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Title: **Anisotropic Soft Composite Based Hyperelastic Model**
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ABSTRACT

Tissues and organs are soft composite systems made of collagen fibers embedded within an extracellular matrix. These soft composite systems exhibit directional and regional material anisotropy due to varying fiber distributions and orientations. To date, anisotropic material properties of soft composite systems have been characterized using simplified isotropic and transversely isotropic hyperelastic material models in various computational and experimental studies. These simplifications may not only lead to inaccurate results from analyses, but also inhibit the study of the effect of important tissue modifications due to disease. In this work, a novel composite based hyperelastic model was developed which can characterize tissue anisotropy. This model considers both the soft fibers and matrix to be hyperelastic materials, which interact through shear deformation. The effect of the individual contribution of the fibers and matrix were introduced into the numerical framework for a single soft composite layer and the changes due to variations in the fiber orientation were incorporated into the strain energy functions. Also, strain energy formulations were developed for multiple soft composite layers with varying fiber orientations and contributions, which can describe the biomechanical behavior of organs consisting of multiple tissue layers. Stress versus strain relationships were derived from the strain energy equations for a uniaxial mechanical test condition. To validate the model parameters, experimental models of soft composites tested under uniaxial loads in literature were characterized using the novel anisotropic hyperelastic model. An average R^2 correlation index of 0.983 was estimated for the developed model. To date, such a robust anisotropic hyperelastic model has not been developed to the best of our knowledge, which would be indispensable for experimental characterization of tissues and for improving the fidelity of computational models of organ systems in future.

INTRODUCTION

Soft tissues and organs exhibit anisotropic mechanical properties [1-4] due to varying distribution and orientation of collagen fibers within a soft extracellular

matrix. In literature, tissue anisotropy has been investigated using histology and imaging techniques such as Diffusion Tensor Magnetic Resonance Imaging (DT-MRI) and confocal microscopy [5]. However, a few numerical and experimental works to date have modeled tissue anisotropy, due to non-availability of anisotropic tissue characterization models. So far, isotropic hyperelastic models such as Neo-Hookean, Mooney-Rivlin, Yeoh, and Ogden have been used to characterize soft tissues. An isotropic hyperelastic model characterizes a soft material using the strain-energy function (ψ), which depends on the principal stretches (λ_1 , λ_2 , and λ_3) or the Cauchy-green tensor invariants (I_1 , I_2 and I_3 , which are also functions of the principal stretches) [6] given by $\psi_{Isotropic} = \psi(I_1, I_2, I_3)$ where

$$I_1 = \sum_{i=1}^3 \lambda_i^2, I_2 = \sum_{i,j=1}^3 \lambda_i^2 \lambda_j^2, I_3 = \prod_{i=1}^3 \lambda_i^2.$$

More recently, transversely-isotropic

hyperelastic models such as Humphrey and Yin, and Martin [6, 7] were developed, which consider the effect of fibers. While isotropic hyperelastic models do not consider the effect of fibers at all, transversely-isotropic models consider the cumulative effect of fibers (Figure 1) and in some cases the fiber contribution, but not the important fiber-matrix interactions (fibers do not interact with matrix stretching as seen in Figure 1B), fiber orientations and distributions in layers.

Figure 1. Schematic of soft composite stretching in: A) Isotropic hyperelastic model and B) Transversely-isotropic hyperelastic model with fibers which do not interact with matrix stretching

In the current work, a novel hyperelastic model was developed, which considers a tissue as a soft composite material with multiple layers of differently oriented fiber layers within a soft matrix. The model formulation includes the individual contribution of the fiber layers and the matrix, fiber-matrix interaction, and the effect of different fiber orientations in layers. The following sections will present the hyperelastic model development and the characterization of nonlinear biomechanical properties of soft composite materials in literature for model validation.

MATERIALS AND METHODS

Numerical Model

The effect of fibers are included into a soft composite matrix by assuming all the fibers to be initially oriented along the x_1 direction, denoted by vector $\mathbf{a}_0$. The strain energy function is written as $\psi = \psi(\mathbf{C}, a_0) = \psi(I_1, I_2, I_3, I_4, I_5)$, where $\mathbf{C}$ is the Cauchy-Green deformation tensor, $I_4 = \mathbf{a}_0 \cdot \mathbf{C} \cdot \mathbf{a}_0 = \lambda_F^2$, $I_5 = \mathbf{a}_0 \cdot \mathbf{C}^2 \cdot \mathbf{a}_0$, and λ_F is the fiber stretch [8-12]. Both the matrix and the fibers are assumed to be incompressible materials, with different stiffness (and deformation). Deformation tensor $\mathbf{C}_m$ is used to define strain energy function invariants for the matrix (which is considered to be a neo-Hookean type material), given by $\psi^M = C_{10}^m(I_1^m - 3)$, $I_1^m = \text{tr}(\mathbf{C}_m)$. C_{10}^m represents the shear modulus of the matrix. The strain energy stored in the fibers is assumed to mainly depend on fiber elongation, written as a function of I_4 , where $\lambda_F = \sqrt{I_4}$. To account for three-dimensional aspect of the fiber, and the nonlinear dependence of strain energy on fiber stretch, the strain energy stored in fibers (also assumed to be a neo-Hookean material) is given by $\psi^F = C_{10}^m f(I_4)(I_1^f - 3)$, $I_1^f = \text{tr}(\mathbf{C}_f)$. Here, $\mathbf{C}_f$ is the deformation tensor for fibers, and $C_{10}^m f(I_4)$ represents the shear modulus of fiber, which is dependent on stretch [8-12].

Figure 2. Schematic of soft composite stretching in the novel soft composite based anisotropic hyperelastic model formulation, where fibers interact with matrix stretching

With initial fiber direction of $\mathbf{a}_0 = \mathbf{e}_1 = [1 \ 0 \ 0]^T$, and assuming an arbitrary perpendicular axis $\mathbf{e}_2$ such that $\mathbf{e}_1 \cdot \mathbf{e}_2 = 0$, the third axis $\mathbf{e}_3 = \mathbf{e}_1 \otimes \mathbf{e}_2 = 0$. The deformed fiber direction $\mathbf{F}\mathbf{a}_0$ (as the fibers interact with matrix stretching in Figure 2) with $\mathbf{F}$ as the deformation is rotated back to the initial fiber direction ($\mathbf{a}_0 = \mathbf{e}_1$). The rotation tensors selected are $\mathbf{R}_1$ (independent of the selection of $\mathbf{e}_2$), and $\mathbf{R}_2$ (depending on $\mathbf{e}_2$). As $\mathbf{R}_1 \mathbf{F} \mathbf{e}_2$ is rotated back to the $\mathbf{e}_1$ - $\mathbf{e}_2$ plane using $\mathbf{e}_2$ as the

rotation axis, the new deformation gradient tensor is given by $\mathbf{F}^* = \mathbf{R}_2 \mathbf{R}_1 \mathbf{F}$. With $\mathbf{R}_1, \mathbf{R}_2$ as rigid body rotations, $(\mathbf{F}^*)^T \mathbf{F}^* = \mathbf{F}^T \mathbf{F}$. Multiplicative decomposition of the deformation gradient is conducted starting with $\mathbf{F}^*$, where $F_{21}^* = F_{31}^* = F_{32}^* = 0$, $F_{11}^* = |\mathbf{F} \mathbf{a}_0| = \lambda_F$. In the coordinate system $\mathbf{e}_1, \mathbf{e}_2, \mathbf{e}_3$, $\mathbf{F}^*$ is written as equation 1 [8-12].

$$\mathbf{F}^* = \begin{bmatrix} \lambda_F & F_{12}^* & F_{13}^* \\ 0 & F_{22}^* & F_{23}^* \\ 0 & 0 & F_{33}^* \end{bmatrix} \quad (1)$$

The deformation gradient ($\mathbf{F}^*$) is multiplicatively decomposed into uniaxial deformation gradient ($\mathbf{F}_f^*$) in the fiber direction and subsequent shear deformation gradient ($\mathbf{F}_s^*$) written as $\mathbf{F}^* = \mathbf{F}_s^* \mathbf{F}_f^*$ (equation 2) [8-12].

$$\mathbf{F}_f^* = \text{diag} \left[\lambda_F \quad \lambda_F^{-\frac{1}{2}} \quad \lambda_F^{-\frac{1}{2}} \right], \mathbf{F}_s^* = \mathbf{F}^* (\mathbf{F}_f^*)^{-1} = \begin{bmatrix} 1 & F_{12}^* \lambda_F^{\frac{1}{2}} & F_{13}^* \lambda_F^{\frac{1}{2}} \\ 0 & F_{22}^* \lambda_F^{\frac{1}{2}} & F_{23}^* \lambda_F^{\frac{1}{2}} \\ 0 & 0 & F_{33}^* \lambda_F^{\frac{1}{2}} \end{bmatrix} \quad (2)$$

$F_{22}^* \lambda_F^{\frac{1}{2}}$ can be set equal to 1 by suitable selection of $\mathbf{e}_2$ axis. With F_{12}^* and F_{13}^* along fiber shears, and F_{23}^* as transverse shear, equation 3 presents the relationship between the shear deformations and invariants of $\mathbf{C}$ given by [8-12].

$$(F_{12}^*)^2 + (F_{13}^*)^2 = \frac{I_5 - I_4^2}{I_4}, (F_{23}^*)^2 = I_1 - \frac{I_5 + 2\sqrt{I_4}}{I_4} \quad (3)$$

Modeling the Effect of Fiber and Matrix Contributions

The matrix volume fraction (v_m) and fiber volume fraction (v_f) were defined to model the effect of individual fiber and matrix contributions respectively on the soft composite material property. Due to uniaxial deformation ($\mathbf{F}_f^*$), the strain energy stored in the soft composite material is given by $\psi_f = \psi_f^M + \psi_f^F = v_m C_{10}^m (I_1(\mathbf{F}_f^*) - 3) + v_f C_{10}^m f(I_4)(I_1(\mathbf{F}_f^*) - 3)$, where $I_1(\mathbf{F}_f^*)$ is the first invariant of $\mathbf{C}_f^* = (\mathbf{F}_f^*)^T \mathbf{F}_f^*$ written as $I_1(\mathbf{F}_f^*) = \lambda_F^2 + \frac{2}{\lambda_F} = I_4 + 2I_4^{-\frac{1}{2}}$. The fiber stretch and stiffness is assumed to remain constant as shear deformation ($\mathbf{F}_s^*$) is

applied, given by $(F_{12}^*)^2 + (F_{13}^*)^2 + (F_{23}^*)^2 = \frac{I_5 - I_4}{I_4} + I_1 - \frac{I_5 + 2\sqrt{I_4}}{I_4} = I_1 - I_1(\mathbf{F}_f^*)$.

Treating the composite to be made of a neo-Hookean type matrix material with neo-Hookean type fibers with the ratio of the fiber and matrix stiffnesses as $f(I_4)$. The energy stored in the neo-Hookean composite during deformation $\mathbf{F}_s^*$ is given by $\psi_s = c_3 [I_1 - I_1(\mathbf{F}_f^*)]$, where c_3 represents the effective neo-Hookean modulus, and $I_1 - I_1(\mathbf{F}_f^*)$ is the portion of I_1 remaining after deformation $\mathbf{F}_s^*$ [8-12]. The net strain energy function of the anisotropic soft composite is the sum of strain energies due to the cumulative effect of $\mathbf{F}_f^*$ and $\mathbf{F}_s^*$, given by equation 4. In equation 4, $C_{10}^m = c_1$ and $C_{10}^m f(I_4) = c_2$ respectively.

$$\psi = \psi_f + \psi_s = v_f c_2 [I_1(\mathbf{F}_f^*) - 3] + v_m c_1 [I_1(\mathbf{F}_f^*) - 3] + c_3 [I_1 - I_1(\mathbf{F}_f^*)] \quad (4)$$

For a uniaxial test condition, λ_f (stretch along fiber direction) coincides with the applied stretch λ [6, 8-12], such that $I_1(\mathbf{F}_f^*) = I_1 = \lambda^2 + \frac{2}{\lambda}$, causing the term $[I_1 - I_1(\mathbf{F}_f^*)]$ to go to zero. Modified equation 4 for a uniaxial test condition can be written as equation 5.

$$\psi_{Neo-Hookean/Anisotropic} = (v_m c_1 + v_f c_2) \left(\lambda^2 + \frac{2}{\lambda} - 3 \right) \quad (5)$$

Applying the boundary conditions for uniaxial mechanical test condition [6, 8-12], the principal Cauchy stress for a hyperelastic strain energy function is given by $\sigma_1 = \lambda_1 \frac{\partial \psi}{\partial \lambda_1} - \lambda_3 \frac{\partial \psi}{\partial \lambda_3}$, $\sigma_2 = \sigma_3 = 0$. Also, for uniaxial testing, $\lambda_1 = \lambda, \lambda_3 = 0$.

Substituting equation 5 into the principal Cauchy stress expression, the uniaxial stress versus stretch expression is written in form of equation 6.

$$\sigma_{Neo-Hookean/Anisotropic} = 2(v_m c_1 + v_f c_2) \left(\lambda - \frac{1}{\lambda^2} \right) \quad (6)$$

Modeling the Effect of Fiber Orientation

The effect of fiber orientation for a single layer soft composite is introduced into the hyperelastic material modeling framework (Figure 3) by substituting $\lambda_f = \lambda \cos \theta$ into the $I_1(\mathbf{F}_f^*)$ expression in equation 4, given by equation 7 (where $0 \leq \theta < 90^\circ$). The anisotropic stress versus stretch relationship for equation 6 changes to equation 8 on incorporation of the fiber orientation effect.

$$I_1(\mathbf{F}_f^*) = \lambda_f^2 + \frac{2}{\lambda_f} = \lambda^2 \cos^2 \theta + \frac{2}{\lambda \cos \theta}, [I_1 - I_1(\mathbf{F}_f^*)] = \left[\lambda^2 (\sin^2 \theta) + \frac{2}{\lambda} (1 - \sec \theta) \right] \quad (7)$$

Figure 3. Schematic showing the stretch along the fiber (λ_F) which is at an angle $+\theta$ or $-\theta$ with respect to the soft composite uniaxial stretch λ

$$\begin{aligned} \sigma_{Neo-Hookean/Anisotropic/\theta} &= 2(v_m c_1 + v_f c_2) \left(\lambda \cos \theta - \frac{1}{\lambda^2 \cos^2 \theta} \right) \\ &+ 2c_3 \left[\lambda (\sin^2 \theta) - \frac{1}{\lambda^2} (1 - \sec \theta) \right] \end{aligned} \quad (8)$$

Modeling the Effect of Multiple Fiber Layers at Arbitrary Orientations

A soft composite was modeled with multiple fiber families embedded within a single soft matrix (Figure 4), in such a way that biomechanical behavior of the overall composite depends only on the fiber distribution (volume fraction and orientation) in the layers [8-12]. For a soft composite with n fiber layers, if v_m is the matrix volume fraction, $v_{f1}, v_{f2}, v_{f3}, \dots, v_{fi} \dots v_{fn}$ are the volume fraction of fibers in n layers, and the fiber orientation of the n layers are $\theta_1, \theta_2, \theta_3, \dots, \theta_i \dots \theta_n, 0 \leq \theta_i < 90^\circ, n > 1$, the net strain energy function is written as $\psi_{Anisotropic \text{ Soft Composite}} = \sum_{i=1}^n \psi^i$. Using the relationships derived in previous sections, the stress versus stretch relationship of an anisotropic soft composite block is given by equation 9.

$$\sigma_{Anisotropic \text{ Soft Composite: Neo-Hookean}} = \sum \left\{ \begin{aligned} &2((1-v_{fi})c_1 + v_{fi}c_2) \left(\lambda \cos \theta_i - \frac{1}{\lambda^2 \cos^2 \theta_i} \right) \\ &+ 2c_3 \left[\lambda (\sin^2 \theta_i) - \frac{1}{\lambda^2} (1 - \sec \theta_i) \right] \end{aligned} \right\}, 1 \leq i \quad (9)$$

Starting with a different hyperelastic model (such as Fung, Ogden, Mooney-Rivlin, Humphrey, Veronda-Westmann, or Martins [8-12]) for defining the fiber and matrix materials, the ψ^M and ψ^F terms will change resulting in a different expression for $\psi_f = \psi_f^M + \psi_f^F$ and ψ_s , and equation 4. Specific equations with respect to other

hyperelastic models have not been derived in this work, and are described in Chanda et al. [13].

Figure 4. Schematic for novel anisotropic material formulation for soft composites with a single matrix and multiple fiber families

MODEL VALIDATION

Validation for the developed anisotropic soft composite based hyperelastic model was conducted using experimental testing of soft composite materials developed by Chanda et al. [13, 14]. These elastomer based soft composite materials were fabricated to simulate tissue anisotropy, and have been able to closely simulate the biomechanical behavior of brain tissue [15, 16], pelvic tissue [17-19], and the skin [20-25]. The nonlinear stress-stretch relationships recorded for soft composites with FVF of 0.17, 0.35, 0.52, and 0.78 respectively, are presented in Figure 5. The stress-stretch testing data from a second set of soft composites with multiple fibers and three fiber angles ($\theta = 0^\circ, \pm 45^\circ, 90^\circ$) are presented in Figure 6.

Figure 5. Average stress-stretch plots on mechanical testing of soft composites with varying FVF [13, 14]

The fiber contribution (v_f), matrix contribution (v_m), single fiber angle (θ), and number of layers ($n = 1$) were substituted for the plots in Figures 5 and 6 into equation

9, and $\sigma - \lambda$ curve fitting was conducted in Microsoft Excel. The model parameters c_1, c_2, c_3 were quantified (Table I and II). The soft composite variants with specifically 90° orientation were not characterized in Table II, due to multiple terms in the current constitutive model going to infinity. The average R^2 correlation index for the curve fitting was estimated to be 0.983.

TABLE I. HYPERELASTIC CURVE FIT COEFFICIENTS FOR THE SOFT COMPOSITE MATERIALS WITH VARYING FVF'S IN FIGURE 5

Fiber Volume Fraction (FVF)	Hyperelastic Curve Fit Parameters	
	c_1	c_2
0.17	0.95	1.23
0.35	1.80	2.18
0.52	2.65	2.80
0.78	3.96	4.15

Figure 6. Average stress-stretch plots on mechanical testing of soft composites with multiple fibers and varying fiber angles [13, 14]

TABLE II. HYPERELASTIC CURVE FIT COEFFICIENTS FOR THE SOFT COMPOSITE MATERIALS WITH DIFFERENT NUMBER OF FIBERS AND ORIENTATIONS IN FIGURE 6

Number of Fibers (Orientation)	Corresponding FVF	Hyperelastic Curve Fit Parameters		
		c_1	c_2	c_3
Two Fiber (0)	0.38	0.01	2.95	-
Three Fiber (0)	0.56	0.01	2.37	-
Two Fiber (± 45)	0.27	-2.54	9.41	1.33
Three Fiber (± 45)	0.41	-5.88	10.63	1.8

CONCLUSIONS

A current gap exists in literature on the availability of an anisotropic soft tissue characterization model, which can simulate varying tissue distributions and orientations. This has led to adoption of simplified isotropic and transversely-isotropic hyperelastic relationships for modeling anisotropic tissues in experimental and computational analyses, which inhibits the study of tissue changes in disease, and raises concerns on the accuracy of numerical modeling results. The current work bridges this literature gap by introducing a novel soft composite based hyperelastic material characterization framework, which is able to accurately model tissue anisotropy due to multiple layers of varying fiber distributions. This material model considers both the matrix and fibers as hyperelastic materials, and simulates the individual fiber and matrix contributions, fiber-matrix interaction, and the effect of multiple differently oriented fiber layers within a soft matrix. Strain energy functions and stress-strain relationships were derived for a specific case of neo-Hookean type fibers embedded within a neo-Hookean type matrix material. The model formulations were validated against experiments conducted on biofidelic soft composites, which have been used in literature to simulate anisotropic soft tissue properties. Few limitations of this anisotropic hyperelastic model includes the non-consideration of the mechanical effect of the presence of blood vessels, capillaries and fat within tissue layers, and strain rate effects, which will be investigated in future studies. To date, such a detailed anisotropic hyperelastic material characterization model has not been developed to the best of our knowledge, which would be indispensable for accurate characterization of normal and diseased tissues.

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