An Inverse Finite Element Analysis Approach to Model Meniscus Tensile Behavior

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INTRODUCTION: Meniscus fibrocartilage is essential in healthy functioning of the knee joint by distributing and dampening mechanical loads. Its fibrous matrix is composed of mainly circumferentially oriented collagen fibers that serve to distribute axial loading into tensile resistance along the fibers [1]. Tensile stress, in response to circumferential strain, is the primary mechanical loading condition of the meniscus under normal human motion [2]. Understanding and characterizing the tensile behavior of the meniscus is essential to comprehending the etiology of tissue pathologies and to develop evidence-based effective treatments. Computational modeling is a powerful tool, quickly becoming a prominent approach in the study of the mechanical behavior of biological tissues. Therefore, the objective of this study was to conduct an inverse finite element analysis to model the tensile behavior of meniscal tissue and to characterize the mechanical properties of the constituents of its extracellular matrix (ECM).

METHODS: ***Specimen preparation:*** The central region of seven porcine menisci (6-9 months old; *Animal Technologies, Tyler, TX*) was cut using a freezing stage microtome (*SM2010 R, Leica Biosystems, Deer Park, IL*). Tissue samples were prepared either in the circumferential direction, to orient the circumferential collagen fibers parallel to the direction of stretch (*Figure 1A*), or in the radial direction, to orient the fibers orthogonal to the direction of stretch (*Figure 1B*). Circumferential samples were 0.49 (±0.12) mm thick and radial samples were 0.51(±0.10) mm thick. Slices were trimmed into rectangles (circumferential samples 10.48±0.96 x 5.30±0.64mm; radial samples 6.19±1.16 x 3.75±0.24mm). A total of 10 samples in each direction (n=10) were stored in protease-inhibited phosphate buffered saline until testing to avoid degradation. ***Mechanical testing:*** Experiments were conducted on a uniaxial, displacement-controlled apparatus (Univert, CellScale, Waterloo, ON) and stretched to 20% of their initial length at a rate of $0.1s^{-1}$. Stress-strain curves were developed. For model calibration purposes, the elastic moduli (E) at the toe region of the radial samples were determined. ***Theoretical modeling:*** The meniscus was modeled as a fiber-reinforced poroviscoelastic solid. The viscoelastic behavior was modeled as a generalized Maxwell model with a discrete spectrum of relaxation times [3] and the elastic behavior was modeled as neo-Hookean [4,5], see *Table 1*. Tissue hydraulic permeability was assumed to be constant. Fibers were considered tension-only components and distributed homogeneously within the tissue geometry, orientation being parallel (to simulate circumferential specimens) or orthogonal (to simulate radial samples) to the direction of stretch. ***Computational analysis:*** Computer simulation of tensile behavior of radial samples was validated via comparison with experimental data. Subsequently, an inverse finite element analysis determined the mechanical properties of meniscal fibers. Curve-fitting was used on the experimental data of the circumferential samples to yield fiber modulus through the finite element model, see *Table 1*.

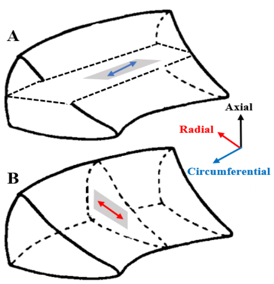

Figure 1. Orientation of samples produced (A) in the circumferential direction parallel to the collagen fibers and (B) in the radial direction orthogonal to the collagen fibers.

RESULTS: The mean value of E for circumferential samples was 104.93 (±30.52) MPa and 9.25 (±7.46) MPa for radial samples. Experimental stress-strain curves suggest hyper-elastic behavior of the meniscal tissue. When compared to the experimental data of the radial samples, the computational model showed good agreement (R^2 = 0.92). The estimate of the value of the fiber modulus via inverse finite element analysis was 13 MPa, see *Table 1*. Simulation results using the estimated fiber modulus were in good agreement with the experimental data of the circumferential samples (R^2 = 0.93), see *Figure 2*.

DISCUSSION: In agreement with previous studies [6], the tensile stiffness of circumferential tissue samples was significantly larger than that in the radial direction. Computer simulations for radial samples were in good agreement with the experimental data. The elastic modulus of the fibers was found to be smaller than that directly measured for collagen fibers [7]. This is due to the fact that this computational model is not a microscopic one, and as such does not specifically model individual fibers in the tissue. Rather, the mechanical response is that of a macroscopic model in which the fibers' contribution to the overall tensile strength is homogenously distributed across the volume of the sample. Nevertheless, model predictions for the circumferential samples were in good agreement with the experimental data, confirming the validity of this new computational tool for modeling meniscal tensile behavior.

SIGNIFICANCE/CLINICAL RELEVANCE: Our adapted computational model for meniscus mechanics can be deployed as a tool to further characterize meniscus pathophysiology and guide the development of tissue engineered constructs aiding novel treatment approaches.

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REFERENCES: [1] Mameri et al. *Curr. Rev. Musculoskelet. Med.* 15 (2022) 323-335. [2] Makris et al. *Biomaterials*. 32(20) (2011) 7411-7431. [3] Schwartz et al. *J. Orthop. Res.* 41(7) (2022)1607-1617. [4] De Rosa et al. *J. Mech. Behav. Biomed. Mater.* 126 (2022)105073. [5] Morejon et al. *Front. Bioeng. Biotechnol.* 8 (2020) 622552. [6] Morejon et al. *Front. Bioeng. Biotechnol.* 11 (2023) 1205512. [7] Peloquin et al. *J. Biomech. Eng.* 138(2) (2016) 021002.

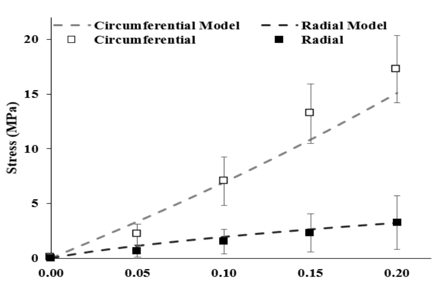

Figure 2. Curve fit of stress-strain relationship comparing the normative curve of the experimental data to the values produced by the computational model.

Table 1. Parameter of the finite element model used to describe the dynamic shear behavior of the meniscus ECM. Viscoelastic behavior is modeled using the generalized Maxwell, where γ_i indicates the ratio G_i/G_0. Elastic behavior was modeled by average Youngs modulus of the radial samples ($E_\perp$) that was experimentally found. Fiber modulus (ξ) was found via curve fitting.

Viscoelastic							Poroelastic			Fibers
G_0 (kPa)	γ_1	γ_2	γ_3	τ_1 (s)	τ_2 (s)	τ_3 (s)	$E_\perp$ (MPa)	ν	k (mm^4/Ns)	$\xi_\parallel$ (MPa)
10.54[2]	0.963[2]	0.324[2]	0.408[2]	0.01[2]	0.19[2]	2.3[2]	9.25	0.3[4]	0.0045[4]	13