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Intraspecies and Interspecies Comparison of the Compressive Properties of the Medial Meniscus

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Abstract—Quantification of the compressive material properties of the meniscus is of paramount importance, creating a "gold-standard" reference for future research. The purpose of this study was to determine compressive properties in six animal models (baboon, bovine, canine, human, lapine, and porcine) at six topographical locations. It was hypothesized that topographical variation of the compressive properties would be found in each animal model and that interspecies variations would also be exhibited. To test these hypotheses, creep and recovery indentation experiments were performed on the meniscus using a creep indentation apparatus and analyzed via a finite element optimization method to determine the material properties. Results show significant intraspecies and interspecies variation in the compressive properties among the six topographical locations, with the moduli exhibiting the highest values in the anterior portion. For example, the anterior location of the human meniscus has an aggregate modulus of 160 ± 40 kPa, whereas the central and posterior portions exhibit aggregate moduli of 100 ± 30 kPa. Interspecies comparison of the aggregate moduli identifies the lapine anterior location having the highest value (450 ± 120 kPa) and the human posterior location having the lowest (100 ± 30 kPa). These baseline values of compressive properties will be of help in future meniscal repair efforts.

Keywords—Biomechanics, Material properties, Meniscal cartilage.

INTRODUCTION

The meniscus (Fig. 1) has been recognized clinically as a crucial structural element in the knee joint due to its exceptional biomechanical functions. For example, animal studies have shown that after total meniscectomy, knee articular cartilage develops osteoarthritic changes, suggesting that the meniscus protects the knee joint from degenerative joint disease.[9,15] Owing to its biomechanical significance, salvage of the damaged meniscus has drawn clinical attention.[8,19] To elucidate and improve healing of the meniscus, various animal models for studying the repair process of this soft tissue have been developed.[3,4,7,26] However, these and other animal models used to investigate the repair of the meniscus require detailed knowledge and baseline data of the biomechanical properties of normal and repaired menisci.

In an effort to better understand pathologic and traumatic processes in the knee meniscus, many studies have investigated the biomechanical behavior of this tissue. The meniscus is a viscoelastic material that undergoes compressive, tensile, and shear stresses during normal function. A multitude of studies have observed the effect of these stresses on meniscal tissue.[2,10–14,16,17,24,25,27,28] The results of these studies demonstrate that meniscal biomechanical properties are anisotropic and inhomogeneous, and vary with location (anterior, central, and posterior), testing direction (radial, axial, and circumferential), and surface (femoral and tibial). Most of the studies performed have been tensile studies,[10–12,16,24,25,27] with some compressive[13,14,17,24] and shear studies.[2,10,28]

One of the first compressive tests performed on the meniscus was performed by Proctor and coworkers.[24] This study used confined compression to determine the aggregate modulus and permeability of the bovine meniscus at different locations and depths. Results showed that the aggregate modulus from the superficial zone did not vary significantly depending on location, though specimens from the deep zone were found to be stiffer in the posterior portion than the anterior portion. Hacker and coworkers[13] tested disks from the anterior, central, and posterior portions of the human meniscus under confined compression. Their results showed that the posterior portion of the meniscus had the highest aggregate modulus and the anterior portion had the lowest aggregate modulus. Unfortunately, in the two aforementioned studies, the topographical compressive properties were only examined in bovine and human menisci. However, in a later study performed by Joshi and

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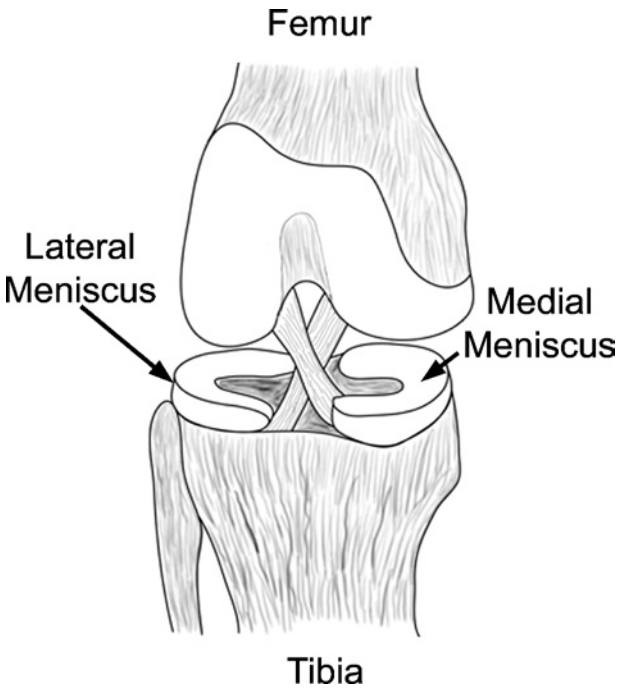

FIGURE 1. Schematic diagram of the knee. The joint space is elongated to show the location of the medial and lateral menisci.

coworkers,[14] biomechanical comparisons were performed among six species: human, bovine, monkey, canine, ovine, and porcine. Properties were determined through confined compression testing of plugs taken only from the posterior portion of the meniscus. This study found statistically significant differences among the animal models and showed that the ovine aggregate modulus most closely resembled the human aggregate modulus.[14] While this study did compare the interspecies variation among the animal models, only one location was used for the testing site.

While some biomechanical studies of the meniscus have been performed, no study has compared either the topographical variation in a multitude of different animal models or the variation at different testing locations among these animal models. However, two general trends have been noted in the previously performed studies as mentioned above: 1) the posterior portion of the human and bovine medial menisci had the highest aggregate modulus and 2) interspecies variation in biomechanical properties occurred in the posterior portion of the tissue. The purpose of this investigation was to test the following two hypotheses: (a) for intraspecies variation, the aggregate and shear moduli will be the greatest in the posterior portion of the tissue, and (b) for interspecies variation, the animal model will have a significant effect on the compressive material properties of the tissue. To test these hypotheses we quantified the compressive biomechanical properties (aggregate modulus – H_A, permeability – k, Poisson's ratio – (ν_S, and shear modulus – μ_S) of the medial meniscus and their topographical distribution in six animal models (human, bovine, monkey, canine, ovine, and porcine) using a creep indentation technique, which we believe may be a more physiologically relevant loading configuration. This approach, which uses both experimental and theoretical means, was then applied to quantify the biomechanical behavior at six topographical locations (anterior, central, and posterior portions; femoral and tibial side) of the medial meniscus.

MATERIALS AND METHODS

Specimen Preparation

Ten bovine medial menisci (1–2 year old animals), eight canine medial menisci (4-year-old animals), nine human medial menisci (average 33.3 years old), 15 baboon medial menisci (average 12.8 years old), six porcine medial menisci (about 1-year old), and 10 rabbit medial menisci (about 9 months old) were harvested from the knee joint. For storage between harvest and testing, the specimens were wrapped in gauze soaked with 0.15-M NaCl solution with protease inhibitors (*N*-ethylmalemide, 10 mM; benzamidine HCl, 5 mM; EDTA, 2 mM; and PMSF, 1 mM) and frozen at -20°C until time of testing. For testing, the menisci were bisected in the axial plane into the tibial and femoral aspects (with the exception of the rabbit, which was too small to perform this technique on reliably), and were then further divided into anterior, central, and posterior segments. A total of 318 mechanical tests were performed. Figure 2 shows a schematic layout of the testing procedure.

Creep Indentation

Menisci were tested mechanically to determine each meniscal specimen's aggregate modulus, Poisson's ratio, permeability, and shear modulus. A creep indentation apparatus[5,6] was used to quantify the creep and recovery deformation behavior of each specimen. The testing apparatus is able to load and unload the meniscus specimen automatically through a closed-loop control system. To test, each specimen was thawed for 1 h in normal saline containing protease inhibitors and then attached with cyanoacrylate cement to a sample holder. The sample holder was positioned with a spherical joint and lead screw assembly, allowing the meniscal surface to be oriented normal to the loading shaft. A tare load of 0.005–0.01 N was then applied with a 0.8–1.0-mm diameter, flat-ended, cylindrical rigid, porous indenter tip (50% porous, $\sim$50-μm pore diameter), and the tissue was allowed to reach tare creep equilibrium. Different combinations of the tare load, test load, and indenter tip were used to ensure that the response of the tissue was within its linear range, with the strain applied to the tissue being under 10%. Samples were tested within a narrow range of strain to minimize variation in testing among animal models. Equilibrium was

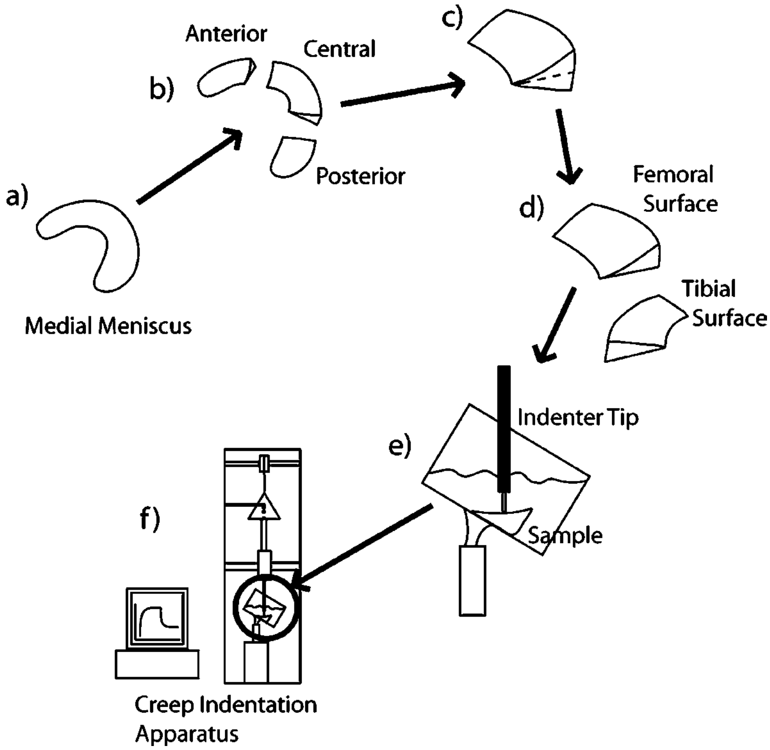

FIGURE 2. A schematic diagram of the testing procedure. The medial meniscus (a) is separated into anterior, central, and posterior regions (b). The meniscus is split in the transverse plane (c) and separated so that the femoral and tibial surfaces can be tested (d). The meniscal sample is then attached to the sample mount (e) and tested in the creep indentation apparatus (f).

automatically determined when the slope of the creep curve became smaller than 1×10^{-6} mm s^{-1}. Once creep equilibrium from the tare load was reached, the tissue was loaded with a step force of 0.02–0.04 N. The tissue's deformation was monitored with a linear variable differential transformer (LVDT) using a computer-based data acquisition system at a 0.25-μm deformation-resolution. The frictional resistance of the system was reduced with air bearings to less than 9.81×10^{-4} N. The bearings were driven with pressurized air (552 kPa) and the air was cleaned with a 5-μm particle filter and two 0.1-μm coalescing filters. The creep response of the specimen under the step force was monitored until equilibrium (defined as slope $< 1 \times 10^{-6}$ mm s^{-1}, or 2 h) was reached. At this point, the test force was automatically removed and the recovery phase began. When recovery equilibrium was achieved (defined as slope $< 1 \times 10^{-6}$ mm s^{-1}, or 1 h), data acquisition was stopped automatically. Overall, the automated creep indenter yielded the creep and recovery deformational behaviors of each meniscal specimen in response to a 0.02–0.04-N step load.

Thickness

The thickness was measured using two methods: First we simply used a micrometer to measure the overall approximate thickness at the test site. Following specimen mounting and creep indentation testing, thickness was also measured using a needle probe attached to a force transducer and an LVDT. The entire probe assembly was moved downward with a linear motor until the needle touched the meniscal surface. At this point, the force transducer noted a significant change in force on the needle probe and the needle continued to move through the sample. When the needle contacted the sample holder underneath the meniscal sample another significant change in the force on the needle probe was noted. The difference between the measured needle positions at the two force readings corresponded to specimen thickness.

Finite Element Modeling

The experimental data for each test site were analyzed using a finite element/nonlinear optimization modeling (FEO) method. This approach, which is based on biphasic finite element routines and nonlinear optimization techniques, uses the entire creep curve to calculate the intrinsic material properties of articular cartilage[6] and the meniscus. The output of this procedure depends significantly on an initial estimate of the tissue's properties. Thus, we used a semi-analytical/seminumerical biphasic procedure to obtain an estimate of the tissue's properties, before applying the finite element/nonlinear optimization routine.[6] More details can be found in a series of papers by Mow and coworkers.[18,20,21]

It should be noted that the tissue was modeled as an axisymmetric cylinder, which is only partially correct for meniscal architecture. The surface of the meniscus consists of isotropically oriented collagen fibers, whereas the deeper tissue has an anisotropic fiber alignment. Due to the small degree of strain placed on the tissue, we believe that the compressive testing only occurs in the isotropic portion, but this might not be the case. However, without knowing the thickness of this surface layer in all of the animal models, more complex modeling cannot be performed.

Statistical Analysis

For the intraspecies and interspecies data one-way analysis of variance (ANOVA) was used to determine statistical significance. In the intraspecies analysis, the aggregate modulus, Poisson's ratio, permeability, and shear modulus were set as the dependent variable and the topographical location as the independent variable. For the interspecies analysis the independent variables were split into the anterior, central, and posterior portions (femoral and tibial sides averaged) of each animal model, and the dependent variables were the same as for the intraspecies study. For both the intraspecies and interspecies analysis, if the F-test showed a significant difference ($p < 0.05$), a post hoc test was performed (Fisher's Protected Least Significant Difference) to compare sample sets. A significance level ($\alpha = 0.05$) was used in all the statistical tests performed.

RESULTS

From the creep-relaxation curve (Fig. 3) the four material properties (aggregate modulus, Poisson's ratio, permeability, and shear modulus) were determined. It should be noted that the time constant found for the tested animal models was much shorter than found by Mow and coworkers[20] for articular cartilage. This is probably due to articular cartilage having an eight-fold higher concentration of proteoglycans than the meniscus.[1] The intrinsic material properties of the six tested animal models exhibited a wide variation in both intraspecies and interspecies values

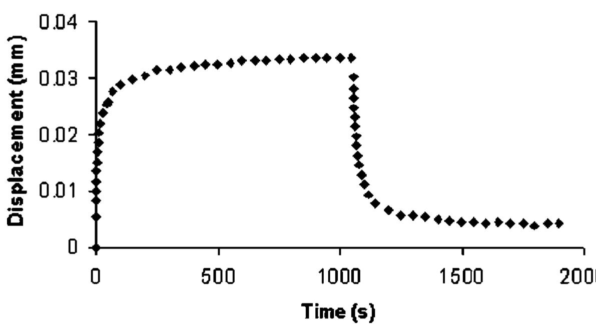

FIGURE 3. A typical creep-recovery curve from the anterior portion (femoral side) of the medial rabbit meniscus.

(Tables 1–6). The size of the testing groups were as follows: baboon, $n = 15$; bovine, $n = 10$; canine, $n = 8$; human, $n = 9$; lapine, $n = 5$; porcine, $n = 6$.

Intraspecies Topographical Variations

Aggregate Modulus

No statistical difference ($p > 0.14$) was found among the aggregate moduli at the six different locations on the meniscus (femoral side: anterior, central, posterior; tibial side: anterior, central, posterior) in the canine and baboon models. In the bovine model the femoral-anterior location was stiffer than any other location on the meniscus ($p < 0.04$). The tibial-anterior location was also stiffer than the femoral-posterior and tibial-central locations ($p < 0.03$). In the porcine model the femoral-anterior location was stiffer than any other location on the meniscus ($p < 0.002$). The tibial-anterior portion was also statistically different than the tibial-posterior location ($p < 0.05$). In the human and lapine models the anterior portion (both femoral and tibial side) was stiffer than the central or posterior portions of the meniscus ($p < 0.007$; Fig. 4).

Poisson's Ratio

No statistical difference ($p > 0.16$) was found for the Poisson's ratio at the six different locations on the meniscus (femoral side: anterior, central, posterior; tibial side: anterior, central, posterior) in all of the models with the exception of the lapine and baboon. In the lapine model, the tibial-anterior portion had a higher Poisson's ratio than the central and posterior portions of the tissue. In the baboon model, the central portion of the tissue had a higher Poisson's ratio than the anterior and tibial-posterior portions of the tissue ($p < 0.03$).

Permeability

No statistical difference ($p > 0.15$) was found for the permeability at the six different locations on the meniscus (femoral side: anterior, central, posterior; tibial side: anterior, central, posterior) in all of the models with the exception of the lapine model. In the rabbit, the anterior portion of the tissue had a higher permeability than the central and posterior portions of the tissue (both femoral and tibial side) ($p < 0.0005$).

Shear Modulus

No statistical difference ($p > 0.10$) was found among the shear moduli at the six different locations on the meniscus (femoral side: anterior, central, posterior; tibial side: anterior, central, posterior) in the canine and baboon models. In the bovine model the femoral-anterior location had a higher modulus than any other location on the meniscus ($p < 0.04$); the tibial-anterior location was also

TABLE 1. Baboon meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.17 ± 0.05	0 ± 0	1.16 ± 0.56	0.09 ± 0.03
	Central	0.18 ± 0.06	0.03 ± 0.04	1.08 ± 0.71	0.09 ± 0.03
	Posterior	0.18 ± 0.05	0.01 ± 0.03	1.36 ± 0.40	0.09 ± 0.03
Tibial					
	Anterior	0.16 ± 0.07	0 ± 0	1.05 ± 0.23	0.08 ± 0.03
	Central	0.18 ± 0.07	0.03 ± 0.08	1.55 ± 1.60	0.09 ± 0.03
	Posterior	0.15 ± 0.04	0 ± 0	1.36 ± 0.60	0.07 ± 0.02

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

TABLE 2. Bovine meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.21 ± 0.06	0 ± 0	6.22 ± 2.55	0.11 ± 0.03
	Central	0.14 ± 0.05	0.01 ± 0.01	5.73 ± 6.19	0.08 ± 0.02
	Posterior	0.11 ± 0.04	0.01 ± 0.02	4.63 ± 2.56	0.06 ± 0.02
Tibial					
	Anterior	0.16 ± 0.06	0 ± 0	5.79 ± 4.31	0.08 ± 0.03
	Central	0.11 ± 0.03	0 ± 0	5.65 ± 4.13	0.06 ± 0.02
	Posterior	0.13 ± 0.06	0 ± 0	5.40 ± 5.36	0.07 ± 0.03

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

TABLE 3. Canine meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.28 ± 0.05	0 ± 0	3.11 ± 1.93	0.14 ± 0.02
	Central	0.22 ± 0.07	0.03 ± 0.07	2.44 ± 2.13	0.10 ± 0.03
	Posterior	0.26 ± 0.11	0 ± 0	2.12 ± 0.61	0.13 ± 0.06
Tibial					
	Anterior	0.26 ± 0.05	0 ± 0	3.27 ± 1.77	0.13 ± 0.03
	Central	0.20 ± 0.09	0.01 ± 0.02	1.56 ± 0.51	0.10 ± 0.04
	Posterior	0.19 ± 0.08	0 ± 0	2.76 ± 1.10	0.10 ± 0.04

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

TABLE 4. Human meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.15 ± 0.03	0 ± 0	1.84 ± 0.64	0.08 ± 0.01
	Central	0.10 ± 0.03	0 ± 0	1.54 ± 0.71	0.05 ± 0.01
	Posterior	0.11 ± 0.02	0.01 ± 0.02	2.74 ± 2.49	0.05 ± 0.01
Tibial					
	Anterior	0.16 ± 0.05	0 ± 0	1.71 ± 0.48	0.08 ± 0.02
	Central	0.11 ± 0.04	0 ± 0	1.54 ± 0.49	0.06 ± 0.02
	Posterior	0.09 ± 0.03	0 ± 0	1.32 ± 0.61	0.05 ± 0.01

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

TABLE 5. Lapine meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.50 ± 0.11	0.04 ± 0.04	4.00 ± 1.66	0.24 ± 0.04
	Central	0.13 ± 0.02	0.00 ± 0.00	0.89 ± 0.21	0.07 ± 0.01
	Posterior	0.12 ± 0.03	0.00 ± 0.00	1.20 ± 0.49	0.06 ± 0.02
Tibial					
	Anterior	0.39 ± 0.11	0.08 ± 0.08	3.95 ± 1.87	0.18 ± 0.07
	Central	0.17 ± 0.08	0.01 ± 0.02	0.89 ± 0.42	0.08 ± 0.04
	Posterior	0.15 ± 0.07	0.00 ± 0.00	0.97 ± 0.32	0.08 ± 0.03

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

higher than the femoral-posterior and tibial-central locations ($p < 0.03$). In the porcine model the femoral-anterior portion had a higher shear modulus than all other locations ($p < 0.002$). In the human model the anterior locations had a higher modulus than the central and posterior locations (both femoral and tibial) ($p < 0.007$). This pattern could also be found in the lapine model ($p < 0.0007$), though the femoral-anterior portion was also statistically higher than the tibial-anterior portion ($p < 0.03$).

Interspecies Topographical Variations

Statistical variations in the compressive properties of the meniscus were observed among the different animal species. General trends noted were that the lapine model exhibits the highest aggregate modulus (Fig. 5), Poisson's ratio, and shear modulus, whereas the bovine model exhibited the highest permeability (Fig. 6). The central and posterior portions of the lapine model exhibited the lowest aggregate and shear modulus, whereas the central and posterior portions of the lapine model exhibited the lowest permeability. Tables 7–10 show where statistical significance ($p < 0.05$) was noted among the testing locations and models.

DISCUSSION

While some intraspecies and interspecies compressive property comparisons have been performed on the meniscus previously, no studies have looked at intraspecies variations in a diversity of animal models and interspecies variation at a variety of different locations. This study was conducted to determine the variation in compressive properties of the medial meniscus at different topographical locations in a variety of animal models. To fulfill this goal, medial meniscal samples were tested using an indentation technique at six different locations: the anterior, central, and posterior portions of the meniscus on both the femoral and tibial surfaces of the tissue. These tests were performed on tissue from six different animal models (baboon, bovine, canine, human, lapine, and porcine). The creep indentation testing used for this study is based on biphasic finite element optimization of the creep response of the medial meniscus and allows for four material properties to be determined: the aggregate modulus, Poisson's ratio, permeability, and shear modulus (calculated from H_A and (ν_S). We believe this is a more physiologically relevant testing method than many other testing methods, such as disk compression, due to the presence of native tissue surrounding the test site and the lack of edge effects when testing the tissue sample. A limitation of this testing method is that the meniscus requires excision from the joint before testing, possibly altering the native resting state of the meniscus. It should be noted that this limitation would also be exhibited by disk compression techniques.

Our original hypotheses were that (a) for intraspecies variation, the aggregate and shear moduli will be the

TABLE 6. Porcine meniscal biomechanical properties (±SD).

Aspect	Segment	H_A (MPa)	ν_S	k (10^{15} m^4 N^{-1} s^{-1})	μ_S (MPa)
Femoral					
	Anterior	0.27 ± 0.09	0 ± 0	3.62 ± 1.41	0.14 ± 0.04
	Central	0.17 ± 0.05	0 ± 0	2.86 ± 0.71	0.08 ± 0.03
	Posterior	0.14 ± 0.03	0 ± 0	3.66 ± 1.20	0.07 ± 0.01
Tibial					
	Anterior	0.18 ± 0.02	0.02 ± 0.05	5.96 ± 1.93	0.09 ± 0.01
	Central	0.13 ± 0.02	0.03 ± 0.06	5.28 ± 4.95	0.07 ± 0.01
	Posterior	0.13 ± 0.03	0 ± 0	6.32 ± 4.20	0.06 ± 0.02

Note. H_A = aggregate modulus, $\delta\nu_S$ = Poisson's ratio, k = permeability, $\delta\mu_S$ = shear modulus.

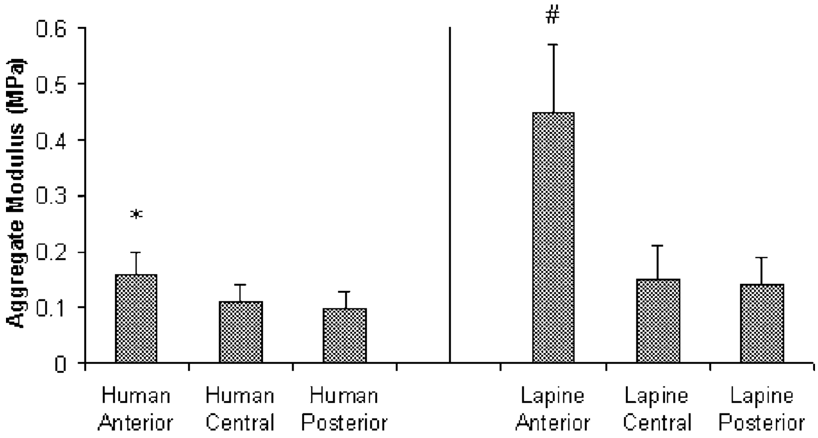

FIGURE 4. Comparison of the aggregate modulus (femoral and tibial sides combined) at the anterior, central, and posterior portions of the human and lapine meniscus. Data shown as mean ± standard deviation. (*) indicates a significant difference between either the human central or human posterior regions and the human anterior region ($p < 0.05$). (#) indicates a significant difference between either the lapine central or lapine posterior regions and the lapine anterior region ($p < 0.05$).

greatest in the posterior portion of the tissue, and (b) for interspecies variation, the animal model will have a significant effect on the compressive material properties of the tissue. Results from the study found the intraspecies hypothesis to be incorrect. Our results showed either no variation in the aggregate and shear modulus depending on location or that the anterior portion of the tissue had the highest values, not the posterior portion. However, our data show that the second hypothesis, that the animal model would have a significant effect on the compressive properties of the tissue, was correct.

The compressive characteristics of the bovine meniscus have now been observed in three different studies, including

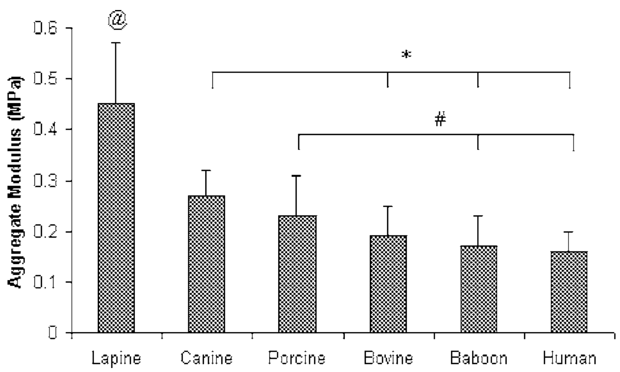

FIGURE 5. Comparison of the aggregate modulus (femoral and tibial sides combined) at the anterior location in the six tested animal models. Data shown as mean ± standard deviation. (@) indicates statistical significance between the lapine aggregate modulus and the aggregate modulus of the other five animal models ($p < 0.0001$). (*) indicates an additional significant difference between either the bovine, baboon, or human aggregate modulus and the canine aggregate modulus ($p < 0.0002$). (#) indicates an additional significant difference between either the baboon or human aggregate modulus and the porcine aggregate modulus ($p < 0.006$).

this one. The other two studies were performed by Proctor and coworkers[24] and Joshi and coworkers.[14] Proctor and coworkers,[24] who tested the femoral side of the meniscus at four different locations (anterior, anterior-central, central-posterior, and posterior) found in the superficial zones an aggregate modulus of 0.393 ± 0.109 MPa in the posterior portion and 0.440 ± 0.108 MPa in the anterior portion. Our results for the femoral side of the bovine meniscus show lower aggregate modulus values: 0.11 ± 0.04 MPa for the posterior portion and 0.21 ± 0.06 MPa for the anterior portion. If the permeability between the Proctor and coworkers[24] study and this study is compared it is found that the Proctor and coworkers[24] study found lower values ($0.7\text{–}1.0 \times 10^{-15}$ $m^4\ N^{-1}\ s^{-1}$) than our study ($5.4\text{–}6.2 \times 10^{-15}$ $m^4\ N^{-1}\ s^{-1}$). These variations are probably due to variations in the testing method, test location, and curve-fitting procedure (our study used a finite element

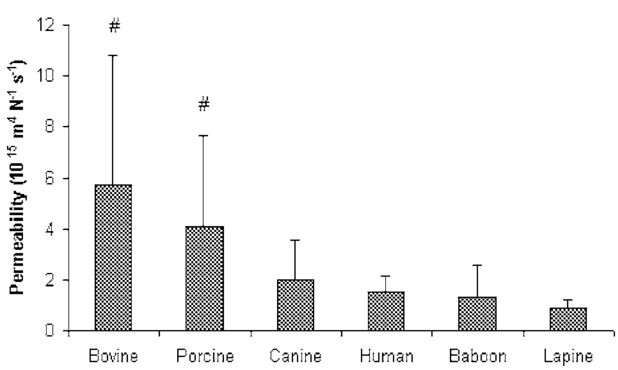

FIGURE 6. Comparison of the permeability (femoral and tibial sides combined) at the central location in the six tested animal models. Data shown as mean ± standard deviation. (#) indicates a significant difference between either the bovine or porcine permeability and the canine, human, baboon, or lapine permeability ($p < 0.02$).

TABLE 7. Interspecies comparison of aggregate modulus.

	MA	MC	MP	BA	BC	BP	CA	CC	CP	HA	HC	HP	LA	LC	LP	PA	PC	PP
MA					X	X	X	X	X		X	X	X			X		
MC					X	X	X		X		X	X	X			X		X
MP					X	X	X	X	X		X	X	X			X		
BA					X	X	X				X	X	X		X			X
BC	X	X	X	X			X	X	X				X			X		
BP	X	X	X	X			X	X	X				X			X		
CA	X	X	X	X	X	X		X		X	X	X	X	X	X		X	X
CC	X		X		X	X	X			X	X	X	X	X	X		X	X
CP	X	X	X		X	X				X	X	X	X	X	X		X	X
HA							X	X	X		X	X	X			X		
HC	X	X	X	X			X	X	X	X			X			X		
HP	X	X	X	X			X	X	X	X			X	X		X	X	
LA	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
LC							X	X	X			X	X			X		
LP				X			X	X	X				X			X		
PA	X	X	X		X	X				X	X	X	X	X	X		X	X
PC							X	X	X			X	X			X		
PP		X		X			X	X	X				X			X		

Note. First letter denotes animal (M = baboon, B = bovine, C = canine, H = human, L = lapine, P = porcine) and second letter denotes location (A = anterior, C = central, P= posterior). "X" denotes statistical significance between test groups ($p < 0.05$).

optimization procedure for curve fitting, the Proctor and coworkers[24] study used a biphasic theory which does not take into consideration the full creep curve). The intraspecies hypothesis was based on the deep-tissue results from the Proctor and coworkers[24] study, which exhibited a higher aggregate modulus in the posterior portion of the tissue, which turned out to be opposite of the results from the current study. This variation is probably due to the difference in testing location. Due to the minor degree of force placed on the meniscal tissue in the current study, only the compressive response at the surface was examined. It is possible that, while the surface of the meniscus consists of an isotropic collagen alignment, the deeper zone, with its anisotropic collagen alignment in the circumferential direction, might exhibit differences in compressive properties. In the Joshi and coworkers[14] study, the aggregate modulus and permeability of the tibial-posterior location were obtained in several different animal models, including the bovine model. Their results show an aggregate modulus of about 0.12 MPa and a permeability of about 3.3×10^{-15}

TABLE 8. Interspecies comparison of Poisson's ratio.

	MA	MC	MP	BA	BC	BP	CA	CC	CP	HA	HC	HP	LA	LC	LP	PA	PC	PP
MA		X						X					X					
MC	X		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X
MP		X											X					
BA		X						X					X					
BC		X											X					
BP		X											X					
CA		X											X					
CC	X			X						X	X		X					
CP		X											X					
HA		X						X					X					
HC		X						X					X					
HP		X											X					
LA	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
LC		X											X					
LP		X											X					
PA		X											X					
PC		X											X					
PP		X											X					

Note. First letter denotes animal (M = baboon, B = bovine, C = canine, H = human, L = lapine, P = porcine) and second letter denotes location (A = anterior, C = central, P = posterior). "X" denotes statistical significance between test groups ($p < 0.05$).

TABLE 9. Interspecies comparison of permeability.

	MA	MC	MP	BA	BC	BP	CA	CC	CP	HA	HC	HP	LA	LC	LP	PA	PC	PP
MA				X	X	X	X						X			X	X	X
MC				X	X	X	X						X			X	X	X
MP				X	X	X	X						X			X	X	X
BA	X	X	X				X	X	X	X	X	X	X	X	X		X	
BC	X	X	X				X	X	X	X	X	X		X	X			
BP	X	X	X				X	X	X	X	X	X		X	X			
CA	X	X	X	X	X	X					X			X	X			X
CC				X	X	X							X			X	X	X
CP				X	X	X										X		X
HA				X	X	X							X			X	X	X
HC				X	X	X	X						X			X	X	X
HP				X	X	X							X			X	X	X
LA	X	X	X	X				X		X	X	X		X	X			
LC				X	X	X	X						X			X	X	X
LP				X	X	X	X						X			X	X	X
PA	X	X	X					X	X	X	X	X		X	X			
PC	X	X	X	X				X		X	X	X		X	X			
PP	X	X	X				X	X	X	X	X	X		X	X			

Note. First letter denotes animal (M = baboon, B = bovine, C = canine, H = human, L = lapine, P = porcine) and second letter denotes location (A = anterior, C = central, P = posterior). "X" denotes statistical significance between test groups ($p < 0.05$).

$m^4\ N^{-1}\ s^{-1}$, whereas our results from that section of tissue show an aggregate modulus of 0.13 ± 0.06 MPa and a permeability of $5.40 \pm 5.36 \times 10^{-15}\ m^4\ N^{-1}\ s^{-1}$. The results of the aggregate modulus are almost identical, and the permeability results are quite similar.[14]

The compressive characteristics of the human meniscus have been observed in three different studies, including this one. A study performed by Hacker and coworkers[13] found the aggregate modulus and permeability of the meniscus at the anterior, central, and posterior portions of the meniscus (tibial side). They found the aggregate modulus to be 0.2 MPa, 0.22 MPa, and 0.28 MPa at the anterior, central, and posterior portions of the tissue, respectively.[13] Our results showed an aggregate modulus of 0.16 ± 0.05 MPa, 0.11 ± 0.04 MPa, and 0.09 ± 0.03 MPa for the respective locations. Our results were lower, and this is probably due to the testing method and different curve-fitting methods. The Hacker and coworkers[13] study used the same curve-fitting method as the Proctor and coworkers[24] study. There were differences noted in the permeability values also. The Hacker and coworkers[13] study found permeability values of $0.9 \times 10^{-15}\ m^4\ N^{-1}\ s^{-1}$,

TABLE 10. Interspecies comparison of shear modulus.

	MA	MC	MP	BA	BC	BP	CA	CC	CP	HA	HC	HP	LA	LC	LP	PA	PC	PP
MA					X	X	X		X		X	X	X			X		
MC					X	X	X		X		X	X	X			X		
MP					X	X	X	X	X		X	X	X			X		
BA					X	X	X				X	X	X		X			X
BC	X	X	X	X			X	X	X				X			X		
BP	X	X	X	X			X	X	X				X			X		
CA	X	X	X	X	X	X		X		X	X	X	X	X	X		X	X
CC			X		X	X	X			X	X	X	X	X	X		X	X
CP	X	X	X		X	X				X	X	X	X	X	X		X	X
HA							X	X	X		X	X	X			X		
HC	X	X	X	X			X	X	X	X			X			X		
HP	X	X	X	X			X	X	X	X			X	X		X	X	
LA	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X
LC							X	X	X			X	X			X		
LP				X			X	X	X				X			X		
PA	X	X	X		X	X				X	X	X	X	X	X		X	X
PC							X	X	X			X	X			X		
PP				X			X	X	X				X			X		

Note. First letter denotes animal (M = baboon, B = bovine, C = canine, H = human, L = lapine, P = porcine) and second letter denotes location (A = anterior, C = central, P = posterior). "X" denotes statistical significance between test groups ($p < 0.05$).

0.8×10^{-15} m^4 N^{-1} s^{-1}, and 0.9×10^{-15} m^4 N^{-1} s^{-1} for the anterior, central, and posterior locations. The current study found the permeability at each of the locations to be $1.71 \pm 0.48 \times 10^{-15}$ m^4 N^{-1} s^{-1}, $1.54 \pm 0.49 \times 10^{-15}$ m^4 N^{-1} s^{-1}, and $1.32 \pm 0.61 \times 10^{-15}$ m^4 N^{-1} s^{-1}. The other study was performed by Joshi and coworkers[14] and is part of the study described above. Their results show an aggregate modulus of about 0.22 MPa and a permeability of about $1.99 \pm 0.79 \times 10^{-15}$ m^4 N^{-1} s^{-1} for the tibial-posterior location, whereas our results from that section of tissue show an aggregate modulus of 0.09 ± 0.03 MPa and a permeability of $1.32 \pm 0.61 \times 10^{-15}$ m^4 N^{-1} s^{-1}. The permeability results are quite similar, though there is a significant difference between the aggregate modulus found in the two studies.[14]

The Joshi and coworkers[14] study also found the aggregate modulus and permeability in the canine and porcine model. For the canine model, Joshi and coworkers[14] found an aggregate modulus of about 0.15 MPa and a permeability of about 3.5×10^{-15} m^4 N^{-1} s^{-1}, whereas our results were 0.19 ± 0.08 MPa and $2.76 \pm 1.10 \times 10^{-15}$ m^4 N^{-1} s^{-1}, respectively. For the porcine model, Joshi and coworkers[14] found an aggregate modulus of about 0.27 ± 0.04 MPa and a permeability of about $1.74 \pm 0.19 \times 10^{-15}$ m^4 N^{-1} s^{-1}, whereas our results were 0.13 ± 0.03 MPa and $6.32 \pm 4.21 \times 10^{-15}$ m^4 N^{-1} s^{-1}, respectively. These values are not very similar, though the difference is slight compared to the variations found in the Proctor and coworkers[24] study. It should be mentioned that in the Joshi and coworkers[14] study a trend of increasing aggregate modulus with decreasing permeability was noted among the different animal models. This trend was not noted in the tibial-posterior location or any other location in our study. Overall, this study found significant variations in the compressive properties of the different animal models, as was hypothesized.

The most common location for injury in the meniscus is the posterior region.[22,23] Our results show a common trend in the tested animals of the posterior region having the lowest shear modulus and, to a lesser extent, aggregate modulus. This trend in material properties could help explain the frequency of tears in that location. The other interesting trend noted was that the aggregate modulus, shear modulus, and permeability of the anterior portion of the lapine model were much greater than the central and posterior portions. We believe that this characteristic is due to the bent-knee resting stance of the rabbit and the frequency that the animal jumps, something not seen in any of the other animal models tested.

The significant variations in the material properties among these different animal models suggest caution when using an animal model to study the human knee joint. By comparison of the four material properties between the human and the other animal models, it can be noted that no model is ideal in all cases. The aggregate modulus and shear modulus in the human are the most similar to the bovine model, but when looking at permeability the canine and baboon values are the closest to human values. The Poisson's ratio indicates that any of the tested animal models have similar values, with the exception of the lapine and baboon model.

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