Which Poroelastic Material Models Can Represent 3D Strain of Knee Meniscus Tissue?

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INTRODUCTION: Biomechanical computer models of the knee have been under development for several decades and there is growing intent to apply them to diagnosis, treatment planning, and premarket approval. For successful application, the model components must have a strong evidentiary foundation. Historically, the knee meniscus has been represented with more than 20 different material models. Poroelastic models have the most evidence in their favor, but it is still unknown which specific models are adequate and which are not, in part due to the difficulty of obtaining suitably challenging validation data but also because only a handful of models have ever been compared at once. We previously obtained a complete set of 3D stress & strain measurements for knee meniscus tissue (the only such dataset) [1], which may be a sufficiently stringent validation target to falsify some meniscus models. The objective of this study was to systematically quantify the compatibility of every published poroelastic model for knee meniscus with this 3D stress–strain dataset.

METHODS: Twenty-six poroelastic material models were fit to circumferential tensile test data from 10 bovine knee meniscus specimens obtained from a commercial abattoir (Figure 1a), with measurement of the applied stress (σ_{xx}) and 3D strain (ε_x, ε_y, ε_z; Figure 1b). Two tests per specimen, stress relaxation and creep, were used (Figure 1d). Each experimental test was simulated using FEBio (Figure 1c) and our own software [2]. Each material model's parameters were fit to each test by minimizing the difference (root mean squared error; RMSE) between the simulation and the test data. In order to interpret a large (> 20%) error as invalidating a model, it is essential that the *best possible* fit be obtained (ideally, < 1% uncertainty). This requires repeated initializations; therefore, each fit was repeated up to 16,384 times per set of test data, with a 95% confidence interval obtained by bootstrapping (currently, < 3% uncertainty in best fit error for all models). The analysis used 69,338,894 simulations and ~ 500 CPU core-years to produce 238,046 fits and 520 best fits (one per test per material model). An example best fit, with very small error, is shown in Figure 1e. The material models and their essential attributes are listed in Figure 2a. Fifteen models were from the knee meniscus literature, including all published poroelastic models for knee meniscus; the others were included speculatively from other sources. The error of each best fit (e.g., Figure 1e) was summarized as a single RMSE value.

RESULTS: The models' median RMSE varied from 11% (an acceptable value) to 51% (practically unusable). Model performance strongly depended on symmetry (repeated measures ANOVA, $p < 1e\text{-}15$). Material models with true 3D orthotropic symmetry (different properties in x, y, and z; "Orthotropic" in Figure 2) performed relatively well; all had median RMSE < 20%. Models that mimic orthotropic or transversely isotropic symmetry by embedding 1D fibers in a 3D model, which is common in the meniscus literature, performed very poorly; all had median RMSE ≥ 30%. Of the meniscus models only two (orthotropic linear elastic and transversely isotropic general exponential) had errors that could be considered acceptable (median RMSE ≈ 13% and 14%, respectively). However, the orthotropic linear elastic models, due to their linearity, have large (~ 30%) errors for σ_{xx} and ε_x during the loading ramp. The best performing model, Fung orthotropic, was cardiovascular in origin [3], with median RMSE < 10%.

DISCUSSION: The mechanical phenomenon that was poorly represented by most models is large (~ 10%) axial (z) contraction combined with moderate (~ 6%) circumferential (x) stretch, with little (~ 2%) strain in y, and associated large volume strain ($\varepsilon_v \approx -8\%$). This strain state is similar to *in vivo* conditions and produces large volume loss, which pressurizes the meniscus' internal fluid to support joint loads [2]. Orthotropic models are generally required to produce this asymmetry, although the general exponential model [5] also achieved this, likely due to the extreme nonlinearity of its equations.

SIGNIFICANCE/CLINICAL RELEVANCE: Of the published poroelastic material models for knee meniscus, only orthotropic linear elastic and transversely isotropic general exponential models were somewhat capable (15–18% best-fit RMSE) of representing experimentally observed 3D mechanics. Nonlinear orthotropic models originally developed to represent arteries and articular cartilage are good choices for future knee meniscus simulations.

REFERENCES: [1] Peloquin+ J Biomech Eng 2023. [2] Peloquin+ J Roy Soc Int 2024. [3] Fung+ Am J Phys 1979. [4] Haemer+ J Biomech Eng 2012.

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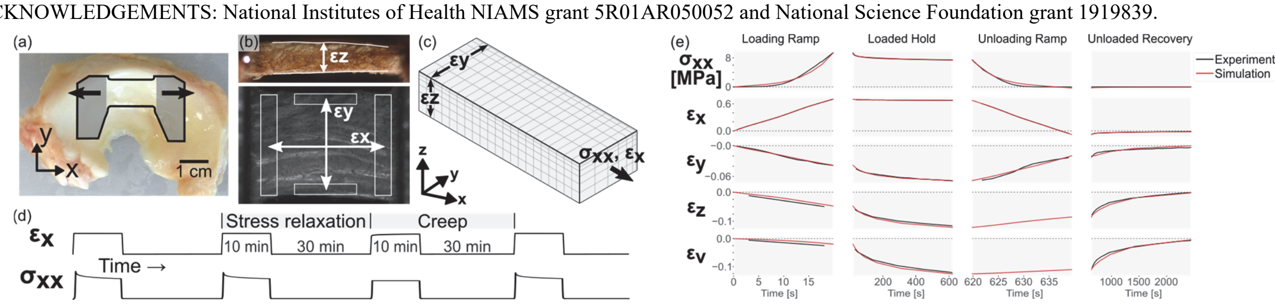

Figure 1: (a) specimen outline and loading axis; (b) strain measurements; (c) FEA ⅛ symmetry mesh; (d) uniaxial tension protocol; (e) example best fit.

(a)

	Symmetry	Linearity	Tissue Literature
Fung orthotropic + Holmes–Mow permeability	Orthotropic	Nonlinear	Cardiovascular
Fung orthotropic + constant permeability	Orthotropic	Nonlinear	Cardiovascular
Orthotropic linear elastic + circumferential 1D exponential fibers + constant permeability	Orthotropic	Nonlinear	Nonspecific
neo-Hookean + ellipsoidally distributed power law fibers + Holmes–Mow permeability	Orthotropic	Nonlinear	Articular Cartilage
neo-Hookean + ellipsoidally distributed power law fibers (isotropic β) + constant permeability	Orthotropic	Nonlinear	Articular Cartilage
neo-Hookean + ellipsoidally distributed power law fibers + constant permeability	Orthotropic	Nonlinear	Articular Cartilage
Transversely isotropic general exponential + constant permeability	Transversely Isotropic	Nonlinear	Meniscus
Transversely isotropic general exponential + Holmes–Mow permeability	Transversely Isotropic	Nonlinear	Meniscus
Orthotropic linear elastic + constant permeability	Orthotropic	Linear	Meniscus
Orthotropic linear elastic + Holmes–Mow permeability	Orthotropic	Linear	Meniscus
neo-Hookean + ellipsoidally distributed power–linear fibers + Holmes–Mow permeability	Orthotropic	Nonlinear	Cardiovascular
neo-Hookean + transversely isotropic ellipsoidally distributed power law fibers (isotropic β) + constant permeability	Transversely Isotropic	Nonlinear	Articular Cartilage
Transversely isotropic linear elastic (FEBio version)	Transversely Isotropic	Linear	Meniscus
Transversely isotropic linear elastic + circumferential 1D exponential fiber + constant permeability	Transversely Isotropic	Nonlinear	Nonspecific
neo-Hookean + 13× 1D neo-Hookean fibers + circumferential 1D neo-Hookean fibers + exponential permeability	Transversely Isotropic (from 1D fibers)	Linear	Meniscus
neo-Hookean + transversely isotropic 3×⊥ 1D neo-Hookean fibers + trans. iso. exponential permeability	Transversely Isotropic (from 1D fibers)	Linear	Meniscus
neo-Hookean + isotropic 13× 1D exponential fibers + circumferential 1D exponential fiber + exponential permeability	Transversely Isotropic (from 1D fibers)	Nonlinear	Meniscus
neo-Hookean + 3×⊥ 1D power–linear fibers + constant permeability	Orthotropic (1D fibers)	Nonlinear	Meniscus
neo-Hookean + transversely isotropic 3×⊥ 1D neo-Hookean fibers + constant permeability	Transversely Isotropic (from 1D fibers)	Linear	Meniscus
Holmes–Mow solid + power–linear fibers + constant permeability	Transversely Isotropic (from 1D fibers)	Nonlinear	Meniscus
Transversely isotropic linear elastic + constant permeability	Isotropic	Linear	Meniscus
deviatoric neo-Hookean + 1D exponential–linear fibers + bulk modulus + constant permeability	Transversely Isotropic (from 1D fibers)	Nonlinear	Meniscus
neo-Hookean + 3×⊥ 1D neo-Hookean fibers + constant permeability	Orthotropic (from 1D fibers)	Linear	Meniscus
Deviatoric neo-Hookean + deviatoric exponential–linear fibers + bulk modulus + constant permeability	Transversely Isotropic (from 1D fibers)	Nonlinear	Meniscus
Deviatoric Holzapfel–Gasser–Ogden (1× fiber) + bulk modulus + constant permeability	Transversely Isotropic (from 1D fibers)	Nonlinear	Meniscus
neo-Hookean + constant permeability	Isotropic	Linear	Meniscus

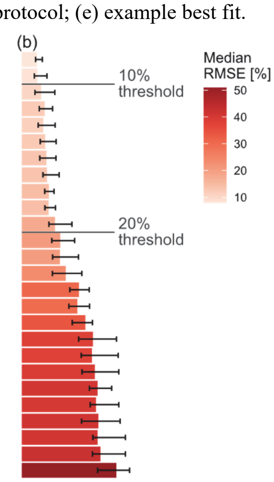

Figure 2: (a) poroelastic material models examined in the present work and (b) associated median & interquartile range RMSE across the 20 tension tests.