential	226.95
Fithian et al. (43)	7 knees/56 samples	Rectangular	Not applicable	Human	Medial	Anterior	Circumferential	159.58
						Central		93.18
						Posterior		110.23
					Lateral	Anterior		159.07
						Central		228.79
						Posterior		294.14
Newton & Mow (44)	Unknown	Dumbbell	400	Bovine	Medial	Anterior	Circumferential	137.50
						Central		156.50
						Posterior		138.50
Tissakht & Ahmed (40)	31 knee joints	Rectangular	800–2,000	Human	Lateral	Anterior	Radial	9.03
						Central		12.52
						Posterior		13.36
					Medial	Anterior		6.61
						Central		10.47
						Posterior		12.73
			1,500–2,000		Lateral	Anterior	Circumferential	108.27
						Central		103.62
						Posterior		123.09
					Medial	Anterior		91.23
						Central		76.82
						Posterior		81.14

(*Continued*)

Table 1 (*Continued*)

Reference	Number of samples	Shape	Thickness (μm)	Type	Location of meniscus	Location within meniscus	Orientation	Average tensile modulus (MPa)
Goertzen et al. (41)	5 menisci	Rectangular	750	Bovine	Medial	Anterior	Radial	25.20
							Circumferential	316.00
Lechner et al. (119)	30 menisci	Dumbbell	500	Human	Medial	Anterior	Circumferential	141.20
						Central		116.40
						Posterior		108.40
			1,500			Anterior		104.60
						Central		93.90
						Posterior		60.70
			3,000			Anterior		72.00
						Central		43.40
						Posterior		67.10
Muratsu et al. (120)	501 samples	Rectangular	1,000	Porcine	Lateral	Central	Circumferential	125.00
					Medial	Central	Circumferential	162.00
Sweigart & Athanasiou (121)	14 menisci	Unknown	100	Rabbit	Medial	Central	Circumferential	156.00
Abdelgaied et al. (122)	15 samples	Dumbbell	1,500	Porcine	Medial	Central	Circumferential	113.00
			1,500					133.00
			2,000					142.00
			3,000					136.00
			3,000					120.00
Lakes et al. (42)	11 menisci	Dumbbell	450	Porcine	Medial	Not applicable	Radial	17
							Circumferential	105
Creechley et al. (123)	21 samples	Dumbbell	1,000	Bovine	Medial	Posterior	Longitudinal	137.5
							Transverse	5.0

Table 2 Confined compression: aggregate modulus of the meniscus

Reference	Test type	Number of samples	Thickness × width (mm)	Type	Location of meniscus	Location within meniscus	Average aggregate modulus (MPa)	Average permeability [10^{15} $m^4/(N \cdot s)$]
Favenesi et al. (45)	Confined	8 menisci	6.35 × 1	Bovine	Medial	Anterior	0.45	0.80
						Anterior-central	0.41	0.85
						Posterior	0.38	0.68
						Posterior-central	0.41	0.93
Proctor et al. (39)	Confined	8 menisci	6.35 × 1	Bovine	Medial	Anterior	0.41	0.69
						Anterior-central	0.38	0.91
						Posterior	0.44	0.84
						Posterior-central	0.41	0.85
Hacker et al. (124)	Confined	16 menisci	4 × 1	Human	Medial	Anterior	0.20	0.91
						Central	0.23	0.8
						Posterior	0.28	0.9
Joshi et al. (47)	Confined	5 menisci	4 × 1	Human	Medial	Posterior	0.23	2.20
				Bovine	Medial	Posterior	0.12	3.40
				Canine	Medial	Posterior	0.15	3.80
				Sheep	Medial	Posterior	0.25	2.10
				Porcine	Medial	Posterior	0.27	1.74
				Monkey	Medial	Posterior	0.11	6.78
Sweigart et al. (46)	Indentation	10 menisci	Unknown	Bovine	Medial	Anterior	0.19	6.01
						Central	0.13	5.69
						Posterior	0.12	5.02
		8 menisci		Canine	Medial	Anterior	0.27	3.19
						Central	0.21	2.00
						Posterior	0.23	2.44
		9 menisci		Human	Medial	Anterior	0.16	1.78
						Central	0.11	1.54
						Posterior	0.10	2.03
		15 menisci		Baboon	Medial	Anterior	0.17	1.11
						Central	0.18	1.32
						Posterior	0.17	1.36

(*Continued*)

Table 2 (*Continued*)

Reference	Test type	Number of samples	Thickness x width (mm)	Type	Location of meniscus	Location within meniscus	Average aggregate modulus (MPa)	Average permeability [10^{15} $m^4/(N \cdot s)$]
		6 menisci		Porcine	Medial	Anterior	0.23	4.79
						Central	0.15	4.07
						Posterior	0.14	4.99
		10 menisci		Rabbit	Medial	Anterior	0.45	3.98
						Central	0.15	0.89
						Posterior	0.14	1.09
Sweigart & Athanasiou (121)	Indentation	6 knees	Unknown	Porcine	Medial	Anterior	0.23	4.62
						Central	0.15	4.40
						Posterior	0.14	4.60
					Lateral	Anterior	0.18	6.81
						Central	0.18	5.02
						Posterior	0.17	6.14
		14 menisci	Unknown	Rabbit	Medial	Anterior	0.46	4.24
						Central	0.16	0.93
						Posterior	0.14	1.06
Seitz et al. (125)	Confined	25 knee joints	4.6[a]	Human	Medial	Unknown	0.06	4.24
					Lateral		0.07	3.62
Andrews et al. (48)	Confined	30 samples	1.5[a]	Bovine	Swollen	Unknown	0.05	Unknown
					Recompressed		0.16	Unknown

[a]Thickness only.

the six species, that as stiffness increased the permeability of the meniscus decreased. In a later study, Sweigart et al. (46) investigated the compressive properties of varying species and found that the bovine model was the most closely correlated with the aggregate modulus of the human meniscus. Andrews et al. (48) investigated the effects of swelling on the meniscus under a confined compression test. They found that material properties differed significantly between swollen and recompressed configurations.

Leslie et al. (49) investigated the human meniscus at different strain rates using unconfined compression and found that Young's modulus was approximately twofold higher in the circumferential versus axial direction at a low strain, with no significant variation at high strain. Their results suggested that fluid flow predominates over matrix composition in determining the compressive strength of the meniscus. Chia & Hull (50) found that the compressive modulus at a physiological strain rate was considerably greater than that at equilibrium, with the difference attributed to the tissue's biphasic behavior. The same study established that the modulus was significantly greater in the anterior region than the posterior region. Results from other investigations followed the same trend observed by Chia and Hull, with the anterior zone of the medial meniscus displaying higher modulus than the posterior zone (50–53). For detailed information about unconfined compression tests and indentation tests, with respect to different test methods, varying sample size, and locations, see **Table 3**.

As described above, moderate or severe OA tends to severely disrupt the meniscal matrix, mainly in the posterior horn (6). This disruption translates into biomechanical alterations during knee flexion, since the femoral condyles revert on the tibial plateau and more force is transmitted to the posterior meniscus. By contrast, the anterior horn seems to be constantly affected to a lesser extent, which may represent either greater resilience to degeneration or less exposure to biomechanical forces. Katsuragawa et al. (30) evaluated OA alterations in the mechanical performance of the meniscal matrix through confined compression testing. They observed changes in the mechanical properties of the medial menisci as a result of OA (the aggregate modulus was 40% lower than in the control menisci), whereas those changes were not as evident in the lateral menisci.

4. MENISCAL TEARS AND CURRENT TREATMENTS

In the United States, meniscal tears are the most common knee injury and are the most frequent cause of surgical procedures performed by orthopedic surgeons (54). One million meniscal surgeries are performed annually in the United States (55), most of which involve a partial or total meniscectomy. The estimated annual cost of meniscal disease in the United States is between $500 million and $5 billion (56).

Meniscal tears are more common in males than females, with reported ratios of three to one and four to one, respectively (57–60), and occur most frequently in the medial meniscus (54, 59). A study performed by Drosos & Pozo (59) found that 32% of meniscal tears occurred in sports-related activities, 38% occurred during non-sports-related activities, and 28% could not be associated with any specific event. In younger patients, meniscal tears are often a result of a traumatic sports injury, whereas in older patients, they are more frequently associated with degeneration of the meniscus and loss of mechanical elasticity. The mechanism of meniscal injury usually involves a twisting or shearing motion with a varus or valgus force (61). As discussed above, poor vascularization of the meniscus leads to irreparable damage once the meniscus tears in the avascular region. Unfortunately, once meniscus injury occurs, knee OA commonly follows (62) due to subsequent loss of the articular cartilage. Additionally, proinflammatory cytokines, such as interleukin (IL)-6, IL-8, and tumor necrosis factor α, display higher levels in the chronic phase of meniscal tears. This increased proinflammatory state is maintained in the joint from the time of initial

Table 3 Unconfined compressive properties of the meniscus

Reference	Test method	Number of samples	Dimensions (mm)	Test procedure	Type	Location	Location within meniscus	Orientation	Modulus (MPa) (Young's/compressive/ equilibrium)
Leslie et al. (49)	Unconfined (load/deformation)	16 menisci	0.89 to 2.69	Strain of 20%	Human	NA	Midanterior	Circumferential	10.00
								Radial	13.00
								Axial	19.00
				Strain of 80%			Midanterior	Circumferential	288.00
								Radial	287.00
								Axial	299.00
Gabrion et al. (126)	Unconfined	18 samples	Cubic	Strain of 2%	Porcine	NA	Central	Circumferential	0.04
								Radial	0.04
								Axial	0.12
Chia & Hull (50)	Unconfined (stress–relaxation)	10 knees	2 × 2 × 2	At equilibrium strain of 3%	Human	Medial	Anterior	Axial	0.04
								Radial	0.04
							Central	Axial	0.02
								Radial	0.02
							Posterior	Axial	0.03
								Radial	0.03
				At equilibrium strain of 6%			Anterior	Axial	0.05
								Radial	0.07
							Central	Axial	0.03
								Radial	0.02
							Posterior	Axial	0.01
								Radial	0.06
				At equilibrium strain of 9%			Anterior	Axial	0.07
								Radial	0.04
							Central	Axial	0.05
								Radial	0.03
							Posterior	Axial	0.04
								Radial	0.06

(*Continued*)

Table 3 (*Continued*)

Reference	Test method	Number of samples	Dimensions (mm)	Test procedure	Type	Location	Location within meniscus	Orientation	Modulus (MPa) (Young's/compressive/ equilibrium)
				At equilibrium strain of 12%			Anterior	Axial	0.14
								Radial	0.10
							Central	Axial	0.08
								Radial	0.03
							Posterior	Axial	0.03
								Radial	0.10
				Physiological loading rate at 12%, strain at 3%			Anterior	Axial	0.14
								Radial	0.10
							Central	Axial	0.06
								Radial	0.05
							Posterior	Axial	0.04
								Radial	0.08
				Physiological loading rate at 12%, strain at 6%			Anterior	Axial	0.28
								Radial	0.20
							Central	Axial	0.13
								Radial	0.11
							Posterior	Axial	0.08
								Radial	0.11
				Physiological loading rate at 12%, strain at 9%			Anterior	Axial	0.57
								Radial	0.45
							Central	Axial	0.30
								Radial	0.24
							Posterior	Axial	0.18
								Radial	0.18
				Physiological loading rate at 12%; strain at 12%			Anterior	Axial	1.13
								Radial	0.97
							Central	Axial	0.67
								Radial	0.55
							Posterior	Axial	0.36
								Radial	0.30

(*Continued*)

Table 3 (*Continued*)

Reference	Test method	Number of samples	Dimensions (mm)	Test procedure	Type	Location	Location within meniscus	Orientation	Modulus (MPa) (Young's/compressive/ equilibrium)
Moyer et al. (52)	Nanoindentation (creep)	8 knees	2	NA	Human	Medial	Anterior	Unknown	1.63
							Central		1.67
							Posterior		1.47
Moyer et al. (51)	Nanoindentation (creep)	8 knees	2	NA	Human	Medial	Anterior	Unknown	1.42
							Central		1.25
							Posterior		1.33
						Lateral	Anterior		1.50
							Central		1.48
							Posterior		1.56
Baro et al. (53)	Indentation (site and rate dependency)	16 knees	10 × 10 × 3	NA	Bovine	Medial	Anterior	Unknown	0.81
							Central		0.63
							Posterior		0.31
Lakes et al. (42)	Unconfined (stress–relaxation)	15 menisci	5 × 3.5	At 20% strain	Porcine	Medial	Unknown	Unknown	12.5
Abdelgaied et al. (122)	Indentation (creep)	12–16 samples	8 × 3	0.05 MPa stress	Porcine	Medial	Central	Unknown	0.29
			8 × 1.5						0.19
Fischenich et al. (127)	Indentation (indentation–relaxation	1–8 samples	NA	NA	Human	Medial	Anterior	Unknown	0.20
						Lateral	Anterior		0.20
							Posterior		0.28
Levillain et al. (128)	Indentation (indentation–relaxation)	6 animals	1	NA	Rabbit	Medial	Anterior		0.60
							Posterior		0.15

Abbreviation: NA, not applicable.

Table 4 Meniscus tear patterns

Tear type	Description	Reference(s)
Horizontal tears	Begin at the inner margin and extend toward the capsule; generally not visible by arthroscopy or MRI. Frequency is associated with age; commonly accompanied by meniscal cysts. Mechanically stable; usually asymptomatic but may give rise to flaps	129, 130
Longitudinal/ bucket-handle tears	Occur along the long axis of the meniscus between the circumferential collagen fibers; may eventually extend into bucket-handle tears. Bucket-handle tears occur in young patients after knee trauma and cause mechanical symptoms or true locking of the knee	130, 131
Oblique/flap tears	May give rise to a flap, which gets caught within the joint during flexion. Usually found between the posterior and middle third of the meniscus. A flap tear results from a short-segment, horizontal meniscal tear with either superior or inferior displacement of a meniscal fragment	130, 132, 133
Radial tears	Occur on the radial axis of the meniscus, perpendicular to the long axis. They section the circumferential collagen fibers, disrupting the meniscal hoop stress and thereby affecting its functionality to transmit load. Commonly found in the avascular zone, and thus are not responsive to repair. Arthroscopy shows that up to 25% of all meniscus tears are radial	131, 132, 134, 135
Complex and degenerative tears	Combination of longitudinal, radial, and horizontal tears. May not be associated with a trauma; may have an insidious onset. Degenerative tears are not associated with trauma and result from slowly developing changes of mucoid degeneration and shear stresses on the meniscus. The exact etiology of degenerative meniscus tear is still unclear; may be associated with the OA disease process. Usually observed in elderly patients; associated with increased risk of radial displacement of the meniscus and meniscus deformation. Degenerative tears usually have no healing capability and are not amenable to repair	131, 136
Root tears	Typically radial-type tears occurring within 1 cm of the meniscal insertion to bone. Posterior of the medial meniscus is most frequently affected. When a root tear occurs, the contact pressure experienced by the medial compartment is of the same magnitude as a total medial meniscectomy, leading to accelerated progression of OA	131, 135, 137–139
Discoid meniscus tears	Due to congenital variance and are abnormalities of the meniscus; most common in Asian populations. Patterns can be classified as type I, II, or III. Type I (incomplete discoid) is larger than the normal meniscus with attachments intact. Type II (complete discoid) covers the entire tibial plateau and has normal attachments. Type III (Wrisberg type) lacks a posterior capsular attachment. Young patients with a torn discoid lateral meniscus display more pronounced valgus inclination of the lower limb versus patients with a torn nondiscoid lateral meniscus	140, 141

Abbreviations: MRI, magnetic resonance imaging; OA, osteoarthritis.

injury to several months later, which may be another key factor in hindering cartilage regeneration (63). In general, meniscal tears are often classified only according to their tear pattern (**Table 4**) or classified clinically into peripheral meniscal lesions and avascular meniscal lesions. **Figure 3** illustrates the most common meniscal tears.

Depending on the type of meniscal tear, various treatments are possible. These include (*a*) no surgery with conservative therapy only, (*b*) partial or complete meniscectomy, (*c*) meniscal repair, and (*d*) meniscus implantation. Therefore, when a tear is identified, the tear pattern and location information are essential to plan the treatment. Determining which patients will benefit from a particular treatment can be challenging, as treatment success is affected by many factors, such as

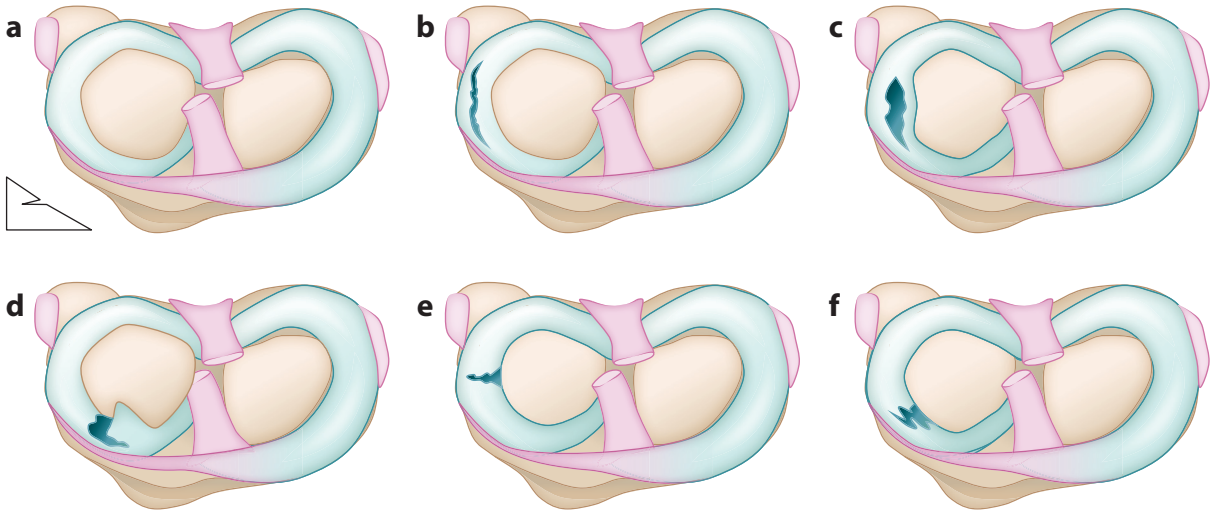

Figure 3

Most common meniscus tears. (*a*) Horizontal tear (cleavage), as shown by the line drawing below the illustration. (*b*) Longitudinal or circumferential tear. (*c*) Bucket-handle tear. (*d*) Oblique tear (flap). (*e*) Radial tear. (*f*) Complex/degenerative tear.

the tear's age, location, and pattern; the patient's age and activity level; and any associated injuries. Obesity, female sex, and preexisting early-stage OA are risk factors that increase the likelihood of developing OA following meniscectomy (64). Meniscectomy is known to predispose the adjacent articular cartilage to increased contact forces, resulting in the early onset of degenerative OA (33, 65). Nevertheless, meniscectomy is still the predominant treatment for meniscal tears. Montgomery et al. (54) suggest that 96% of patients undergo meniscectomy, with only 4% undergoing meniscal repair.

4.1. Meniscectomy

Meniscectomy generates high contact stress on the articular cartilage, which leads to degradation and development of OA. This is because the tibiofemoral contact area is significantly decreased while the contact pressure is considerably increased (66). A finite-element model showed that after meniscectomy the shear stress at the bone–cartilage interface is approximately 150% (67).

In a long-term clinical study, Roos et al. (68) compared meniscectomized knees with controls, confirming that increased pressure leads to radiographic evidence of OA. Furthermore, removal of the lateral meniscus leads to greater risk of developing OA compared with removal of its medial counterpart (69). This is because the lateral meniscus covers a greater percentage of the tibial plateau and carries 70% of the compartment load. Additionally, the lateral tibial plateau is slightly convex, and this juxtaposition of the convex lateral tibial plateau against the convex distal femoral condyle results in greater point loads. Because the medial tibial plateau is concave, it leads to lesser point loads and provides some congruity (70).

Once the effects of total meniscectomy became clear, interest in the field shifted toward preserving as much of the meniscus as possible. As a result, surgeons began performing partial meniscectomies. In a partial meniscectomy, only the torn area is removed and much of the meniscus remains intact, especially the peripheral rim, which is essential for transferring the axial load into hoop stress. Partial meniscectomy is an attractive treatment for meniscal tears because it allows athletes to return to sporting activities within 2 weeks (71). However, although early short-term

studies showed promising results (72, 73), long-term studies have shown that partial meniscectomy does not prevent joint degeneration, but merely delays it (74). For patients with a meniscal tear and mild to moderate knee OA who were treated with either (*a*) arthroscopic partial meniscectomy and postoperative physical therapy or (*b*) physical therapy alone, there were no significant differences between the two groups in terms of the magnitude of improvement in functional status and pain after 6 and 12 months (75). Overall, the literature suggests that there is no significant difference in outcome between physical therapy only and partial meniscectomy. Additionally, physical therapy before surgery does not compromise the surgical outcome (76). A recent study (77) reported that patients with meniscal tears and knee OA treated with arthroscopic meniscectomy had a threefold-increased risk of future knee replacement surgery.

The value of arthroscopic surgery for meniscus tears continues to be debated, in particular for degenerative knees (78–80). Recent systematic reviews and meta-analyses have presented evidence that arthroscopic knee surgery has little benefit for most patients with knee pain (81–84). On the basis of these reviews, patients with degenerative knee disease have been recommended not to undergo arthroscopic knee surgery (85). Due to the adverse effects of meniscectomies and predisposition of the knee to subsequent disease progression and accelerated degenerative changes once injured, surgeons and researchers are now focusing on preservation, repair, and regeneration of the meniscus in an effort to halt the onset of disease and knee arthroplasty.

4.2. Meniscal Repair

The avascular nature of the meniscus poses the most significant obstacle to repair of this tissue, as limited blood supply prevents the meniscus from healing (86). However, whenever possible, meniscal repair is preferred over meniscectomy. Meniscal repair techniques can be categorized as inside out, outside in, or all inside (33).

Inside-out repair involves the use of a single- or double-barreled cannula, and sutures are passed from inside to outside using long flexible needles. In this technique, a cannulated 18-gauge spinal needle is passed across the tear from the outside in. The suture is then passed through the lumen of the needle and pulled through the arthroscopic ipsilateral portal. An interference knot is then tied, and the suture is pulled back. The free ends are tied together over the capsule through an accessory skin incision to stabilize the tear (87). Despite their promise, all-inside meniscal repair devices have demonstrated higher failure and complication rates compared with other repair techniques. In an effort to overcome these problems, researchers have developed all-inside meniscal repair devices that are flexible and suture based and allow for variable compression and tensioning across the tear (88). A recent review that compared the inside-out technique with modern all-inside devices found no differences in failure rates, functional outcome scores, or complication rates (56); however, the quality of the evidence comparing all-inside and inside-out meniscal repair remains low.

The gold standard for meniscal repair remains the inside-out technique. The success rate averages 60–80% for isolated meniscal repairs and up to 90% when repaired in conjunction with the anterior cruciate ligament (89). The main disadvantage of this technique is the risk of neurovascular damage, as the peroneal nerve can be injured on the lateral side and the saphenous nerve and vein are at risk on the medial side (87).

4.3. Allograft

Meniscal allograft transplants were initially performed in open surgery; at present, they are mostly performed in arthroscopically assisted and arthroscopic procedures (90). Allografts may simply be secured in place by peripheral suturing (91, 92). However, bone bridge or plug fixation, combined

with peripheral suturing, is the preferred method (92). In the plug fixation method, the allograft is implanted using anterior and posterior bone plugs through transosseous tunnels. In the bone bridge method, the bone bridge is secured to the tibia using transosseous sutures (61).

Meniscal transplantation has become an accepted treatment for relatively young, active, symptomatic meniscectomized patients (93). Patients who display symptoms of early degenerative changes, such as pain and swelling, are typical candidates for allograft transplantation (61). Although allograft transplantation has been performed for 30 years, there have been no randomized clinical trials; estimates of its efficacy come from pooled case studies and systematic reviews (90). A systematic review by Verdonk et al. (94) found that allograft transplantation had a chondroprotective effect in 30–40% of patients, although OA may still develop in most patients. Second-look arthroscopy and magnetic resonance imaging (MRI) evaluations demonstrated healing of the allograft to the rim. However, all allografts showed some shrinkage over the long term (94).

Another systematic review used patient-reported outcome measures (PROMs) as an assessment tool (92). The Lysholm scale (0–100, with 100 the optimum) was the most commonly used PROM, and the average score improved from 56 preoperatively to a mean of 81 at final follow-up. Other PROMs, such as International Knee Documentation Committee and Tegner scores, showed similar results (92). Furthermore, a review of animal studies showed that, in comparison to meniscectomy, allografts do not prevent cartilage damage but merely slow it down (95). Recently, Samitier et al. (93) reviewed literature on the optimal timing of transplantation, finding that there was not enough evidence to suggest that meniscal allograft transplant must be performed at the same time as or immediately after meniscectomy to prevent cartilage degradation. Meniscal transplantation at 7 to 14 years' follow-up showed improved function and patient quality of life. In long-term follow-up, the overall failure rate was found to be 10–29%, which resulted in the need for knee arthroplasty.

In the short term, allografts improve knee function and reduce pain, which may justify their use in younger patients who are symptomatic after meniscectomy (96). However, meniscus allografts undergo a deleterious remodeling process and eventually fail. This procedure is not curative in the long term, and subsequent surgeries are to be expected (97).

5. COMMERCIALLY AVAILABLE SCAFFOLDS FOR MENISCAL REGENERATION

Meniscal scaffolds were developed in the early 1990s in an effort to prevent the negative effects of partial meniscectomies. The aim of a meniscal scaffold is to provide the structure and environment to allow and promote the ingrowth of tissue, with the eventual goal of degradation of the scaffold as well as replacement of new healthy meniscal tissue. Various materials are under investigation for use as a meniscus scaffold (98). However, only two meniscal scaffolds are commercially available: the Collagen Meniscus Implant (CMI®) and Actifit®.

The CMI (Ivy Sports Medicine GmbH, Gräfelfing, Germany), developed by Stone et al. (99, 100), is composed of collagen type I from purified bovine Achilles tendon with supplemented glycosaminoglycans. The scaffold is cross-linked with aldehydes and is molded in the shape of the medial or lateral meniscus. The scaffold is bioresorbable and is usually resorbed over 12 to 18 months (101). For the meniscus implant to work effectively, the meniscal rim must be intact in order to support hoop stress and serve as a cell source for the scaffold. If the meniscal rim is deficient or extruded outside the joint margin, it will not provide the required support (90).

Monllau et al. (102) studied the clinical outcome of CMIs implanted in injured medial menisci after a minimum of 10 years' follow-up. Twenty-five patients received the implant, which overall provided significant pain relief and functional improvement. However, this study lacked a control

group and was a nonrandomized trial (102). A nonrandomized study by Zaffagnini et al. (103) on 33 patients compared use of the CMI in the medial meniscus to partial meniscectomy at a minimum follow-up of 10 years. These authors used several clinical outcome scores along with radiography and MRI to evaluate the effectiveness of the CMI. Patients who received an implant reported significantly lower scores for pain and displayed higher activity levels, and radiographic evaluation demonstrated significantly less joint space narrowing (103). Despite reports of improved clinical scoring with implantation of the CMI, some studies have observed drawbacks of the implant. For example, the CMI shrinks over time (102–106). Furthermore, its signal intensity does not match that of native meniscus (102, 103, 105), suggesting that the regenerated tissue is not fibrocartilage, and it has been reported to generate predominantly scar tissue in its place (106).

Scaffold fixation and retention have also posed problems, due to the scaffold's highly porous structure and insufficient robustness and strength, leading to challenges in handling during arthroscopic procedures as well as sutures cutting through the implant. A recent study (107) that explored the pull-out strength of different suture materials, along with the type or temperature of irrigation fluid, for the fixation of the CMI found that implant stability can be improved by altering the type of suture material and irrigation fluid and electrolyte-free mannitol–sorbitol irrigation fluid provided the best biomechanical properties. Overall, clinical studies have produced inconclusive results. Long-term randomized controlled trials conducted in large populations will be required to confirm the benefits of the CMI.

The Actifit implant (Orteq, London, United Kingdom) is a porous scaffold made of synthetic material that promotes tissue ingrowth. The product is CE (Conformité Européene) marked and available in the European Union. Similar to the CMI, over time, the Actifit is replaced by tissue as it slowly degrades. It is made from stiff segments of polyurethane, which provides good mechanical strength, and soft segments of poly(ε-caprolactone), which provides flexibility and control of degradation. The soft segment constitutes 80% of the implant and is biodegradable (108, 109). Compared with the CMI, the Actifit is stiffer, with easier handling for insertion and a slower degradation rate once implanted (approximately 5 years).

More studies have been performed on the CMI than on Actifit, simply because the CMI has been in use longer. Verdonk et al. (109) published the first outcomes of a case study for Actifit with 52 patients and a follow-up of 12 months. After 3 months, dynamic contrast–enhanced MRI scans revealed successful early tissue ingrowth into the scaffold. Biopsies were taken from the center of the inner free edge of the implanted scaffold at 12 months. All biopsies showed fully vital material, with no signs of necrosis or cell death, demonstrating the success of the scaffold in supporting cell growth. Furthermore, the authors observed a distinct, layered tissue organization resembling that of native human meniscus tissue (109). This finding was contradicted by a later study (101), which observed an edema-like signal rather than fibrocartilage. In a study with a follow-up period of 24 months, Verdonk et al. (110) demonstrated that patients had statistically significant improvements in both pain and function. Furthermore, more than 90% of the patients showed stabilization or improvement of the articular cartilage condition, suggesting that the implant has a chondroprotective effect.

More recently, Baynat et al. (111) studied 18 patients with an Actifit implant over a 24-month follow-up period. After 1 year, the mean Lysholm score was 92%, indicating excellent outcomes. Furthermore, MRI scans showed no degeneration of neighboring cartilage, and histological examination showed scaffold ingrowth by normal chondrocytes and fibrochondrocytes (111).

Although the Actifit implant has shown positive results, similar to the CMI it has not been the subject of long-term, randomized controlled studies. Only when these studies are conducted can the long-term benefits of the Actifit implant be determined.

6. COMMERCIALLY AVAILABLE MENISCAL REPLACEMENT

Currently, only one permanent or artificial meniscal replacement product is on the market: the NUsurface®. This implant requires the presence of the peripheral rim of the meniscus for implantation, indicating that at present there is no implant on the market for patients requiring a total meniscectomy.

The NUsurface (Active Implants, Memphis, TN) is a free-floating meniscal replacement implant made of polycarbonate urethane (PCU) and ultrahigh-molecular-weight polyethylene. The implant has been used in Europe under the CE mark since 2008 and in Israel since 2011. It is currently pending investigational device exemption approval in the United States. Originally, the implant was studied in vivo, as a fixed implant, circumferentially reinforced with Kevlar® fibers. The implant showed promising results in a sheep model, and 6 months postoperatively it remained securely in place and displayed high durability with no adverse effect on the articular cartilage (112). For human testing, the design of the implant was changed to free floating with no embedded fibers. The location of the implant was tracked during static weight-bearing conditions within a range of motion of 0° to 120°. During flexion, both the anterior and posterior sections of the implant moved significantly backward. Additionally, the radial displacement was observed to be larger in the implant than in the native meniscus (113).

The clinical results of the NUsurface were investigated in a short- to medium-term study. Clinical scores such as KOOS (knee injury and osteoarthritis outcome score) and Lysholm along with MRI data were obtained postoperatively at 1, 2, and 5 years; the results showed significant pain relief 1 year postoperatively. However, complications including inflammation and effusion occurred in 78% of the patients. Furthermore, 19 of the 41 implants were removed at 2 to 26 months' follow-up due to radial tear or rupture ($n = 7$); dislocation ($n = 4$); synovitis and hydrops, possibly due to reaction to polymer particles ($n = 2$); medial pressure caused by a too-large size ($n = 3$); and persistent pain or development of OA ($n = 3$). Overall, the investigators concluded that the short-term failure rates were too high to support widespread clinical use of the implant (114).

In meniscal implant designs, both the circumferential and axial/radial moduli are important determinants of the contact pressure distribution and the risk of OA (115). Furthermore, finite-element modeling has established that the optimum stiffness of an artificial meniscus should be in the range of 100–120 MPa to minimize the susceptibility of the articular cartilage to degeneration arising from excessive shear stresses (67).

7. FUTURE PROSPECTS FOR MENISCAL REGENERATION AND REPLACEMENT

Several scaffold materials, cells, and growth factors are currently being investigated for regeneration or replacement purposes in an effort to find alternative treatments to meniscectomy. The implants discussed in this section are expected to attract much attention in the coming years.

Azellon, a spin-off company from the University of Bristol, United Kingdom, is developing and commercializing a scaffold for tissue repair known as the Cell Bandage, with a primary focus on the treatment of white zone meniscal tears. The technology utilizes mesenchymal stem cells (MSCs) infused into a biological scaffold. A prototype version of the Cell Bandage has undergone trials in five patients, aged 18 to 45 years, with white zone meniscal lesions. The scaffold was made from collagen and seeded with autologous MSCs isolated from an iliac crest bone marrow biopsy. A 2-year follow-up showed encouraging results. Three patients were asymptomatic, with no evidence of recurrent tear on MRI; however, two patients required subsequent meniscectomy due to retear or nonhealing (116). The Cell Bandage is undergoing further development as part of an Innovate UK grant–funded project.

TRAMMPOLIN is a Dutch national consortium developing an anatomically shaped nonresorbable meniscus implant. The consortium consists of surgeons, tribological experts, biomechanical engineers, material scientists, and biologists. Private partners include DSM, Biomet, and Baat Medical, and academic partners include RUNMC, TU/e, and UMCG (see **http://www.lifesciencesatwork.nl/profile/trammpolin/**). The implant is made from PCU (Bionate® II 80A; DSM Biomedical, Berkeley, CA) produced via injection molding. A short-term study of meniscal replacement in a goat model (117) found that the implant did not cause an inflammatory response, and no sign of wear was observed after 3 months. However, implant fixation was not successful, and severe cartilage damage was observed in all animal models (117). Changes in articular cartilage tribology in the presence of PCU have been studied through the use of a cartilage–meniscus in vitro model, which mimicked the stance and swing phases of the gait cycle. During stance, a low coefficient of friction (COF) was observed in the cartilage implant model. However, during swing, high COF was observed, indicating a breakdown in interstitial fluid lubrication, which may lead to cartilage wear over the long-term (118). The manufacturers of this implant are currently focusing on new fixation strategies.

Orthonika, a spin-off company from Imperial College London, United Kingdom, is developing a novel total meniscal replacement, MenisciKnit™, which is the result of collaboration with Sierra MedTech. The implant is atomically designed and nondegradable and is based on a proprietary high-strength synthetic polymer with embedded reinforcing fibers. Its structure is intended to replicate the structure–function properties of the native meniscus, whereby the embedded fibers can replicate the hoop stress mechanism that allows for load redistribution. It also aims to replicate the underlying microstructure and anisotropic properties affiliated with the native tissue. The implant is currently in development at the preclinical stage.

8. CONCLUSION AND OUTLOOK

Meniscus cartilage is crucial for knee homeostasis, and clinicians are tending to treat meniscal tears with partial meniscectomy so as to preserve as much tissue as possible. However, this treatment is not sufficient to preserve appropriate contact biomechanics of the knee and leads to OA. Physical therapy alone may be more beneficial than partial meniscectomy. Therefore, more in-depth studies should be performed to confirm physical therapy as a preventative measure against further knee degeneration. Recent efforts toward meniscal tear treatment have concentrated on designing implants for regeneration and replacement purposes. Although good clinical results for meniscus implants have been reported, long-term, randomized controlled studies should be performed to determine their long-term effects. Finally, despite the progress in this field, the key issue remains the development of a biofunctional and patient-specific implant that has the biomechanical function of native meniscus and is capable of restoring knee contact mechanics. The unique and complex structure of the meniscus renders the creation of such an implant a challenging task. It is likely that future therapies will involve biopolymers, which exhibit immunomodulatory properties.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

M.N.C., A.K.G., and C.A.M. acknowledge the Johnson & Johnson 3D Printing Centre of Excellence, Manufacturing Technology and Innovation, and Automation Centre of Excellence. C.A.M.

thanks the Irish Research Council for support under Project ID-EPSPG/2015/93. J.S.C. and J.M.O. acknowledge the Portuguese Foundation for Science and Technology (FCT) for financial support provided under the program "Investigador FCT" (IF/00115/2015 and IF/01285/2015, respectively).

LITERATURE CITED

1. Petersen W, Tillmann B. 1995. Age-related blood and lymph supply of the knee menisci. A cadaver study. *Acta Orthop. Scand.* 66:308–12
2. Makris EA, Hadidi P, Athanasiou KA. 2011. The knee meniscus: structure–function, pathophysiology, current repair techniques, and prospects for regeneration. *Biomaterials* 32:7411–31
3. Rongen JJ, van Tienen TG, van Bochove B, Grijpma DW, Buma P. 2014. Biomaterials in search of a meniscus substitute. *Biomaterials* 35:3527–40
4. Danzig L, Resnick D, Gonsalves M, Akeson WH. 1983. Blood supply to the normal and abnormal menisci of the human knee. *Clin. Orthop. Relat. Res.* 172:271–76
5. Arnoczky SP, Warren RF. 1982. Microvasculature of the human meniscus. *Am. J. Sports Med.* 10:90–95
6. Pauli C, Grogan SP, Patil S, Otsuki S, Hasegawa A, et al. 2011. Macroscopic and histopathologic analysis of human knee menisci in aging and osteoarthritis. *Osteoarthr. Cartil.* 19:1132–41
7. Cengiz IF, Pereira H, Silva-Correia J, Ripoll PL, Espregueira-Mendes J, et al. 2017. Meniscal lesions: from basic science to clinical management in footballers. In *Injuries and Health Problems in Football: What Everyone Should Know*, ed. J Espregueira-Mendes, pp. 145–63. Berlin: Springer
8. Pereira H, Cengis IF, Silva-Correia J, Cucciarini M, Gelber PE, et al. 2016. Histology-ultrastructure-biology. In *Surgery of the Meniscus*, ed. C Hulet, H Pereira, G Peretti, M Denti, pp. 23–33. Berlin: Springer
9. Voloshin AS, Wosk J. 1983. Shock absorption of meniscectomized and painful knees: a comparative in vivo study. *J. Biomed. Eng.* 5:157–61
10. Krause WR, Pope MH, Johnson RJ, Wilder DG. 1976. Mechanical changes in the knee after meniscectomy. *J. Bone Jt. Surg. Am.* 58:599–604
11. Shrive NG, O'Connor JJ, Goodfellow JW. 1978. Load-bearing in the knee joint. *Clin. Orthop. Relat. Res.* 131:279–87
12. Herwig J, Egner E, Buddecke E. 1984. Chemical changes of human knee joint menisci in various stages of degeneration. *Ann. Rheum. Dis.* 43:635–40
13. McDermott ID, Masouros SD, Amis AA. 2008. Biomechanics of the menisci of the knee. *Curr. Orthop.* 22:193–201
14. Ghosh P, Ingman AM, Taylor TK. 1975. Variations in collagen, non-collagenous proteins, and hexosamine in menisci derived from osteoarthritic and rheumatoid arthritic knee joints. *J. Rheumatol.* 2:100–7
15. Wu JJ, Eyre DR, Slayter HS. 1987. Type VI collagen of the intervertebral disc. Biochemical and electron-microscopic characterization of the native protein. *Biochem. J.* 248:373–81
16. Eyre DR, Wu JJ. 1983. Collagen of fibrocartilage: a distinctive molecular phenotype in bovine meniscus. *FEBS Lett.* 158:265–70
17. McDevitt C, Webber R. 1990. The ultrastructure and biochemistry of meniscal cartilage. *Clin. Orthop. Relat. Res.* 252:8–18
18. Beaupre A, Choukroun R, Guidouin R, Garneau R, Gerardin H, Cardou A. 1986. Knee menisci: correlation between microstructure and biomechanics. *Clin. Orthop. Relat. Res.* 208:72–75
19. Petersen W, Tillmann B. 1998. Collagenous fibril texture of the human knee joint menisci. *Anat. Embryol.* 197:317–24
20. Bullough PG, Munuera L, Murphy J, Weinstein AM. 1970. The strength of the menisci of the knee as it relates to their fine structure. *Bone Jt. J.* 52:564–70
21. Andrews SHJ, Rattner JB, Abusara Z, Adesida A, Shrive NG, Ronsky JL. 2014. Tie-fibre structure and organization in the knee menisci. *J. Anat.* 224:531–37

22. Skaggs DL, Warden WH, Mow VC. 1994. Radial tie fibers influence the tensile properties of the bovine medial meniscus. *J. Orthop. Res.* 12:176–85
23. Bansal S, Mandalapu S, Aeppli C, Qu F, Szczesny SE, et al. 2017. Mechanical function near defects in an aligned nanofiber composite is preserved by inclusion of disorganized layers: insight into meniscus structure and function. *Acta Biomater.* 56:102–9
24. Ghosh P, Taylor TK. 1987. The knee joint meniscus: a fibrocartilage of some distinction. *Clin. Orthop. Relat. Res.* 224:52–63
25. Habuchi H, Yamagata T, Iwata H, Suzuki S. 1973. The occurrence of a wide variety of dermatan sulfate chondroitin sulfate copolymers in fibrous cartilage. *J. Biol. Chem.* 248:6019–28
26. Adams ME, Muir H. 1981. The glycosaminoglycans of canine menisci. *Biochem. J.* 197:385–89
27. Sanchez-Adams J, Willard VP, Athanasiou KA. 2011. Regional variation in the mechanical role of knee meniscus glycosaminoglycans. *J. Appl. Physiol.* 111:1590–96
28. Nakano T, Thompson JR, Aherne FX. 1986. Distribution of glycosaminoglycans and the nonreducible collagen crosslink, pyridinoline in porcine menisci. *Can. J. Vet. Res.* 50:532–36
29. Nakano T, Dodd CM, Scott PG. 1997. Glycosaminoglycans and proteoglycans from different zones of the porcine knee meniscus. *J. Orthop. Res.* 15:213–20
30. Katsuragawa Y, Saitoh K, Tanaka N, Wake M, Ikeda Y, et al. 2010. Changes of human menisci in osteoarthritic knee joints. *Osteoarthr. Cartil.* 18:1133–43
31. Ghadially FN, Lalonde JM, Wedge JH. 1983. Ultrastructure of normal and torn menisci of the human knee joint. *J. Anat.* 136:773–91
32. van der Bracht H, Verdonk R, Verbruggen G, Elewaut D, Verdonk P. 2007. Cell-based meniscus tissue engineering. *Top. Tissue Eng.* 3:1–13
33. Scotti C, Hirschmann MT, Antinolfi P, Martin I, Peretti GM. 2013. Meniscus repair and regeneration: review on current methods and research potential. *Eur. Cell Mater.* 26:150–70
34. Nakata K, Shino K, Hamada M, Mae T, Miyama T, et al. 2001. Human meniscus cell: characterization of the primary culture and use for tissue engineering. *Clin. Orthop. Relat. Res.* 391:208–18
35. McDevitt CA, Mukherjee S, Kambic H, Parker R. 2002. Emerging concepts of the cell biology of the meniscus. *Curr. Opin. Orthop.* 13:345–50
36. McDevitt CA, Li H, Zaramo C, Prajapati R. 2001. *The isolation of a cell–pericellular matrix complex from meniscus fibrocartilage: the fibrochondron*. Poster presented at Annu. Meet. Orthop. Res. Soc., 47th, San Francisco, Febr. 25–28
37. Verdonk PCM, Forsyth RG, Wang J, Almqvist KF, Verdonk R, et al. 2005. Characterisation of human knee meniscus cell phenotype. *Osteoarthr. Cartil.* 13:548–60
38. Cengiz IF, Pereira H, Pêgo JM, Sousa N, Espregueira-Mendes J, et al. 2017. Segmental and regional quantification of 3D cellular density of human meniscus from osteoarthritic knee. *J. Tissue Eng. Regen. Med.* 11:1844–52
39. Proctor CS, Schmidt MB, Whipple RR, Kelly MA, Mow VC. 1989. Material properties of the normal medial bovine meniscus. *J. Orthop. Res.* 7:771–82
40. Tissakht M, Ahmed AM. 1995. Tensile stress-strain characteristics human meniscal material. *J. Biomech.* 28:411–22
41. Goertzen DJ, Budney DR, Cinats JG. 1997. Methodology and apparatus to determine material properties of the knee joint meniscus. *J. Med. Eng. Phys.* 19:412–19
42. Lakes EH, Kline CL, McFetridge PS, Allen KD. 2015. Comparing the mechanical properties of the porcine knee meniscus when hydrated in saline versus synovial fluid. *J. Biomech.* 48:4333–38
43. Fithian DC, Kelly MA, Mow VC. 1990. Material properties and structure–function relationships in the menisci. *J. Clin. Orthop. Relat. Res.* 252:19–31
44. Newton PM, Mow VC. 1992. The effects of strain rate on the tensile properties of bovine meniscus. *Trans. Orthop. Res. Soc.* 17:626
45. Favenesi JA, Shaffer JC, Mow VC. 1983. Biphasic mechanical properties of knee meniscus. *Trans. Orthop. Res. Soc.* 8:57
46. Sweigart MA, Zhu CF, Burt DM, Deholl PD, Agrawal CM, et al. 2004. Intraspecies and interspecies comparison of the compressive properties of the medial meniscus. *Ann. Biomed. Eng.* 32:1569–79

47. Joshi MD, Suh JK, Marui T, Woo SLY. 1995. Interspecies variation of compressive biomechanical properties of the meniscus. *J. Biomed. Mater. Res.* 29:823–28
48. Andrews SHJ, Rattner JB, Shrive NG, Ronsky JL. 2015. Swelling significantly affects the material properties of the menisci in compression. *J. Biomech.* 48:1485–89
49. Leslie BW, Gardner DL, McGeough JA, Moran RS. 2000. Anisotropic response of the human knee joint meniscus to unconfined compression. *Proc. Inst. Mech. Eng. H* 214:631–35
50. Chia HN, Hull ML. 2008. Compressive moduli of the human medial meniscus in the axial and radial directions at equilibrium and at a physiological strain rate. *J. Orthop. Res.* 26:951–56
51. Moyer JT, Priest R, Bouman T, Abraham AC, Haut Donahue TL. 2013. Indentation properties and glycosaminoglycan content of human menisci in the deep zone. *Acta Biomater.* 9:6624–29
52. Moyer JT, Abraham AC, Donahue TLH. 2012. Nanoindentation of human meniscal surfaces. *J. Biomech.* 45:2230–35
53. Baro VJ, Bonnevie ED, Lai X, Price C, Burris DL, Wang L. 2013. Functional characterization of normal and degraded bovine meniscus: rate-dependent indentation and friction studies. *Bone* 51:232–40
54. Montgomery SR, Zhang A, Ngo SS, Wang JC, Hame SL. 2013. Cross-sectional analysis of trends in meniscectomy and meniscus repair. *Orthopedics* 36:e1007–13
55. Jones JC, Burks R, Owens BD, Sturdivant RX, Svoboda SJ, Cameron KL. 2012. Incidence and risk factors associated with meniscal injuries among active-duty US military service members. *J. Athl. Train.* 47:67–73
56. Fillingham YA, Riboh JC, Erickson BJ, Bach BR, Yanke AB. 2017. Inside-out versus all-inside repair of isolated meniscal tears: an updated systematic review. *Am. J. Sports Med.* 45:234–42
57. Steinbrück K. 1999. [Epidemiology of sports injuries—25-year-analysis of sports orthopedic–traumatologic ambulatory care.] *Sport. Sport.* 13:38–52 (In German)
58. Casteleyn PP, Handelberg F, Opdecam P. 1988. Traumatic haemarthrosis of the knee. *Bone Jt. J.* 70:404–6
59. Drosos GI, Pozo JL. 2004. The causes and mechanisms of meniscal injuries in the sporting and non-sporting environment in an unselected population. *Knee* 11:143–49
60. Baker BE, Peckham AC, Pupparo F, Sanborn JC. 1985. Review of meniscal injury and associated sports. *Am. J. Sports Med.* 13:1–4
61. Fox AJS, Wanivenhaus F, Burge AJ, Warren RF, Rodeo SA. 2015. The human meniscus: a review of anatomy, function, injury, and advances in treatment. *Clin. Anat.* 28:269–87
62. Pihl K, Englund M, Lohmander LS, Jørgensen U, Nissen N, et al. 2017. Signs of knee osteoarthritis common in 620 patients undergoing arthroscopic surgery for meniscal tear. *Acta Orthop.* 88:90–95
63. Bigoni M, Turati M, Sacerdote P, Gaddi D, Piatti M, et al. 2017. Characterization of synovial fluid cytokine profiles in chronic meniscal tear of the knee. *J. Orthop. Res.* 35:340–46
64. Englund M, Lohmander LS. 2004. Risk factors for symptomatic knee osteoarthritis fifteen to twenty-two years after meniscectomy. *Arthritis Rheum.* 50:2811–19
65. Guo W, Liu S, Zhu Y, Yu C, Lu S, et al. 2015. Advances and prospects in tissue-engineered meniscal scaffolds for meniscus regeneration. *Stem Cells Int.* 2015:517520
66. Fukubayashi T, Kurosawa H. 1980. The contact area and pressure distribution pattern of the knee. A study of normal and osteoarthritic knee joints. *Acta Orthop. Scand.* 51:871–79
67. Vaziri A, Nayeb-Hashemi H, Singh A, Tafti BA. 2008. Influence of meniscectomy and meniscus replacement on the stress distribution in human knee joint. *Ann. Biomed. Eng.* 36:1335–44
68. Roos H, Laurbn M, Adalberth T, Roos EWAM, Jonsson K, et al. 1998. Knee osteoarthritis after meniscectomy prevalence of radiographic changes after twenty-one years, compared with matched controls. *Arthritis Rheum.* 41:687–93
69. Chatain F, Adeleine P, Chambat P, Neyret P. 2003. A comparative study of medial versus lateral arthroscopic partial meniscectomy on stable knees: 10-year minimum follow-up. *Arthroscopy* 19:842–49
70. McDermott I. 2011. Meniscal tears, repairs and replacement: their relevance to osteoarthritis of the knee. *Br. J. Sports Med.* 45:292–97
71. Carpanen D, Hillstrom H, Walker R, Reisse F, Cheah K, Mootanah R. 2016. Partial meniscectomy: How much can be removed before reconstruction is required? *Bone Jt.* 98(Suppl. 9):54

72. Northmore-Ball MD, Dandy DJ, Jackson RW. 1983. Arthroscopic, open partial, and total meniscectomy: a comparative study. *Bone Jt. J.* 65:400–4
73. Jaureguito JW, Elliot JS, Lietner T, Dixon LB, Reider B. 1995. The effects of arthroscopic partial lateral meniscectomy in an otherwise normal knee: a retrospective review of functional, clinical, and radiographic results. *Arthroscopy* 11:29–36
74. Faunø P, Nielsen AB. 1992. Arthroscopic partial meniscectomy: a long-term follow-up. *Arthroscopy* 8:345–49
75. Katz JN, Brophy RH, Chaisson CE, De Chaves L, Cole BJ, et al. 2013. Surgery versus physical therapy for a meniscal tear and osteoarthritis. *N. Engl. J. Med.* 368:1675–84
76. Katz JN, Wright J, Spindler KP, Mandl LA, Safran-Norton CE, et al. 2016. Predictors and outcomes of crossover to surgery from physical therapy for meniscal tear and osteoarthritis: a randomized trial comparing physical therapy and surgery. *J. Bone Jt. Surg. Am.* 98:1890–96
77. Rongen JJ, Rovers MM, van Tienen TG, Buma P, Hannink G. 2017. Increased risk for knee replacement surgery after arthroscopic surgery for degenerative meniscal tears: a multi-center longitudinal observational study using data from the osteoarthritis initiative. *Osteoarthr. Cartil.* 25:23–29
78. Järvinen TL, Guyatt GH. 2016. Arthroscopic surgery for knee pain: a highly questionable practice without supporting evidence of even moderate quality. *Br. J. Sports Med.* 50:1426–27
79. Thorlund JB. 2017. Deconstructing a popular myth: why knee arthroscopy is no better than placebo surgery for degenerative meniscal tears. *Br. J. Sports Med.* 51:1630–31
80. Thorlund JB, Englund M, Christensen R, Nissen N, Pihl K, et al. 2017. Patient reported outcomes in patients undergoing arthroscopic partial meniscectomy for traumatic or degenerative meniscal tears: comparative prospective cohort study. *BMJ* 2017:j356
81. Thorlund JB, Juhl CB, Roos EM, Lohmander LS. 2015. Arthroscopic surgery for degenerative knee: systematic review and meta-analysis of benefits and harms. *BMJ* 2015:350.h2747
82. Khan M, Evaniew N, Bedi A, Ayeni OR, Bhandari M. 2014. Arthroscopic surgery for degenerative tears of the meniscus: a systematic review and meta-analysis. *Can. Med. Assoc. J.* 186:1057–64
83. Devji T, Guyatt GH, Lytvyn L, Brignardello-Petersen R, Foroutan F, et al. 2017. Application of minimal important differences in degenerative knee disease outcomes: a systematic review and case study to inform BMJ Rapid Recommendations. *BMJ Open* 7:e015587
84. Brignardello-Petersen R, Guyatt GH, Buchbinder R, Poolman RW, Schandelmaier S, et al. 2017. Knee arthroscopy versus conservative management in patients with degenerative knee disease: a systematic review. *BMJ Open* 7:e016114
85. Siemieniuk RAC, Harris IA, Agoritsas T, Poolman RW, Brignardello-Petersen R, et al. 2017. Arthroscopic surgery for degenerative knee arthritis and meniscal tears: a clinical practice guideline. *BMJ* 357:j1982
86. Taylor SA, Rodeo SA. 2013. Augmentation techniques for isolated meniscal tears. *Curr. Rev. Musculoskelet. Med.* 6:95–101
87. Jouve F, Ovadia H, Pujol N, Beaufils P. 2010. Meniscal repair: technique. In *The Meniscus*, ed. P Beaufils, R Verdonk, pp. 119–28. Berlin: Springer
88. Tuman J, Haro MS, Foley S, Diduch DR. 2012. All-inside meniscal repair devices and techniques. *Expert Rev. Med. Devices* 9:147–57
89. Turman KA, Diduch DR, Miller MD. 2009. All-inside meniscal repair. *Sports Health* 1:438–44
90. Smith NA, Parkinson B, Spalding T. 2015. Meniscal allograft transplantation and meniscal scaffolds: Where are we up to now? *Orthop. Trauma* 29:31–37
91. McDermott ID, Lie DTT, Edwards A, Bull AMJ, Amis AA. 2008. The effects of lateral meniscal allograft transplantation techniques on tibio-femoral contact pressures. *Knee Surg. Sport Traumatol. Arthrosc.* 16:553–60
92. Smith NA, MacKay N, Costa M, Spalding T. 2014. Meniscal allograft transplantation in a symptomatic meniscal deficient knee: a systematic review. *Knee Surg. Sport Traumatol. Arthrosc.* 23:270–79
93. Samitier G, Alentorn-Geli E, Taylor DC, Rill B, Lock T, et al. 2015. Meniscal allograft transplantation. Part 2: Systematic review of transplant timing, outcomes, return to competition, associated procedures, and prevention of osteoarthritis. *Knee Surg. Sport Traumatol. Arthrosc.* 23:323–33

94. Verdonk R, Volpi P, Verdonk P, Van Der Bracht H, Van Laer M, et al. 2013. Indications and limits of meniscal allografts. *Injury* 44(Suppl. 1):21–27
95. Rongen JJ, Hannink G, Van Tienen TG, Van Luijk J, Hooijmans CR. 2015. The protective effect of meniscus allograft transplantation on articular cartilage: a systematic review of animal studies. *Osteoarthr. Cartil.* 23:1242–53
96. Noyes FR, Barber-Westin S. 2015. Meniscal transplantation in symptomatic patients under fifty years of age: survivorship analysis. *Bone Jt. Surg. Am.* 97:1209–19
97. Noyes FR, Barber-Westin SD. 2016. Long-term survivorship and function of meniscus transplantation. *Am. J. Sports Med.* 44:2330–38
98. Murphy CA, Costa JB, Silva-Correia J, Oliveira JM, Reis RL, Collins MN. 2018. Biopolymers and polymers in the search of alternative treatments for meniscal regeneration: state of the art and future trends. *Appl. Mater. Today* 12:51–71
99. Stone KR, Rodkey WG, Webber R, McKinney L, Steadman JR. 1992. Meniscal regeneration with copolymeric collagen scaffolds in vitro and in vivo studies evaluated clinically, histologically, and biochemically. *Am. J. Sports Med.* 20:104–11
100. Stone KR, Steadman JR, Rodkey WG, Li ST. 1997. Regeneration of meniscal cartilage with use of a collagen scaffold. Analysis of preliminary data. *J. Bone Jt. Surg. Am.* 79:1770–77
101. Spencer SJ, Saithna A, Carmont MR, Dhillon MS, Thompson P, Spalding T. 2012. Meniscal scaffolds: early experience and review of the literature. *Knee* 19:760–65
102. Monllau JC, Gelber PE, Abat F, Pelfort X, Abad R, et al. 2011. Outcome after partial medial meniscus substitution with the collagen meniscal implant at a minimum of 10 years' follow-up. *Arthroscopy* 27:933–43
103. Zaffagnini S, Marcheggiani Muccioli GM, Lopomo N, Bruni D, Giordano G, et al. 2011. Prospective long-term outcomes of the medial collagen meniscus implant versus partial medial meniscectomy: a minimum 10-year follow-up study. *Am. J. Sports Med.* 39:977–85
104. Zaffagnini S, Giordano G, Vascellari A, Bruni D, Neri MP, et al. 2007. Arthroscopic collagen meniscus implant results at 6 to 8 years follow up. *Knee Surg. Sport Traumatol. Arthrosc.* 15:175–83
105. Genovese E, Angeretti MG, Ronga M, Leonardi A, Novario R, et al. 2007. Follow-up of collagen meniscus implants by MRI. *Radiol. Med.* 112:1036–48
106. Martinek V, Ueblacker P, Bräun K, Nitschke S, Mannhardt R, et al. 2006. Second generation of meniscus transplantation: in-vivo study with tissue engineered meniscus replacement. *Arch. Orthop. Trauma Surg.* 126:228–34
107. Gwinner C, Von Roth P, Schmidt S, Ode J, Wulsten D, Hoburg A. 2017. Biomechanical performance of a collagen meniscus implant with regard to suture material and irrigation fluid. *Knee* 24:726–32
108. de Groot J. 2010. Actifit, polyurethane meniscus implant: basic science. In *The Meniscus*, ed. P Beaufils, R Verdonk, pp. 383–88. Berlin: Springer
109. Verdonk R, Verdonk P, Huysse W, Forsyth R, Heinrichs E-L. 2011. Tissue ingrowth after implantation of a novel, biodegradable polyurethane scaffold for treatment of partial meniscal lesions. *Am. J. Sports Med.* 39:774–82
110. Verdonk P, Beaufils P, Bellemans J, Djian P, Heinrichs EL, et al. 2012. Successful treatment of painful irreparable partial meniscal defects with a polyurethane scaffold: two-year safety and clinical outcomes. *Am. J. Sports Med.* 40:844–53
111. Baynat C, Andro C, Vincent JP, Schiele P, Buisson P, et al. 2014. Actifit synthetic meniscal substitute: experience with 18 patients in Brest, France. *Orthop. Traumatol. Surg. Res.* 100:S385–89
112. Zur G, Linder-Ganz E, Elsner JJ, Shani J, Brenner O, et al. 2011. Chondroprotective effects of a polycarbonate-urethane meniscal implant: histopathological results in a sheep model. *Knee Surg. Sport Traumatol. Arthrosc.* 19:255–63
113. De Coninck T, Elsner JJ, Linder-Ganz E, Cromheecke M, Shemesh M, et al. 2014. In-vivo evaluation of the kinematic behavior of an artificial medial meniscus implant: a pilot study using open MRI. *Clin. Biomech.* 29:898–905
114. Van Der Straeten C, Doyen B, Dutordoir C, Goedertier W, Pirard S, Victor J. 2016. Short- and medium-term results of artificial meniscal implants. *Bone Jt. J.* 98(Suppl. 4):91

115. Haut Donahue TL, Hull ML, Rashid MM, Jacobs CR. 2003. How the stiffness of meniscal attachments and meniscal material properties affect tibio-femoral contact pressure computed using a validated finite element model of the human knee joint. *J. Biomech.* 36:19–34
116. Whitehouse MR, Howells NR, Parry MC, Austin E, Kafienah W, et al. 2016. Repair of torn avascular meniscal cartilage using undifferentiated autologous mesenchymal stem cells: from in vitro optimization to a first-in-human study. *Stem. Cells Transl. Med.* 6:1237–48
117. Vrancken ACT, Madej W, Hannink G, Verdonschot N, Van Tienen TG. 2015. Short term evaluation of an anatomically shaped polycarbonate urethane total meniscus replacement in a goat model. *PLOS ONE* 10:1–16
118. Majd SE, Rizqy AI, Kaper HJ, Schmidt TA, Kuijer R, Sharma PK. 2017. An in vitro study of cartilage–meniscus tribology to understand the changes caused by a meniscus implant. *Colloids Surf. B* 155:294–303
119. Lechner K, Hull ML, Howell SM. 2000. Is the circumferential tensile modulus within a human medial meniscus affected by the test sample location and cross-sectional area? *J. Orthop. Res.* 18:945–51
120. Muratsu H, Ishimoto K, Kurosaka M, Yoshima S, Mizuno K. 2000. *The mechanical mapping of the meniscus*. Poster presented at Annu. Meet. Orthop. Res. Soc., 46th, Orlando, FL, March 12–15
121. Sweigart MA, Athanasiou KA. 2005. Tensile and compressive properties of the medial rabbit meniscus. *Proc. Inst. Mech. Eng. H* 219:337–47
122. Abdelgaied A, Stanley M, Galfe M, Berry H, Ingham E, et al. 2015. Comparison of the biomechanical tensile and compressive properties of decellularised and natural porcine meniscus. *J. Biomech.* 48:1389–96
123. Creechley JJ, Krentz ME, Lujan TJ. 2017. Fatigue life of bovine meniscus under longitudinal and transverse tensile loading. *J. Mech. Behav. Biomed. Mater.* 69:185–92
124. Hacker SA, Woo SLY, Wayne JS, Kwan MK. 1992. Compressive properties of the human meniscus. *Trans. Orthop. Res. Soc.* 1992:627
125. Seitz MA, Galbusera F, Krais C, Ignatius A, Dürselen L. 2013. Stress–relaxation response of human menisci under confined compression conditions. *J. Mech. Behav. Biomed Mater.* 26:68–80
126. Gabrion A, Aimedieu P, Laya Z, Havet E, Mertl P, et al. 2005. Relationship between ultrastructure and biomechanical properties of the knee meniscus. *Surg. Radiol. Anat.* 27:507–10
127. Fischenich KM, Lewis J, Kindsfater KA, Bailey TS, Haut Donahue TL. 2015. Effects of degeneration on the compressive and tensile properties of human meniscus. *J. Biomech.* 48:1407–11
128. Levillain A, Magoariec H, Boulocher C, Decambron A, Viateau V, et al. 2017. Viscoelastic properties of rabbit osteoarthritic menisci: a correlation with matrix alterations. *J. Mech. Behav. Biomed. Mater.* 65:1–10
129. van Dijk CN. 2008. *ISAKOS/ESSKA standard terminology, definitions, classification and scoring systems for arthroscopy*. Report, ISAKOS/ESKA, Amsterdam
130. Mordecai SC, Al-Hadithy N, Ware HE, Gupte CM. 2014. Treatment of meniscal tears: an evidence based approach. *World J. Orthop.* 5:233–41
131. Nguyen JC, De Smet A, Graf BK, Rosas HG. 2014. MR imaging–based diagnosis and classification of meniscal tears. *Radiographics* 34:981–99
132. Maffulli N, Longo UG, Campi S, Denaro V. 2010. Meniscal tears. *Open Access J. Sports Med.* 1:45–54
133. Lecas LK, Helms CA, Kosarek FJ, Garret WE. 2000. Inferiorly displaced flap tears of the medial meniscus: MR appearance. *Am. J. Roentgenol.* 174:161–64
134. Harper KW, Helms CA, Lambert HS, Higgins LD. 2005. Radial meniscal tears: significance, incidence, and MR appearance. *Am. J. Roentgenol.* 185:1429–34
135. Jarraya M, Roemer FW, Englund M, Crema MD, Gale HI, et al. 2017. Meniscus morphology: Does tear type matter? A narrative review with focus on relevance for osteoarthritis research. *Semin. Arthritis Rheum.* 46:552–61
136. Englund M, Haugen IK, Guermazi A, Roemer FW, Niu J, et al. 2016. Evidence that meniscus damage may be a component of osteoarthritis: the Framingham study. *Osteoarthr. Cartil.* 24:270–73
137. Forkel P, Reuter S, Sprenker F, Achtnich A, Herbst E, et al. 2014. Different patterns of lateral meniscus root tears in ACL injuries: application of a differentiated classification system. *Knee Surg. Sport Traumatol. Arthrosc.* 23:112–18

138. Allaire R. 2008. Biomechanical consequences of a tear of the posterior root of the medial meniscus. *J. Bone Jt. Surg.* 90:1922–31
139. LaPrade CM, James EW, Cram TR, Feagin JA, Engebretsen L, et al. 2015. Meniscal root tears: a classification system based on tear morphology. *Am. J. Sports Med.* 43:363–69
140. Watanabe M, Takada S, Ikeuchi H. 1979. *Atlas of Arthroscopy*. Tokyo: Igaku-Shoin
141. Wang J, Xiong J, Xu Z, Shi H, Dai J, et al. 2015. Short-term effects of discoid lateral meniscectomy on the axial alignment of the lower limb in adolescents. *J. Bone Jt. Surg. Am.* 97:201–7