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A Microstructural Constitutive Framework for Injured Ligament

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A Microstructural Constitutive Framework for Injured Ligament

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Introduction

Clinical Significance

- Ligament injuries account for over 7 million hospital visits per year in the U.S[1].
- After one year of healing, injured ligament has only half the strength of native ligament[2].
- Ligament injuries can lead to chronic disability due to poor structural quality of the healed tissue[2,3].

Developing effective treatments for ligament injury requires an understanding of the functional impact of microstructural adaptations after injury.

Background

- The primary load-bearing constituent of ligament is type I collagen[2].
- In native tissue, collagen fiber networks align to resist tensile deformation[4-6].
- Fiber networks are altered after injury achieving only modest realignment over time[2] (Fig. 1).

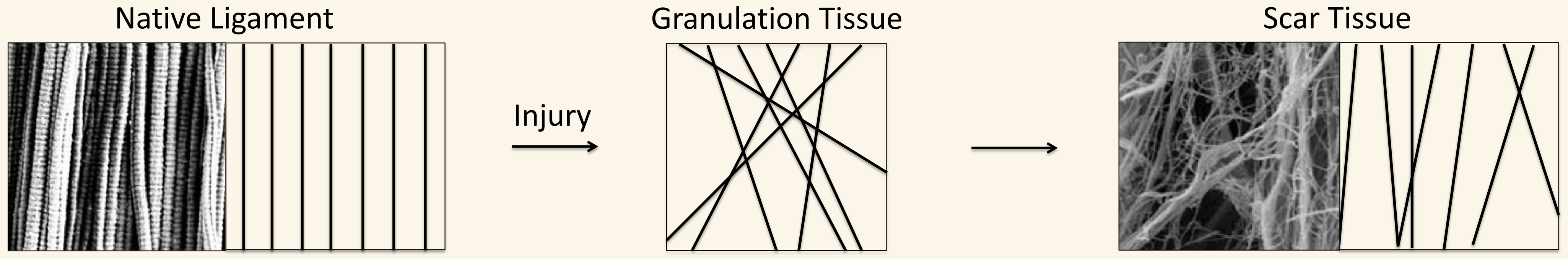

Figure 1. Collagen fibers during healing[3]. SEM images of rat tail (courtesy of R. Vanderby and M. Loghmani [7,8]).

Challenge: Current ligament constitutive models assume parallel collagen fibers[9-11], and are therefore unable to characterize the functional impact of structural alterations post-injury.

Hypothesis: The mechanical behavior of ligament with non-aligned fiber networks can be predicted using an anisotropic hyperelastic model that incorporates a fiber distribution term[12].

Objective: Test if model can predict differences in the mechanical behavior of bovine ligament by only accounting for differences in fiber distribution.

Methods

Overview

1. Function Mechanical Testing of Bovine Ligament → **2. Structure** Measure Fiber Distribution → **3. Model** Predict Stress using Fiber Distribution

stress-strain data → **VALIDATION**

1. Function: Experiment (Fig. 2)

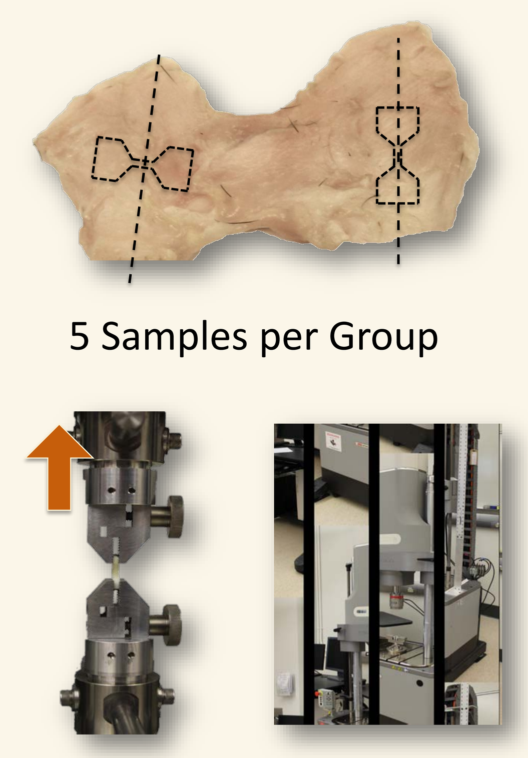

Figure 2. Mechanical test setup.

2. Structure: Confocal Microscopy

Challenge: Measuring the fiber distribution term k from the confocal images.

Solution: Custom Matlab program developed that discretizes fibers to build a Von Mises distribution to calculate k (Fig. 3).

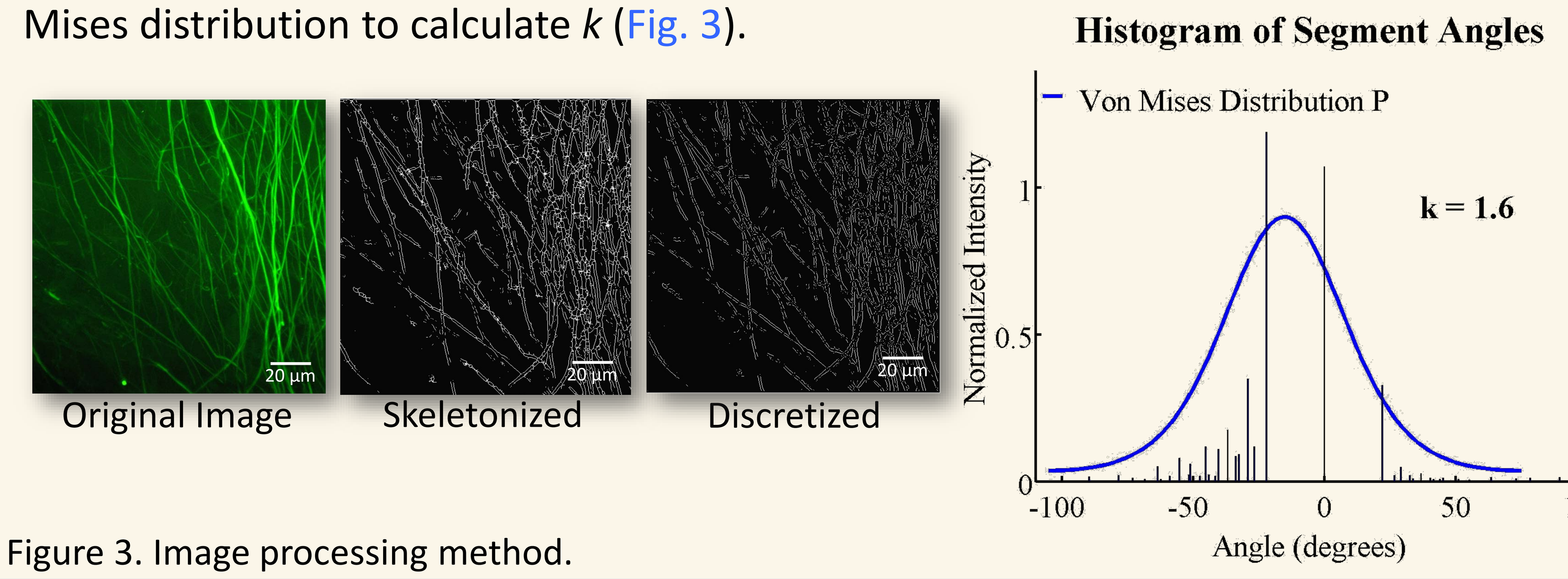

Figure 3. Image processing method.

3. Model: Anisotropic Hyperelastic Model with a Fiber Distribution Term[10,12]

$$\boldsymbol{\sigma} = \int_{\theta_p - \pi/2}^{\theta_p + \pi/2} P(\theta,k)\lambda(\theta)W_\lambda(\theta)\,(\boldsymbol{a}(\theta)\otimes\boldsymbol{a}(\theta))\,d\theta \quad \text{where} \quad P(\theta,k) = \frac{1}{\pi I_o(k)} e^{k\cos(2(\theta-\theta_p))}$$

→ The summation of stress for the normal distribution of fibers.

Results

- The fiber distribution term k was calculated for each group (Fig. 4).
- A strong correlation existed between the anisotropic hyperelastic model that incorporates a fiber distribution term and experimental data (Fig. 5).

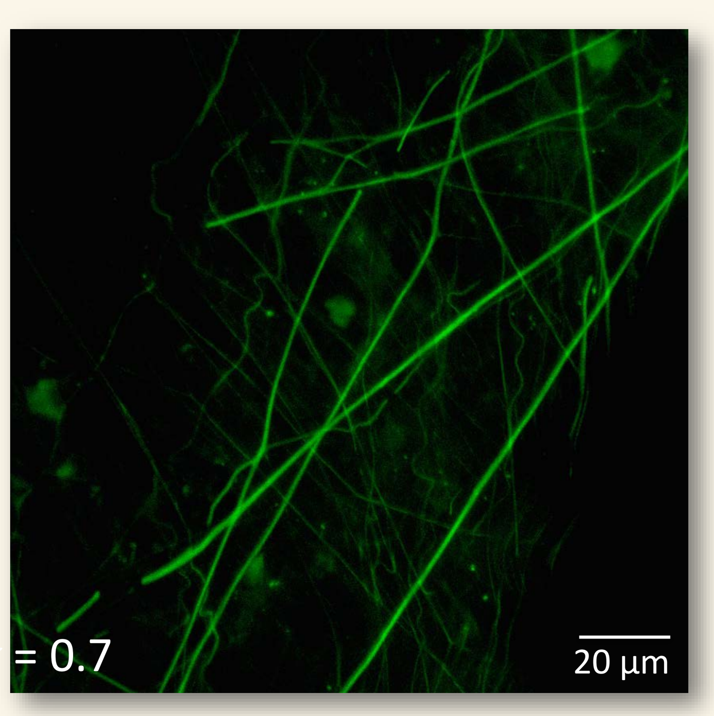

Figure 4. Sample confocal image showing z-stack projection of the autofluorescence of fibers for the longitudinal non-aligned group.

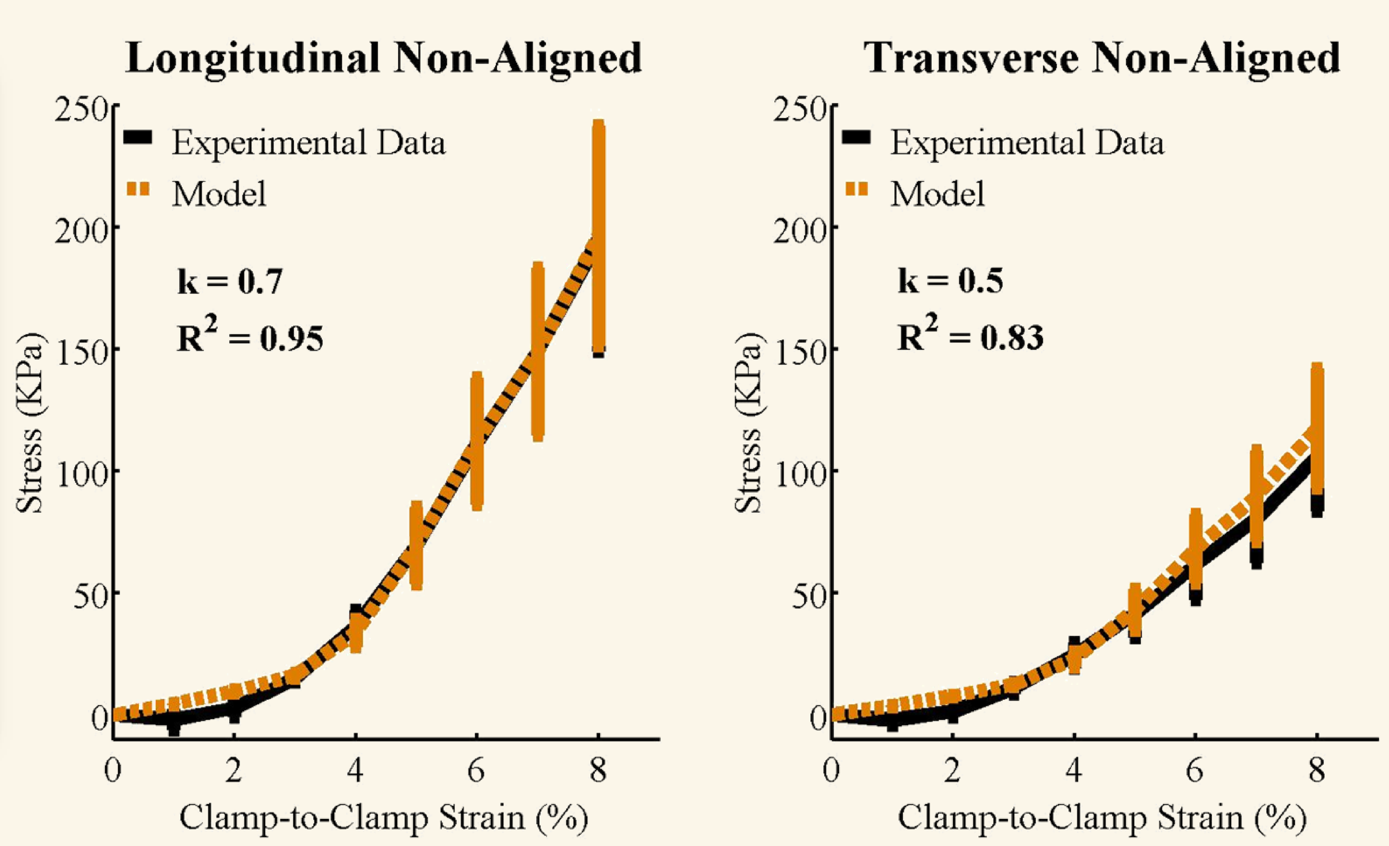

Figure 5. Average strain-strain curves for the two groups.

Discussion

- Differences in the mechanical behavior of ligament with non-aligned fiber networks were predicted by **only** accounting for fiber distribution from imaging data.

Future Work

- Use specimen specific k.
- Test under complex loading configurations.
- Validate model for highly aligned fiber networks.

Clinical Significance: Once the functional impact of fiber distribution is characterized, the efficacy of mechanostimulation can be understood and adapted to enhance ligament strength and lessen chronic disability (Fig. 6).

Figure 6. Augmented soft tissue massage performed to enhance collagen fiber alignment[13].

Conclusion: Promising mathematical framework to model ligament at different healing stages by adaptation of the fiber distribution term, k.

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The Biomolecular Research Center at Boise State University

References

1. Chen, L. H. et al. *Vital Health Stat 10,* (241): 1-55, 2009.
2. Frank, C. B. *J Musculoskelet Neuronal Interact*, 4(2), 199-201.
3. Jung, H. F. et al. *Sports Med, Arth, Rehab, Therapy & Tech 1*(9).
4. Chamberlain, C. S. et al. *Microsc Microanal*, 17(5): 779-87, 2011.
5. Woo, S. L. et al. *J Biomech*, *39*(1), 1-20.
6. Frank, C. B. et al. *Osteoarthritis and Cartilage*, *7*, 130-140.
7. Loghmani, M. T et al. *J Orthop Sports Phys Ther*, *39*(7), 506-514.
8. Provenzano, P. P. & Vanderby Jr., R. *Matrix Biology, 1-14*
9. Weiss, J. A. et al. *Comp Meth in Applied Mech and Eng*, *135*, 107-128.
10. Quapp, K. M., & Weiss, J. A. *J Biomech Eng*, *120*(6), 757-763.
11. Weiss, J. A., & Gardiner, J. C. *Critical Reviews in Biomed Eng*, 29(4),1-70
12. Girard, M. D. et al. *Journal of Biomechanical Engineering*, *131*.
13. Davidson, C. J. et al. *Med Sci Sport Exer, 29(3), 313-319.*