Osmotic Swelling Alters Tensile Mechanics in Fiber-Reinforced Tissues

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Introduction

- Fiber-reinforced tissues, such as annulus fibrosus (AF) and tendon, consist of collagen fibers embedded in a extrafibrillar matrix of water (~70%) and proteoglycans (~4% wet weight; Fig 1)[1, 2].
- Fiber-reinforced tissues have excellent swelling capacity [3]; however, the effect of swelling on tensile tissue mechanics is not well understood.
- Many computational models describe extrafibrillar matrix as a hyperelastic material, which ignores tissue swelling effects.
- We developed a **multi-lamella model** to evaluate the effect of the osmotic loading on tensile mechanics of fiber-reinforced tissues.

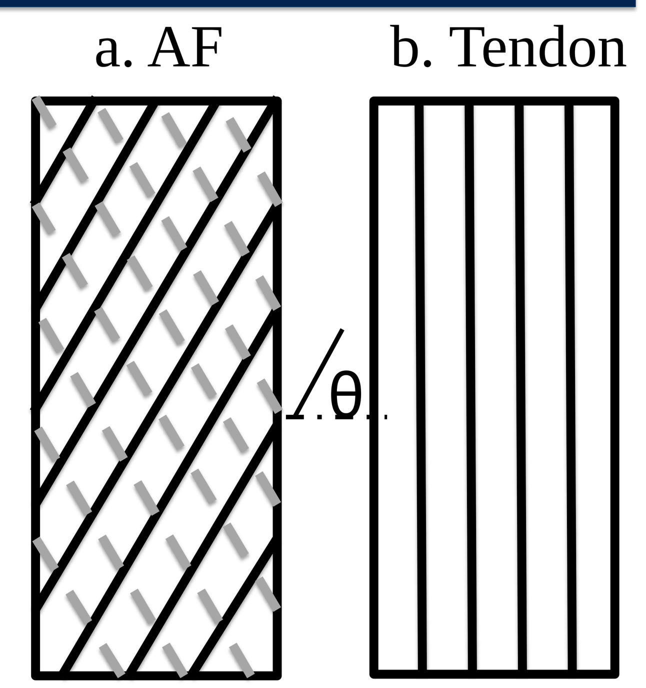

Fig. 1. *Sample fiber-reinforced soft tissue fiber architectures. θ: fiber angle orientation.*

- Tissue swelling was described using the **triphasic mixture theory**, and **fiber angle orientation** was varied to represent a variety of fiber-reinforced tissues; however, the material properties used were based on AF experimental data.

Method

Geometry

- Models were developed in FEBio and consisted of three welded lamellae with alternating fibers (Fig. 2; ~34k nodes, 31k elements).
- Fiber angles include 0º, ±30º, ±45º, ±60º, and ±90º.

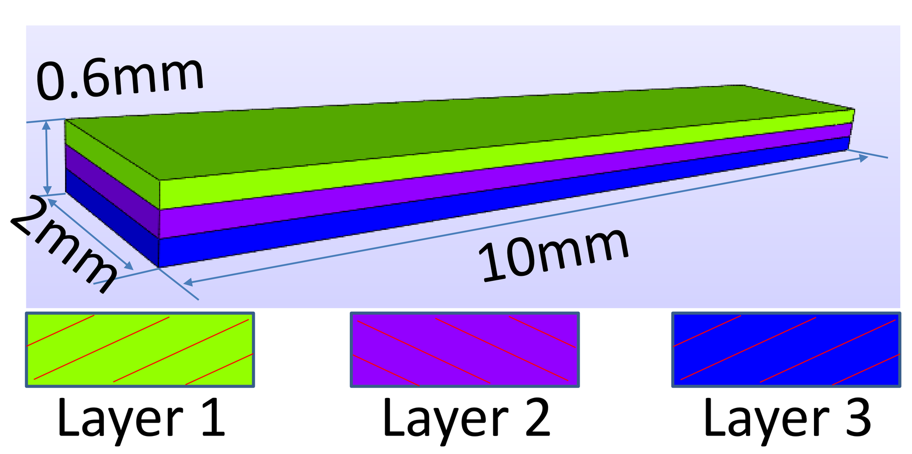

Fig. 2. *Three lamellae model.*

Material coefficients

- The extrafibrillar matrix solid was described as a Holmes-Mow material (Table 1) [4]

Table 1: *Triphasic model material parameters for extracellular matrix*

Holmes-Mow model (solid) [4]	*E (MPa)*	Poisson's ratio: *n*	Stiffening coefficient: *b*
	0.0649	0.24	0.95
Holmes-Mow (Strain-dependent permeability)	Permeability:	Exponential coefficient: M	Exponential term
	0.0064 mm^4/Ns	4.8	$\alpha = 2$

Fixed charge density	-120 *mmol/L*
Solid volume fraction [2]	0.3
Diffusivity for Na^+ and Cl^-	0.00199 mm^2/s
Osmotic coefficient [5]	0.91
Solubility κ	1

- Fibers were described using an exponential-linear function [6]. $C_3 =$ 0.052 MPa; $C_4 =$ 98; $C_5 =$ 88 MPa; $\lambda = 1.025$.

Load conditions

- Equilibrium swelling was simulated under osmotic loading conditions (*hydration:* 0.15 M (control), 0.75 M, and 1.5 M PBS).
- Then, uniaxial tension to 20% strain was applied (*rates:* steady state, 1%/s, and 4%/s).

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Results

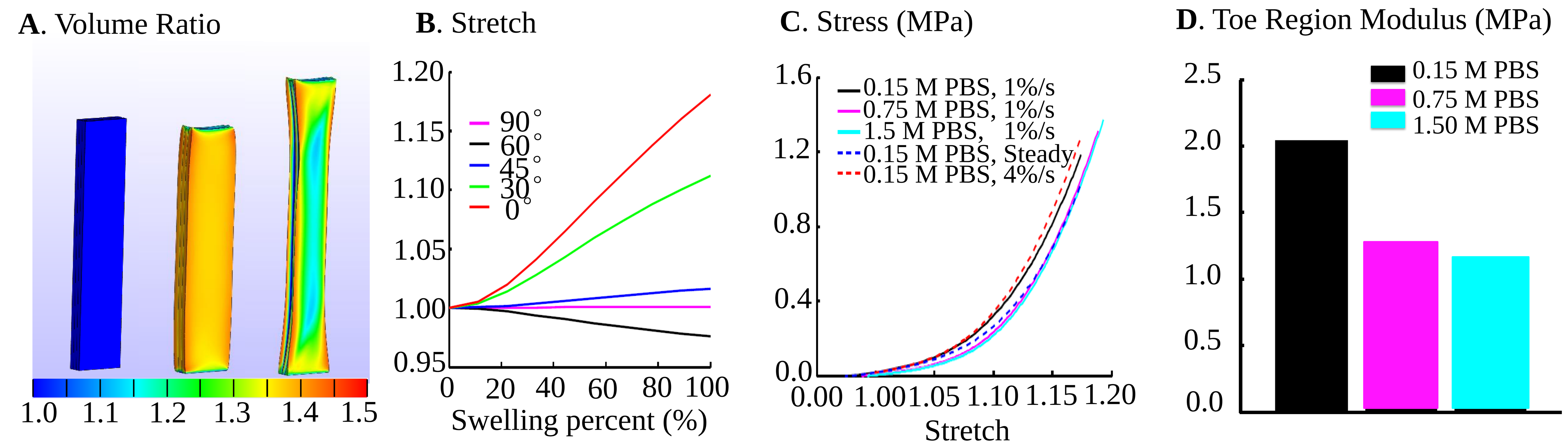

Fig. 3. (A) *Tissue (±60deg fiber) before testing (left), during swelling (0.15M PBS; center) and under tension (right).* ***(B)*** *Fiber stretch during swelling with respect to fiber angle orientation.* ***(C)*** *Tensile stress-stretch behavior with respect to osmolality and loading rate.* ***(D)*** *Toe-region tensile modulus of tissue (±60° fiber) after swelling in different osmolality PBS.*

- Swelling decreased with osmolality: 45% increase in volume for 0.15 M PBS (Fig 3A) *vs.* 10% in1.5 PBS.
- Tissue elongation or contraction during swelling was dependent on the fiber angle orientation (Fig. 3B).
- The model was able to describe rate dependent effects (Fig. 3C - blue dashed line versus red dashed line).
- The toe-region modulus was more sensitive to changes in hydration (Fig. 3D).

Discussion

- We developed a swelling-based model of fiber-reinforced tissues that demonstrated the effect of fiber angle orientation on tissue swelling and tensile mechanics.
- The model was able to describe rate-dependent increase in tissue stiffness, which has been widely reported for biological tissues [7], but is not described by hyperelastic model descriptions [6].
- Our simulation showed that the change in collagen fiber orientation significantly altered tissue pre-stress during swelling. Large shear stresses and strains developed at the layer interfaces (±30º, ±45º, ±60º models), decreasing bulk tissue swelling compared to the 0º and ± 90º cases.
- AF experiences tensile strains under physiological levels of axial compression, and these results suggest that **fluid pressurization is important for load support during tension**.
- A decrease in swelling, due to osmotic loading, resulted in a decrease in tissue toe-region stiffness, causing larger strains, which may lead to tear and damage accumulation (Poster #1780 on AF failure mechanics) [8].
- Future work will evaluate the role of fluid pressurization on failure mechanics of fiber-reinforced materials.
- ***In conclusion, tissue hydration plays an important role in tensile mechanics of fiber-reinforced tissues and its contribution is highly dependent on fiber orientation.***

References

[1] Cassidy, J + Conn. Tiss. 23(1): 75-88, 1989; [2] Iatridis, JC + Spine, 32:1493-97, 2007; [3] Bezci, SE + J Biomech Eng 137.10: 101007, 2015; [4] Lai, WM + J Biomech Eng., 113(3):245-58,1991; [5] Stadie, WC + J Bio Chem., 91:227-241, 1931; [6] Yang, B + Proc. of SB3C, MD, 2016; [7] Holzapfel G.A. + Biomech Model Mechanobiol. 3(3): 125-40, 2005; [8] Werbner B, +ORS, CA, 2017