

A Microstructural Finite Element Model of Passive Skeletal Muscle Validated Under Tension and Compression

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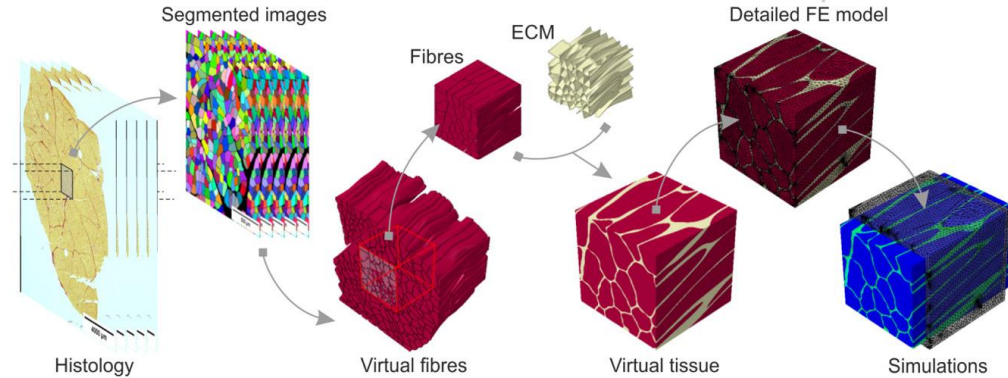
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INTRODUCTION

- Microstructural FEA of muscle tissue links structure to function^{1,2}
- Goal: to better understand and prevent disease and impairment
- Key components: muscle fibers, extracellular matrix



Model from Kuravi et al¹

Current gaps in microstructural model development:

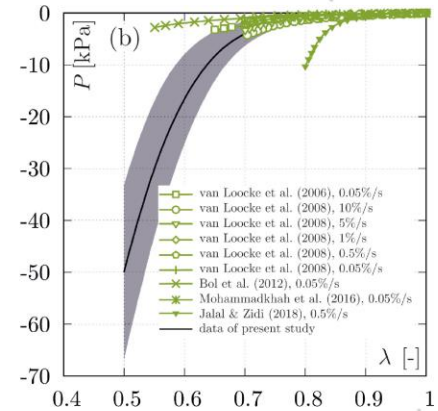
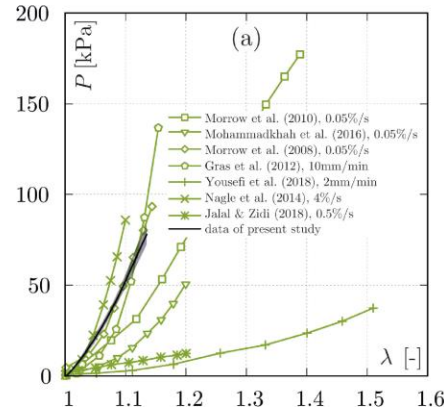
1. Focus on simplified uniaxial tension/compression^{3,4}
2. Do not incorporate fluid^{5,6}

STUDY GOALS

Develop, calibrate, validate, and implement a microstructural model of muscle tissue that:

Uses multiaxial tension/compression deformations

Incorporates fluid pressurization and fluid flow

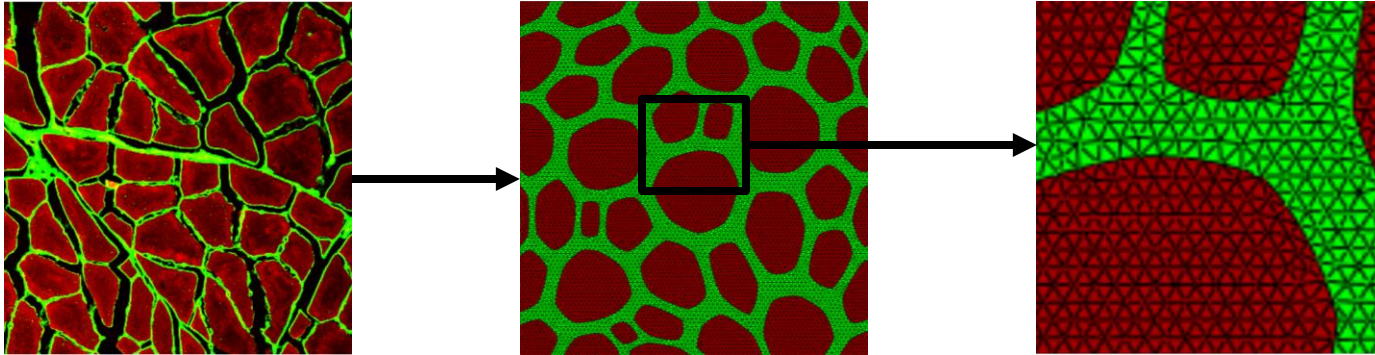


Data from Böl et al¹

1. Böl, M., et al. *Acta Biomaterialia*. (2014).

MODEL GEOMETRY

- Voronoi-generated¹ 2D model (tri)
- 3D extrusion to wedge elements

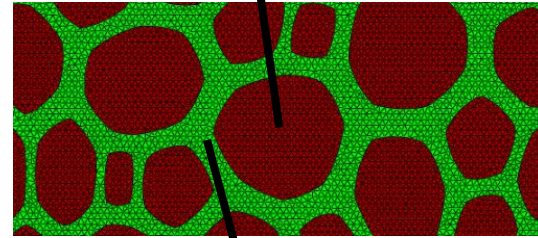


1. Moerman, K. *JOSS*. (2018).

CONSTITUTIVE MODEL

- **Muscle fibers**
 - Visco-hyperelastic
 - Nonlinear fiber reinforced (1D fibers)
- **Extracellular Space (ECM & fluid)**
 - Biphasic visco-hyperelastic
 - Nonlinear fiber reinforced (3D fibers)

$$\bar{\Psi}_{\text{fibers-aniso}}(\bar{I}_4) = \frac{\xi^{\text{fibers}}}{\beta^{\text{fibers}}} (\bar{I}_4 - 1)^{\beta^{\text{fibers}}}$$



$$q = -\frac{k}{u} \Delta p_F$$

$$\Psi_{\text{ECM-aniso}}(\mathbf{n}, I_n) = \xi^{\text{ECM}}(\mathbf{n}) (I_n - 1)^{\beta^{\text{ECM}}(\mathbf{n})}$$

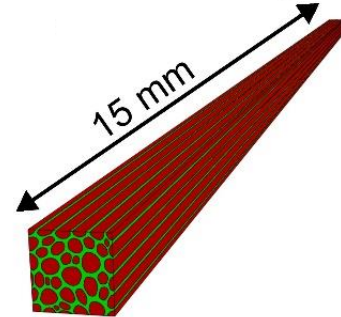
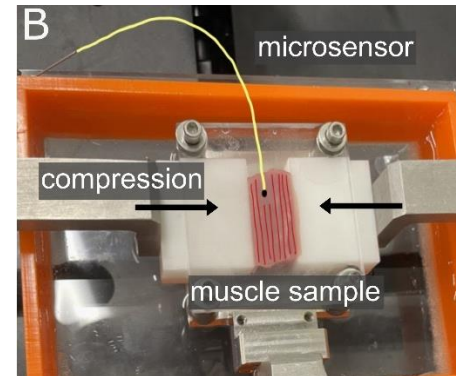
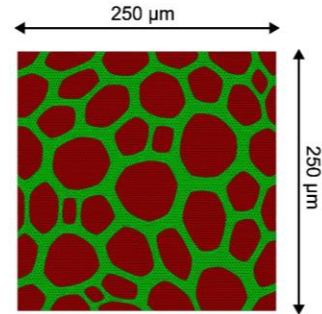
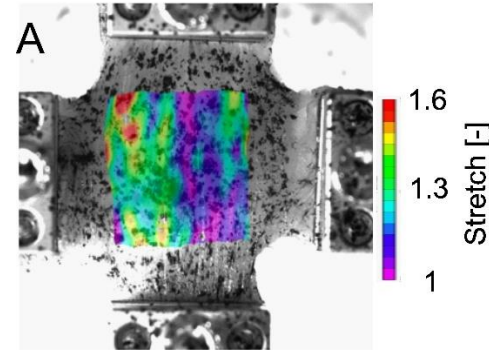
EXPERIMENTAL DATA

- **Tension:**

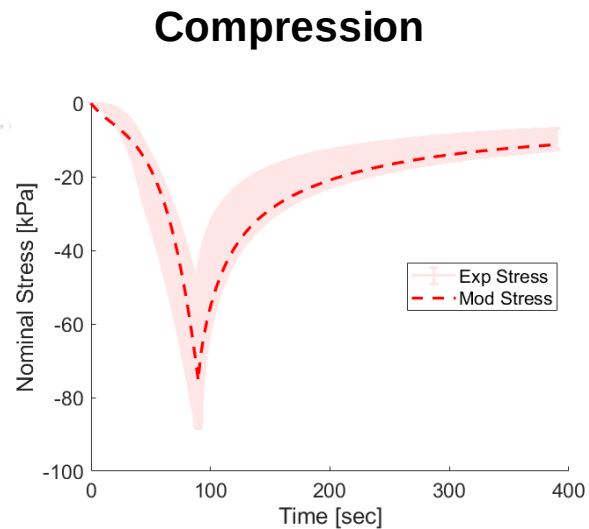
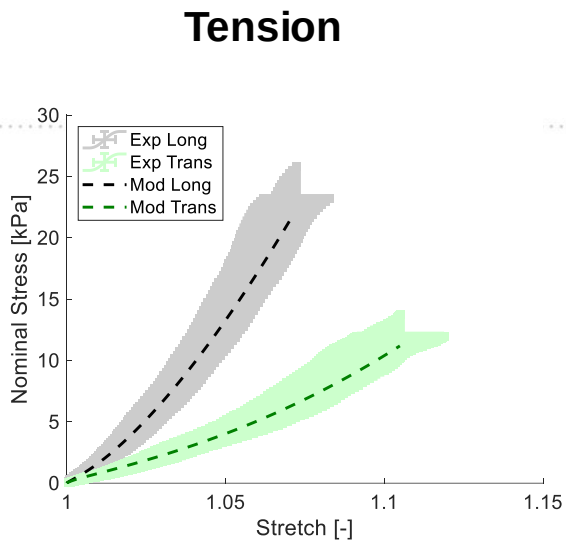
- Planar equibiaxial and uniaxial tension
- Quasi-static loading

- **Compression:**

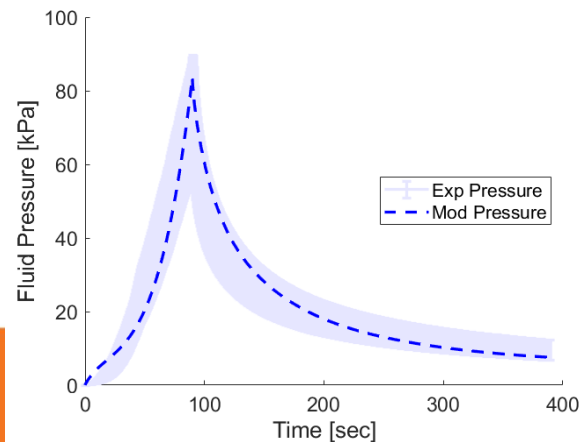
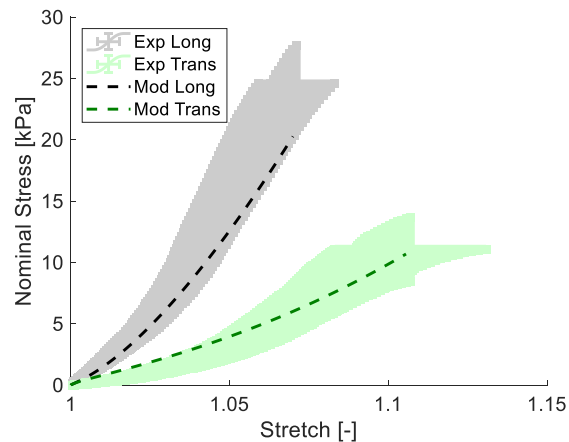
- Semi-confined compression
- Fluid pressure measurement (microsensor)
- Stress relaxation loading



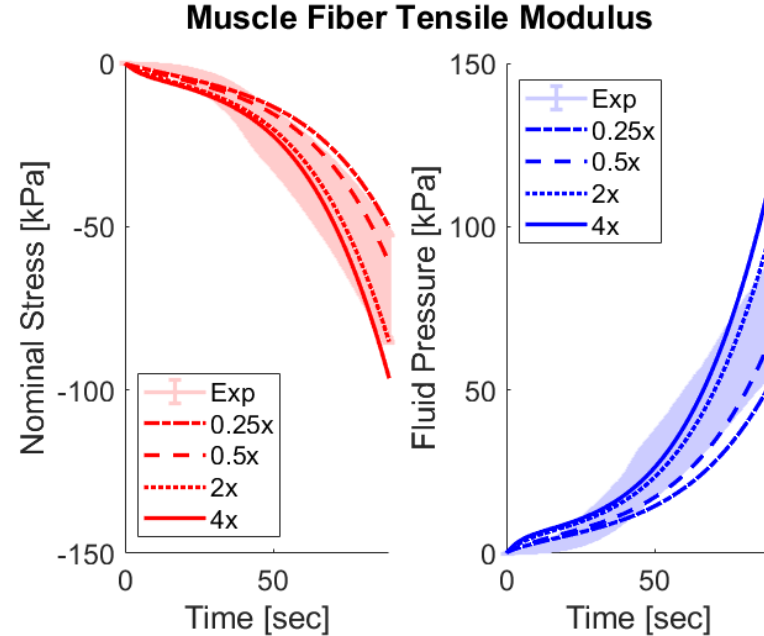
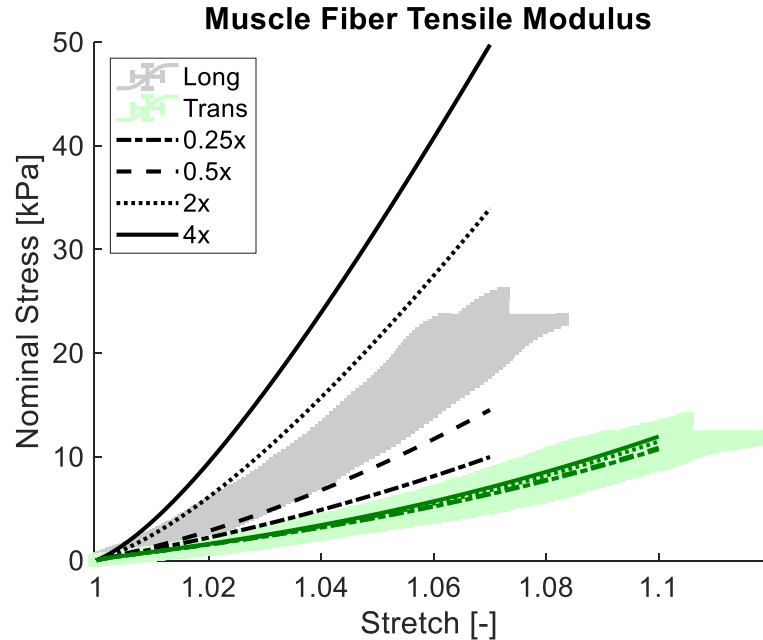
Calibration (Fitting)



Validation (Predicting)

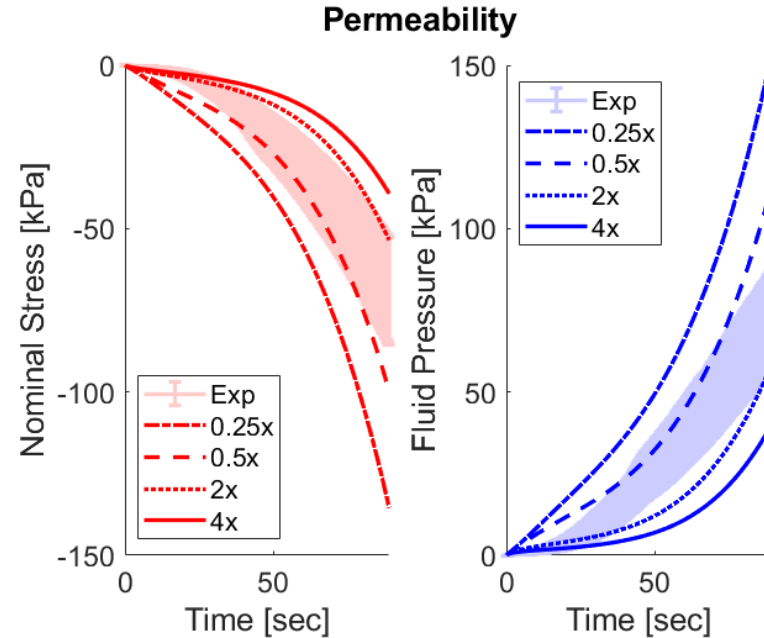
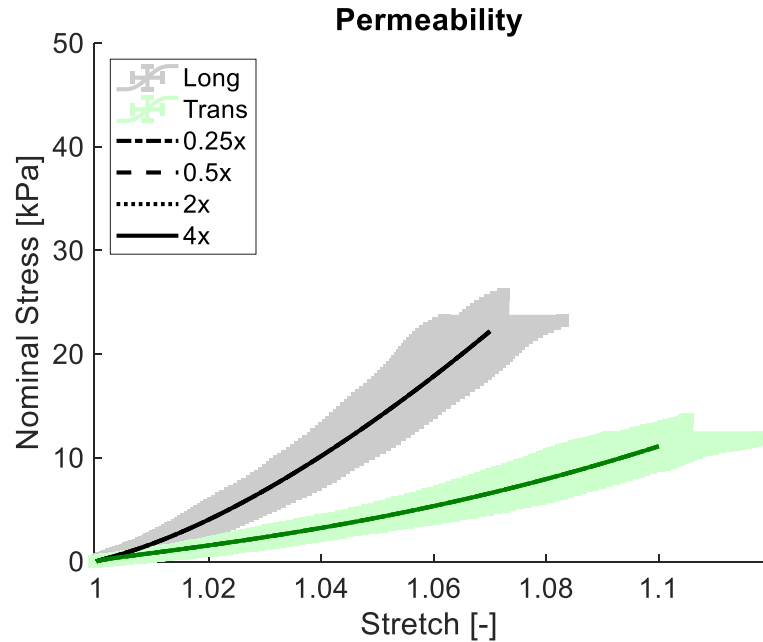


PARAMETRIC ANALYSIS



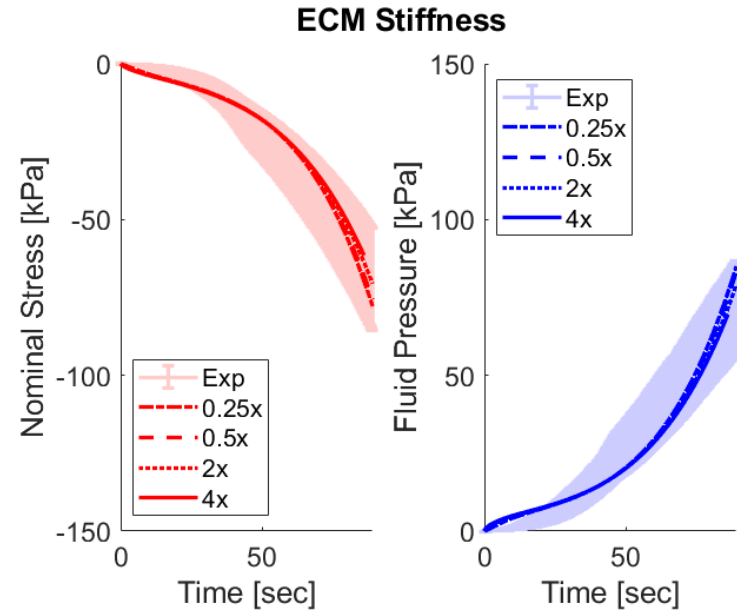
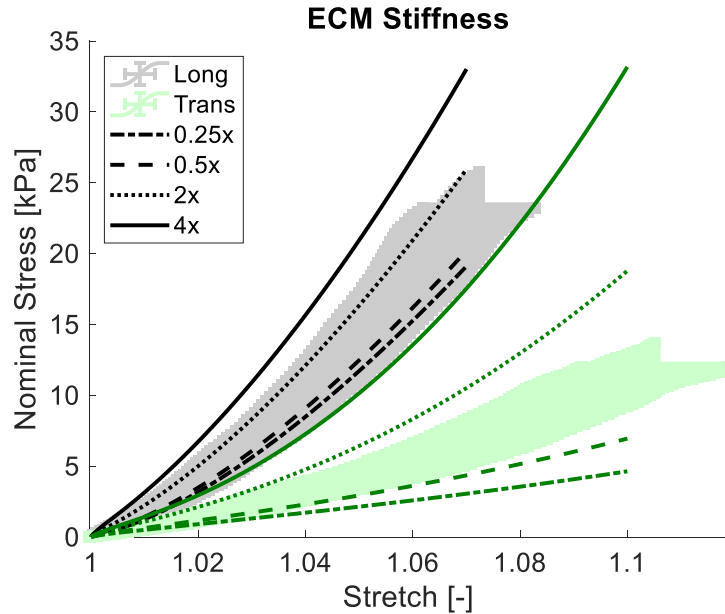
Muscle fiber modulus affects tension and compression

PARAMETRIC ANALYSIS



Permeability affects compression

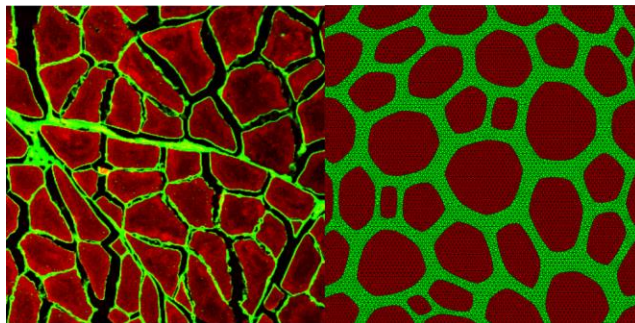
PARAMETRIC ANALYSIS



ECM stiffness affects tension

DISCUSSION

- Microstructural finite element model with:
 - Muscle fibers
 - Extracellular matrix
 - Saturating fluid



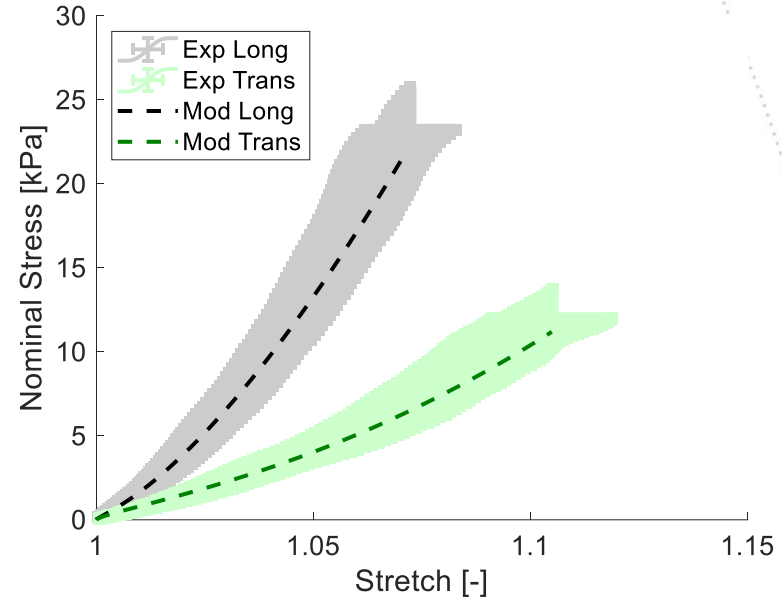
$$\bar{\Psi}_{\text{fibers-aniso}}(\bar{I}_4)$$

$$\Psi_{\text{ECM-aniso}}(\mathbf{n}, I_n)$$

$$\mathbf{q} = -\frac{k}{u} \Delta p_F$$

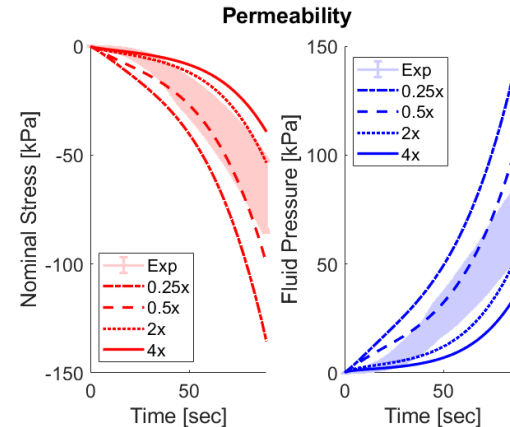
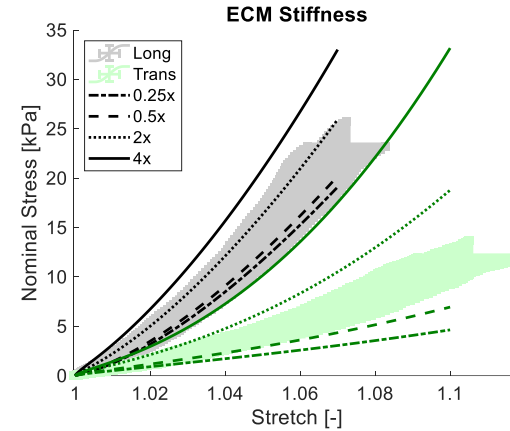
DISCUSSION

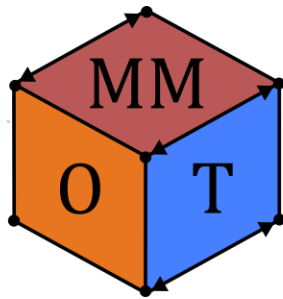
- Microstructural finite element model
- Calibrated/validated in tension & compression



DISCUSSION

- Microstructural finite element model
- Calibrated/validated in tension & compression
- Preliminary parametric analysis:
 - Muscle fibers – tension/compression
 - Permeability – compression
 - ECM - tension





THANK YOU

Bucknell University
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