

INTRODUCTION

Aponeurosis is a fibrous connective tissue that joins muscle to tendon (Fig. 1) and is vital to force transmission in muscle-tendon units [1]

Aponeurosis material properties are similar to that of tendon [2], but aponeurosis heterogeneity is poorly understood

Modeling aponeurosis mechanics in muscle-tendon units can greatly alter simulated muscle function [3,4]

- Properly modeling aponeurosis function is crucial to implementing computational models of the musculoskeletal system

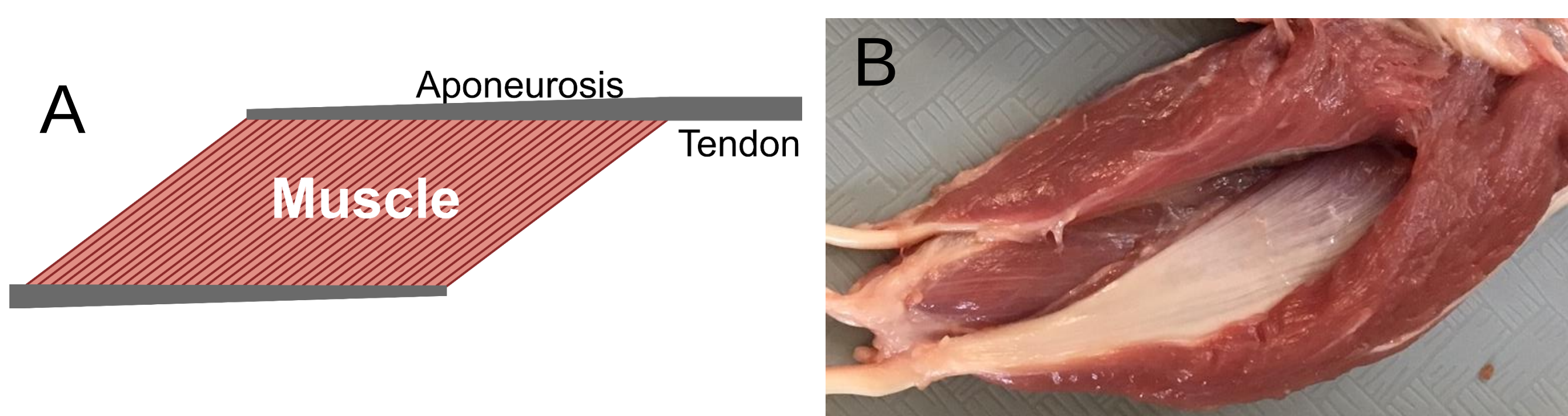


Figure 1. A) Muscle-tendon unit schematic with aponeurosis. B) Example of porcine hindlimb muscle-tendon units and silver aponeurosis.

Project Goals:

- 1) Establish heterogeneous structure function mechanisms in aponeurosis tissue.
- 2) Model the effect of aponeurosis heterogeneity on muscle function.

STRUCTURE-FUNCTION MECHANISMS METHODS

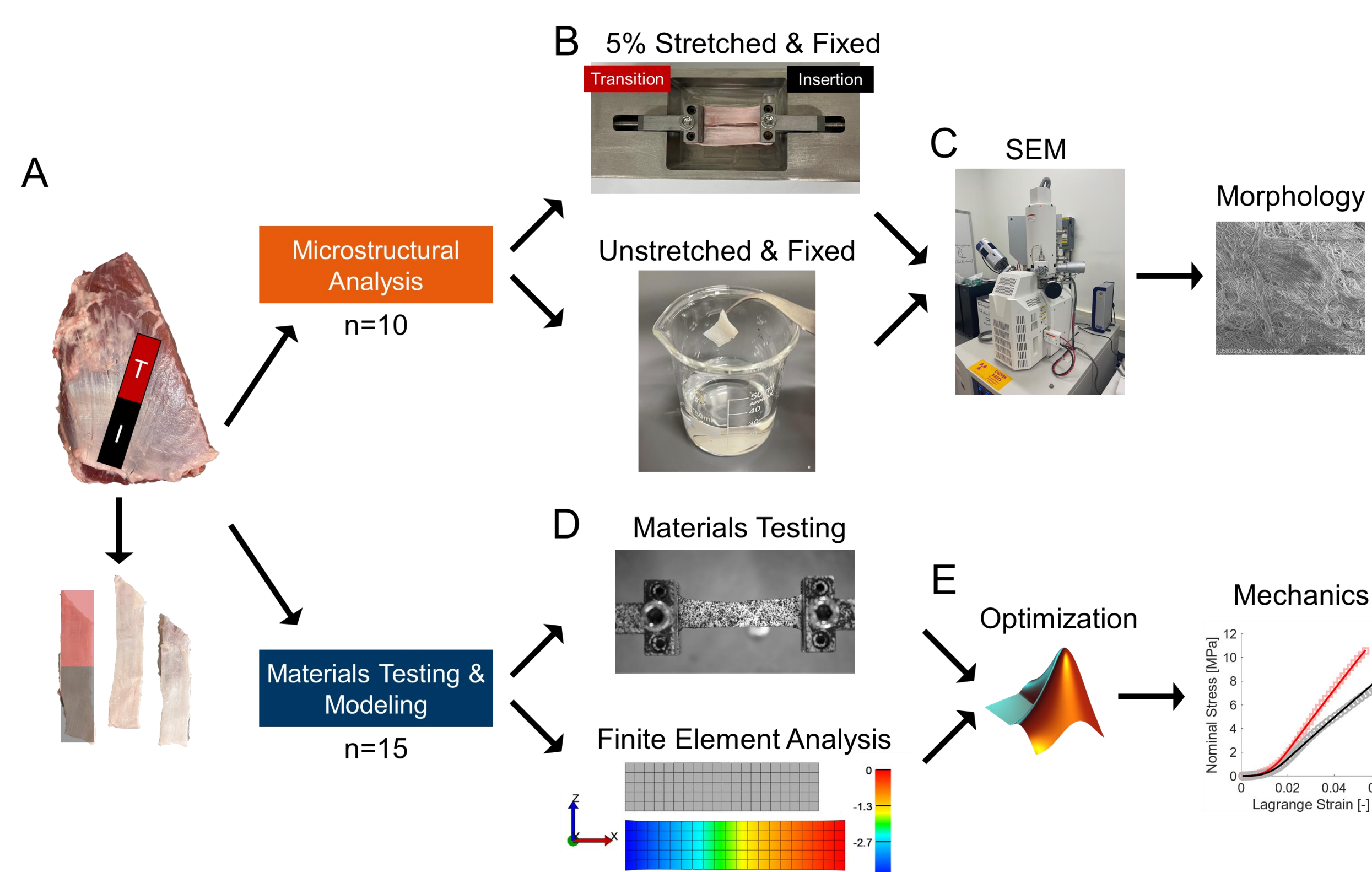


Figure 2. Overview of structure-function characterization methods.

A) Aponeurosis tissue showing insertion (I – near tendon) and transition (T – near muscle midbelly) regions.

B) Structural analysis was performed on stretched and unstretched (n=10 each) fixed samples with a custom tissue stretcher.

C) Scanning electron microscopy was used to evaluate morphological characteristics of tissue microstructure.

D) Uniaxial tensile testing (n=15) was performed with 2D strain tracking through digital image correlation along with finite element analysis of the experiment.

E) Optimization in MATLAB was used to fit model stress-strain curves with experimental stress-strain curves to extract material parameter values.

STRUCTURE-FUNCTION MECHANISMS RESULTS

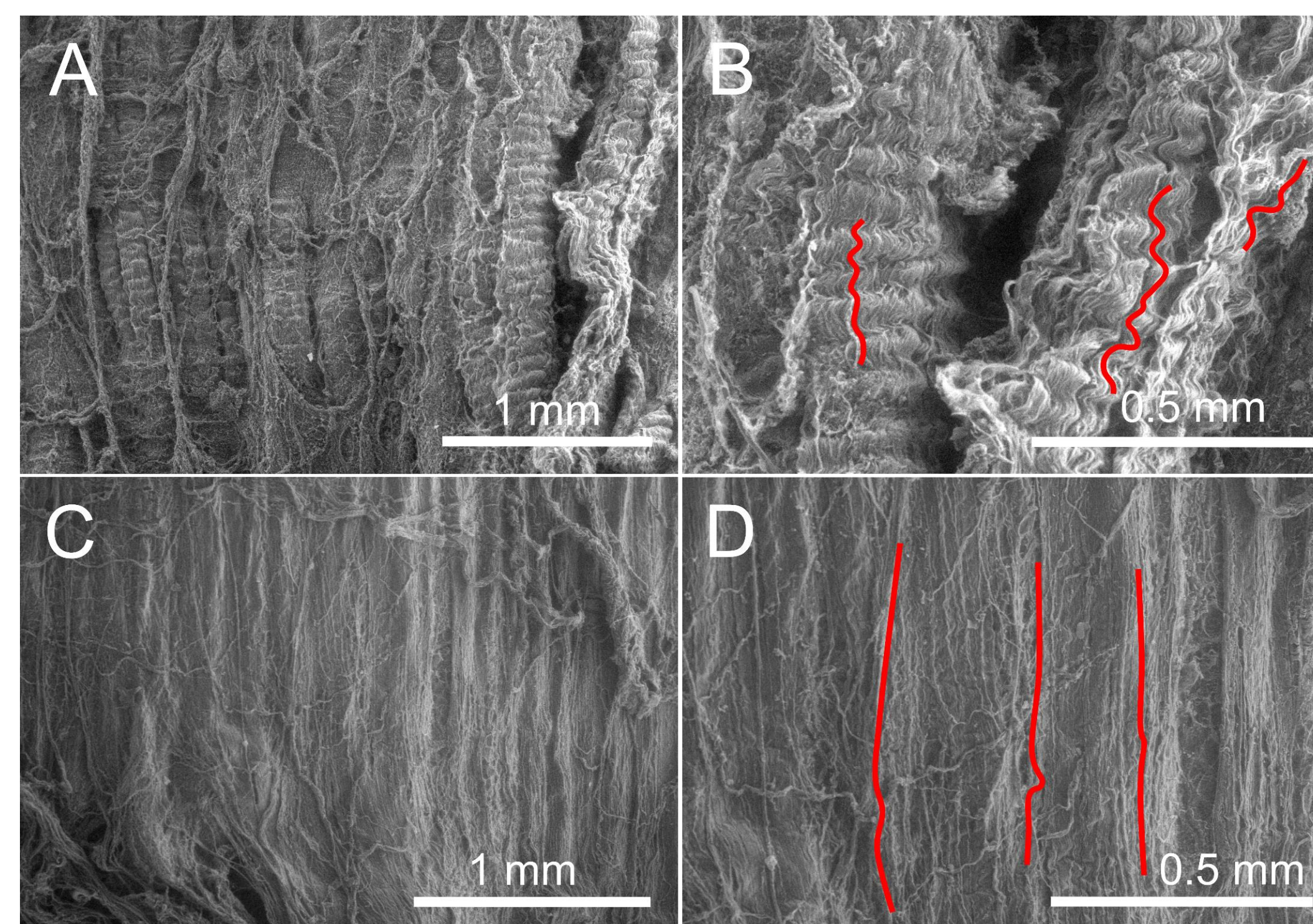


Figure 3. (A/B) SEM images of unstretched porcine triceps brachii at (A) 40x magnification and (C) 100x magnification. Collagen crimp is highly observed in the 40x and 100x magnification and the average waviness values of the unstretched aponeurosis tissue was 1.174 ± 0.211 .

(C/D) SEM images of five percent stretched porcine triceps brachii at (C) 40x magnification and (D) 100x magnification. The waviness of collagen fibers is drastically reduced once stretched five percent.

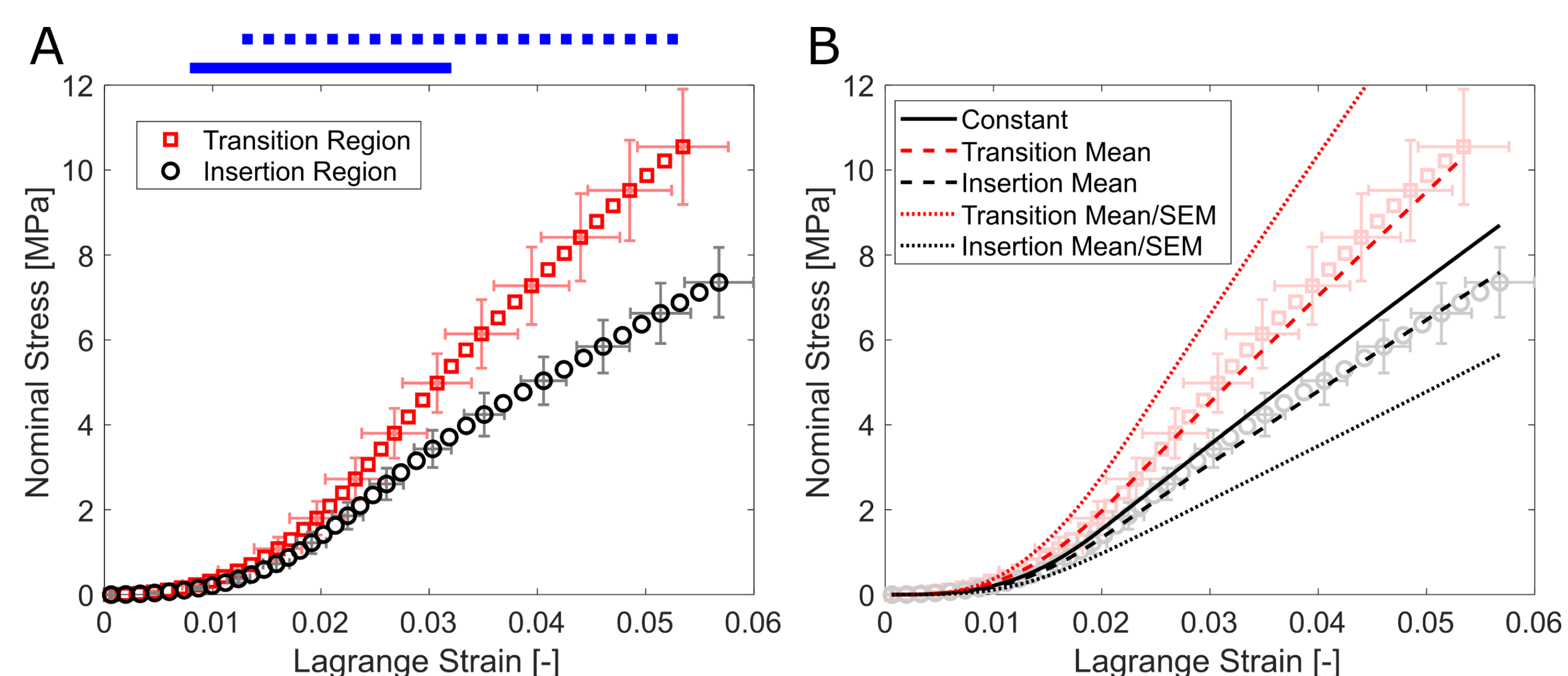


Figure 4. A) Mean stress strain data (with standard error bars) graphed for the insertion (black circles) and transition (red squares) regions.

The blue solid bar above the graph denotes the region of the stress-strain curve where the differences in tangent moduli between the two data sets are statistically significant ($p < 0.05$), and the dashed blue bar above the graph denotes the region of the stress-strain curve where the differences in stress:strain ratio between the two data sets are statistically significant ($p < 0.05$).

B) Optimized finite element model fits to experimental data for various modulus modeling approaches. Optimizations include a homogeneous modulus fit (solid curve), varying modulus fits to the mean transition and insertion stress-strain data, and varying modulus fits to the mean $\pm$ standard error data.

Table 1. Waviness values of the unstretched and stretched tissue including combined and by region (mean $\pm$ standard deviation).

	Unstretched Tissue	Stretched Tissue	p-value
Combined	1.17 ± 0.21	1.05 ± 0.06	<0.001
Insertion Region	1.20 ± 0.24	1.05 ± 0.05	<0.001
Transition Region	1.12 ± 0.14	1.05 ± 0.08	0.0054
p-value	0.055	0.45	

MUSCLE MODELING

Simplified muscle model with aponeurosis geometry

- Varying aponeurosis modulus heterogeneity (Fig. 5)
- Muscle and aponeurosis constitutive models based on prior work [2,5]
- Simulated passive stretch and muscle activation (contraction)

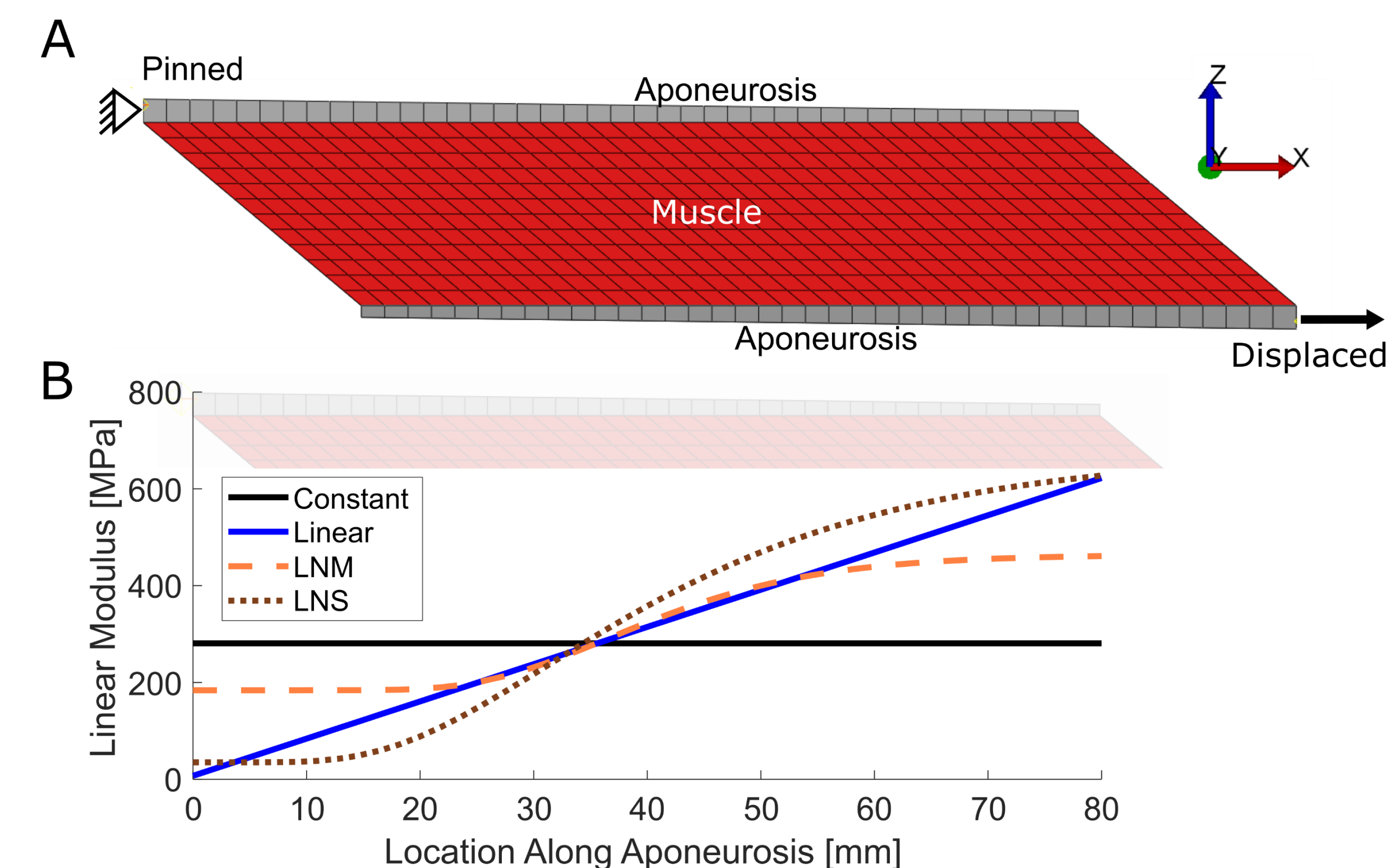


Figure 5. Finite element modeling approach for whole muscle slice model. A) Muscle slice model mesh, geometry, and boundary conditions (top left point pinned, bottom right point displaced in X-direction with no other boundary conditions, and front face fixed in the Y-direction). B) Variations in aponeurosis linear modulus as a function of location for various models.

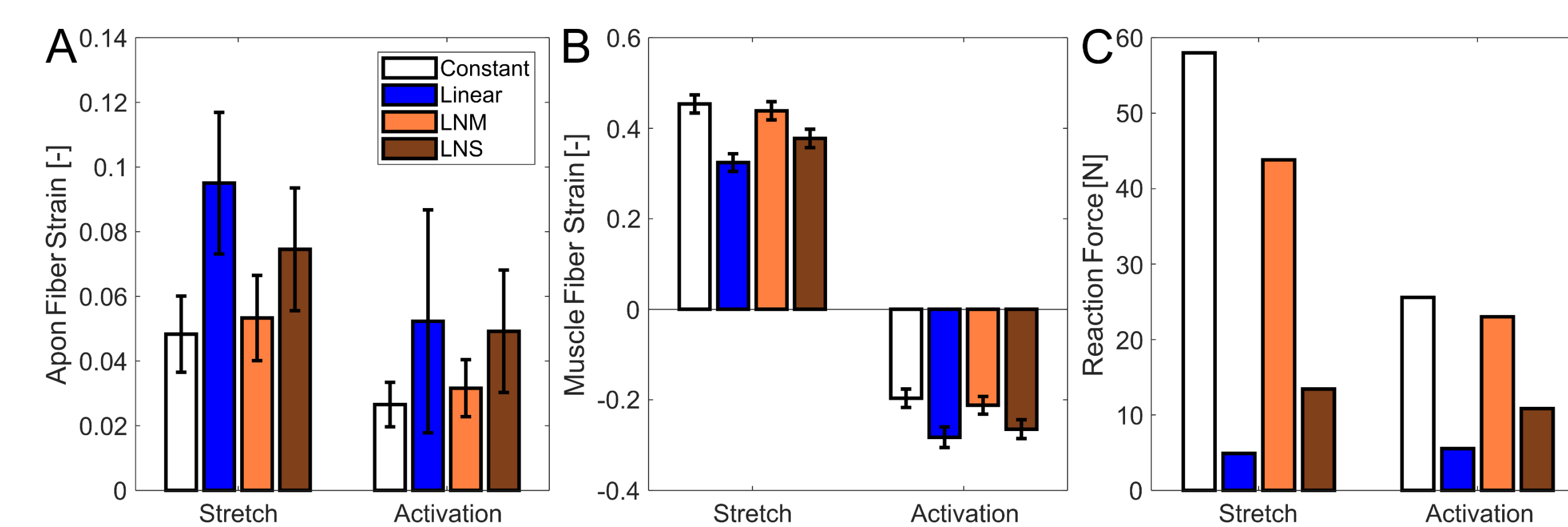


Figure 6. Muscle slice finite element modeling results. A) Mean (with standard deviation bars) aponeurosis fiber strain during passive stretch and activation. B) Mean (with standard deviation bars) muscle fiber strain during passive stretch and activation. C) Whole model reaction force at the end of the stretch step and activation step.

CONCLUSIONS AND FUTURE WORK

Aponeurosis microstructure and stress-strain behavior are heterogeneous

- Insertion region (near tendon) $\rightarrow$ more wavy collagen microstructure and less stiff
- Transition region (near muscle) $\rightarrow$ less wavy collagen microstructure and more stiff

Finite element analysis of muscle function with various aponeurosis heterogeneity altered muscle function

- Large variations in aponeurosis modulus $\rightarrow$ shorter muscle fibers and less stiff muscle-tendon unit with poor force transmission
- Constant aponeurosis modulus $\rightarrow$ longer muscle fibers and stiff muscle-tendon unit with high force transmission

Our results suggest that aponeurosis material properties are heterogeneous and the extent to which aponeurosis stiffness varies alters muscle fiber length and muscle-tendon unit function

ACKNOWLEDGEMENTS and REFERENCES

Funding for equipment used in this work was provided by the National Science Foundation under Major Research Instrumentation Grant No. 1828082. Authors would like to thank the Bucknell-Geisinger Research Initiative and the Program for Undergraduate Research at Bucknell University for funding to support this work.

[1] Eng. *J App Phys.* 10.1152/japplphysiol.00151.2018 [2] Grega. *J Mech Behav Biomed Mater.* 10.1016/j.jmbbm.2020.103889 [3] Rehorn. *J Biomech.* 10.1016/j.jbiomech.2010.05.011 [4] Herzog. *BMC Biomed Eng.* 10.1186/s42490-019-0031-y [5] Wheatley. *Front Phys.* 10.3389/fphys.2020.01021