INTRODUCTION: Fluid pressurization of the meniscus is an important mechanism for load support and distribution in the knee joint (1). The hydraulic permeability is an important parameter governing fluid pressurization and flow-dependent mechanical effects in the meniscus. Collagen fiber orientation contributes to a fiber-induced anisotropy for the meniscus, which gives rise to transversely isotropic material symmetry (2). Fiber-induced anisotropy has been shown to affect the material properties of the extracellular matrix, such as the Young’s modulus and Poisson’s ratio (3,4,5). While the hydraulic permeability has been experimentally determined for the meniscus in uniaxial compression tests (6,7), it has not measured in a configuration for which there is a mechanical contribution from the collagen fibers (i.e., tension). Thus, the effect of fiber orientation on the hydraulic permeability is not known. For a transversely isotropic model, two permeability coefficients are required, \( k_1 \) and \( k_2 \), which describe fluid flow parallel and transverse to the collagen fibers, respectively. In this study, tensile testing was conducted to study the transversely isotropic material properties of the meniscus. A 3-D linear biphasic and anisotropic FEM was developed to model the meniscal samples in simple tension, and optimization was used to determine \( k_1 \) and \( k_2 \). Values for the hydraulic permeability were obtained for varying strains to detect potential nonlinear effects. The results for permeability coefficients and matrix properties (i.e., Young’s moduli, Poisson’s ratios) were evaluated for significant effects of collagen fiber anisotropy and strain level on the material properties of the meniscus.

EXPERIMENTAL METHODS: Tensile testing was conducted on meniscal samples from skeletally mature dogs (n=10) in circumferential and radial directions (Fig. 1). Planar samples of uniform thickness (0.5 mm) and constant width from the midsubstance were prepared. Samples were subjected to successive increments of tensile strain (\( \varepsilon = \pm 2-10\% \)) followed by a period of stress-relaxation to equilibrium. Optical strain analysis was performed to measure mid-substance strains and for calculation of the Poisson’s ratios \( \nu_{12} \) and \( \nu_{21} \). The aspect ratio of \( k_1 \) and \( k_2 \) were determined from circumferential and radial samples (\( \varepsilon - \theta \) orientation), respectively (Fig. 1). For determination of hydraulic permeability in the direction of the collagen fibers, a second set of tests was performed on samples radially oriented in the \( r-z \) plane (see Fig. 1). The equilibrium stress-strain response was modeled by an exponential law and a Poisson’s ratio demonstrated that the extracellular matrix of the meniscus was anisotropic and strain level on the material properties of the meniscus.

FEM OPTIMIZATION: The tensile experiments were modeled with a 3-D custom-written FE code based on biphasic mixture theory (2). A \( u-p \) formulation of the governing equations was implemented. The aspect ratio of the samples permitted the assumption that fluid flow was dominant in the thickness direction (width:thicknss of 3.6:1, length:thicknss of 15:1). Thus, individual permeability coefficients could be determined from each of circumferential and radial test configurations. The meniscus was modeled as a linear elastic material with transverse isotropy based on the principal collagen fiber orientations. The subject-specific 3-D geometry and experimentally determined transversely isotropic properties were incorporated into a FE model of each sample. The Young’s moduli, \( E_1 \) and \( E_2 \), from mechanical testing were used to define the solid matrix in the model, and isotropic behavior was assumed in shear. To obtain a thermodynamically-permissible database, \( v_{23} \) was set to 0.5, the limit for an isotropic material. For circumferential samples, an iterative least-squares optimization routine was performed on axial stress during stress-relaxation to determine \( k_1 \) and \( v_{23} \). For radial samples (\( r-z \) orientation), the optimization procedure was repeated to determine \( k_2 \) using \( v_{23} \) from the corresponding circumferential sample.

RESULTS: Anisotropy did not have a significant effect on the determined permeability coefficients (\( p<0.05 \), ANOVA, Fig. 2). Permeability coefficients averaged over four strain increments were 0.89x10^{-17} m^4/Ns for \( k_1 \) and 0.97x10^{-17} m^4/Ns for \( k_2 \). The permeability coefficients significantly decreased with increasing strain (\( p<0.05 \), ANOVA, Fig. 1). The permeability coefficients at \( \varepsilon = 2-8\% \) were fit to an empirical exponential model used to represent strain-dependence (8). The results for the intrinsic permeability coefficient, \( k_{01} \) and \( k_{02} \), were similar, 0.17±0.14 x10^{-16} m^4/Ns and 0.25±0.37 x10^{-16} m^4/Ns, respectively. The strain-dependent parameter \( M \) provided evidence of significant nonlinear permeability effects, with an average of 10.2±6.9 for \( M_1 \) and 16.3±10.9 for \( M_2 \). The average Poisson’s ratio \( v_{23} \) from optimization was 1.2±0.3. The experimental results for Young’s modulus and Poisson’s ratios demonstrated that the extracellular matrix of the meniscus was highly anisotropic, as the circumferential modulus \( E_1 \) was 67.8 MPa, 8 times the radial modulus \( E_2 \). There was a significant effect of collagen fiber orientation on \( E_1 \) and \( E_2 \) (\( p<0.05 \), ANOVA), but not on the Poisson’s ratios (\( p>0.05 \), ANOVA) with values for \( v_{23} \) and \( v_{32} \) of 2.1±1.3 and 1.5±1.1, respectively.

Figure 1. Sample orientations

Figure 2. Permeability coefficients

DISCUSSION: To our knowledge, this study presents the first reported values for the permeability of a cartilaginous tissue in a configuration for which the collagen fibers significantly contribute to tissue mechanics (i.e., tension). Our findings for the permeability coefficients \( k_1 \) and \( k_2 \) showed no significant effects of collagen fiber orientation on fluid flow in the meniscus. This suggests that an isotropic representation of fluid flow may be adequate for the meniscus. This finding is consistent with previous studies that used compression testing to evaluate the effect of anisotropy on the permeability of other soft tissues (9,10). The permeability coefficients determined in the present study were two orders of magnitude lower than reported permeability coefficients for meniscus determined from 1-D compression tests. These low values for permeability may occur because dilation will be higher when testing in simple tension than in a confined compression configuration, and higher dilation may dramatically impede fluid flow. Our results for permeability on the order of 10^{-17} m^4/Ns would predict an increase in the extent to which fluid pressurization is the dominant mechanism for load support over predictions that used permeabilities on the order of 10^{-15} m^4/Ns (2). The evidence of nonlinear effects, as seen in the values for \( M \), may indicate that nonlinear permeability and finite strain models are warranted, as have been used for articular cartilage (11). Our findings provide insight into the significance of fluid pressurization and suggest that a low permeability to fluid flow is an important characteristic to emulate in meniscal repair.

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