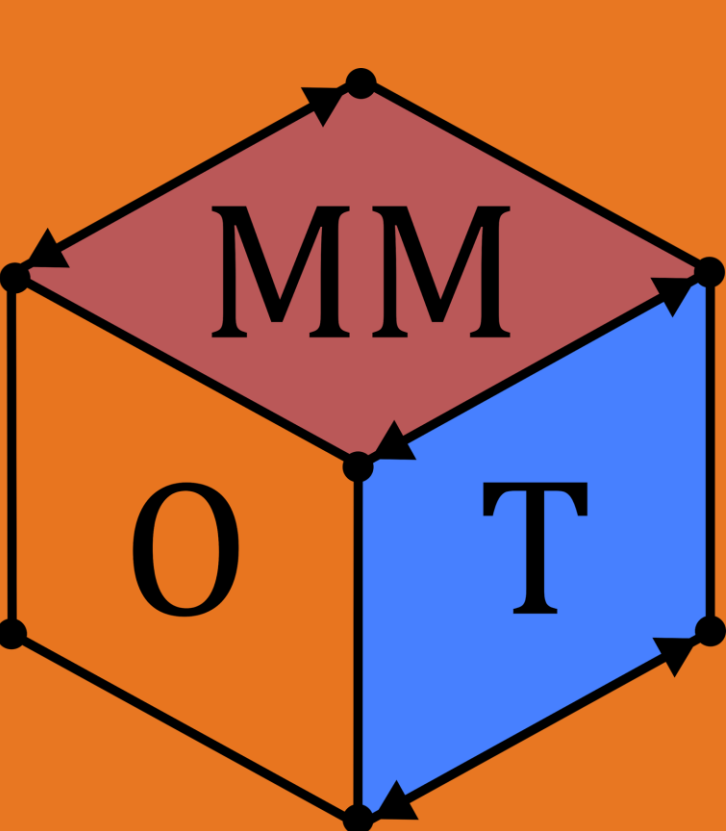




Variations in the Contribution of Fluid Pressurization to Compressive Muscle Stiffness: from Local to Global Indentation

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Introduction

- Hospital acquired pressure ulcers (Figure 1) are a major health concern for extended bed rest patients and cost \$20B+ to the United States healthcare system [1]
- Understanding mechanisms of muscle stiffness in compression are essential to preventing and treating pressure ulcers
 - Fluid is a contributor under *volumetric* (global) compression [3,4]; unknown how it contributes under *localized* compression (Figure 2)

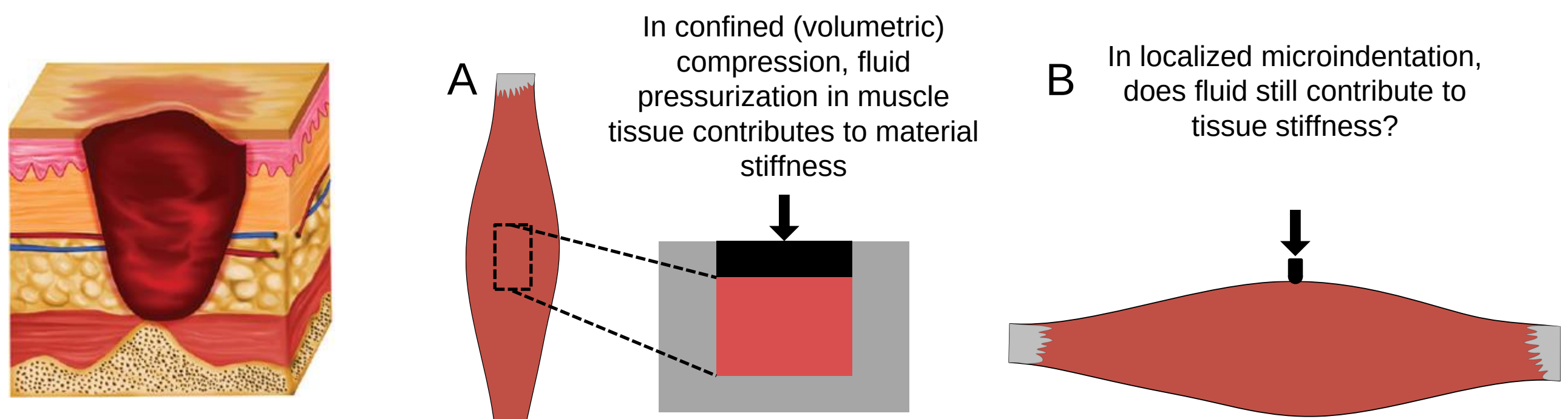


Figure 1. Schematic of a pressure ulcer; often caused by extended bed rest.

Figure 2. A) Skeletal muscle tissue under volumetric and B) localized compression.

Goal: Use microindentation and finite element analysis (Figure 3) to study the role of fluid pressurization in compressive muscle stiffness.

Hypothesis: Fluid pressurization contributes to muscle stiffness in under both volumetric and localized compression.

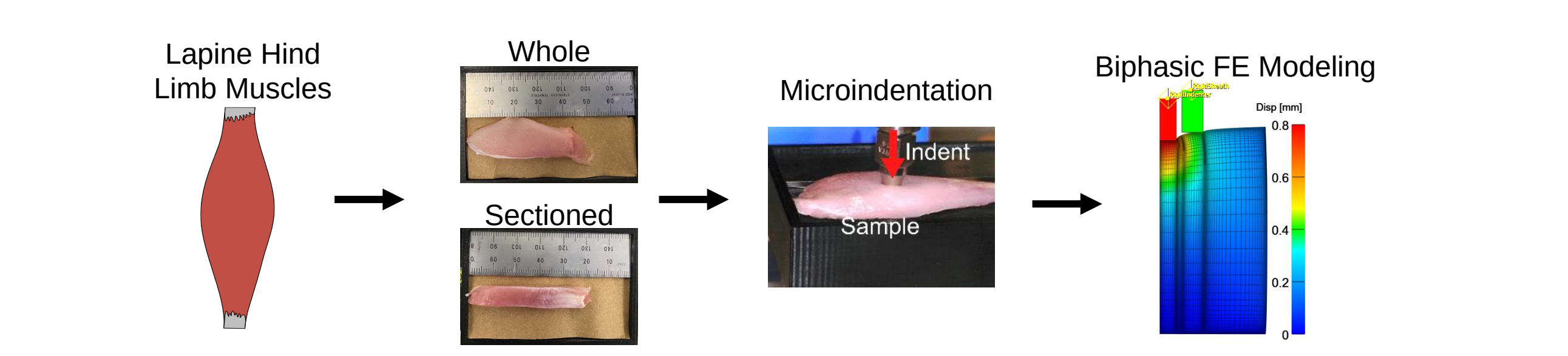


Figure 3. Study overview. Lapine hindlimb muscles were tested under microindentation either whole or sectioned. Various biphasic finite element models were used to interpret experimental results and investigate fluid pressurization under different volumetric compression conditions.

Microindentation Experiments

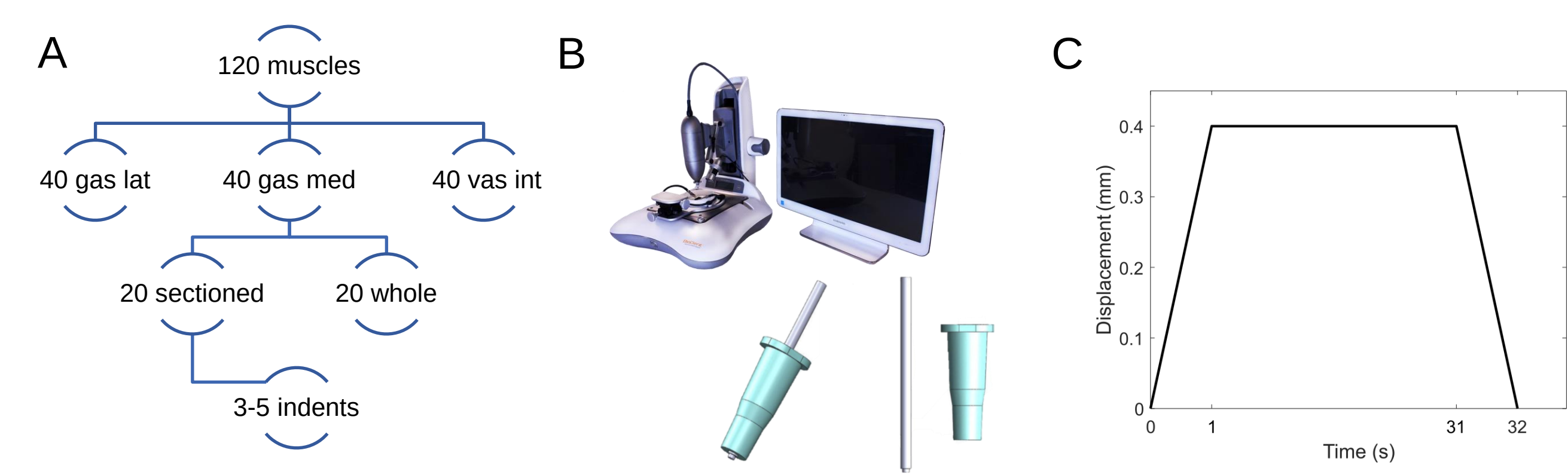


Figure 4. Experimental overview. A) Muscle sample groups. B) BioDent [2] microindentation equipment, including outer sheath and inner indentation probe. C) Indentation protocol, showing indentation ramp period and stress-relaxation period.

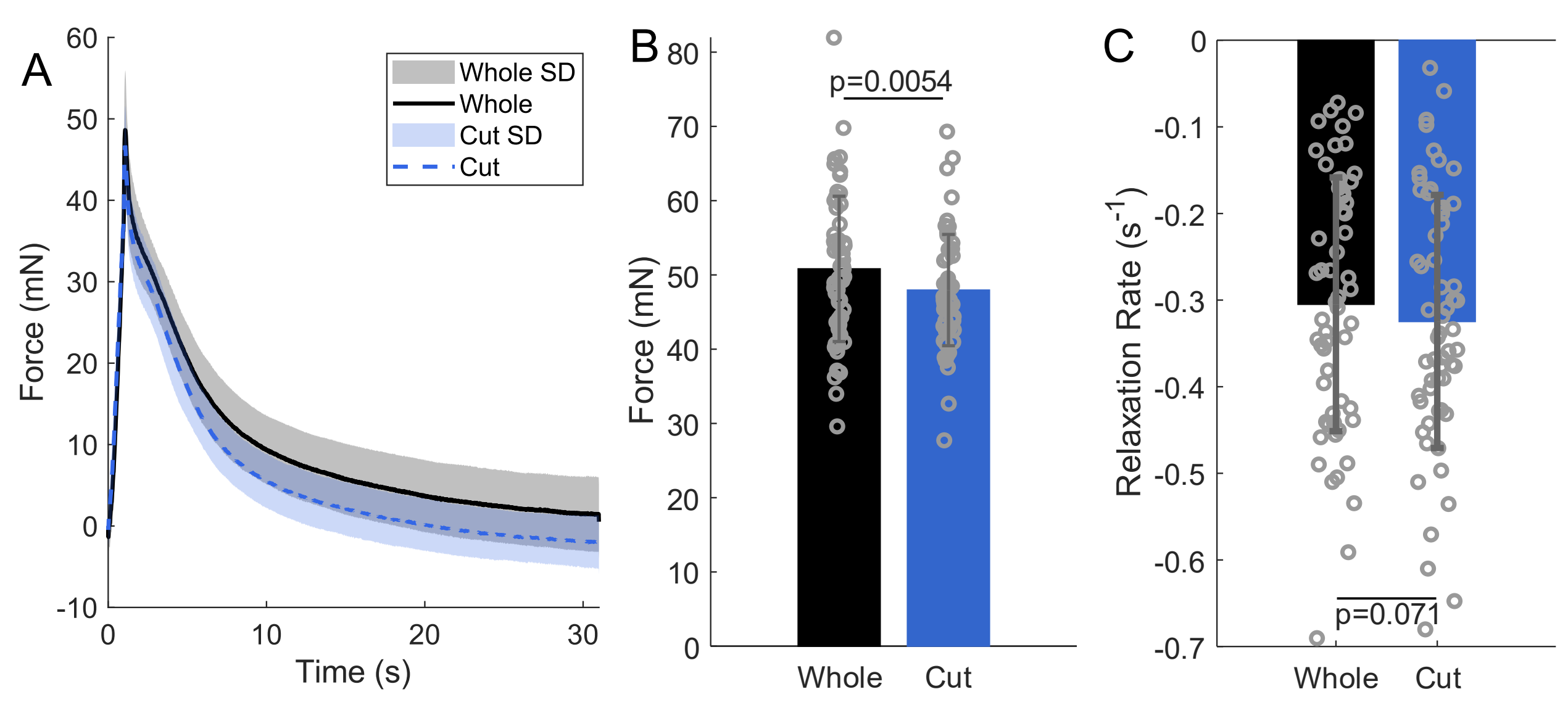


Figure 5. Experimental results. A) Force-time data showing indentation peak and relaxation. Data are smoothed and zeroed from pre-load, which explains negative values at the end of relaxation. B) Indentation peak force. Whole muscles exhibited statistically significant increases in stiffness. C) Relaxation rate. Sectioned muscles exhibited a higher relaxation rate, with differences between groups non-significant but trending.

Microindentation Modeling

- An axisymmetric microindentation model of muscle tissue was developed in FEBio (Figure 6)
 - Different boundary conditions approximate whole and sectioned experimental samples
- A visco-biphasic viscoelastic constitutive model was used for muscle tissue [4,5]:

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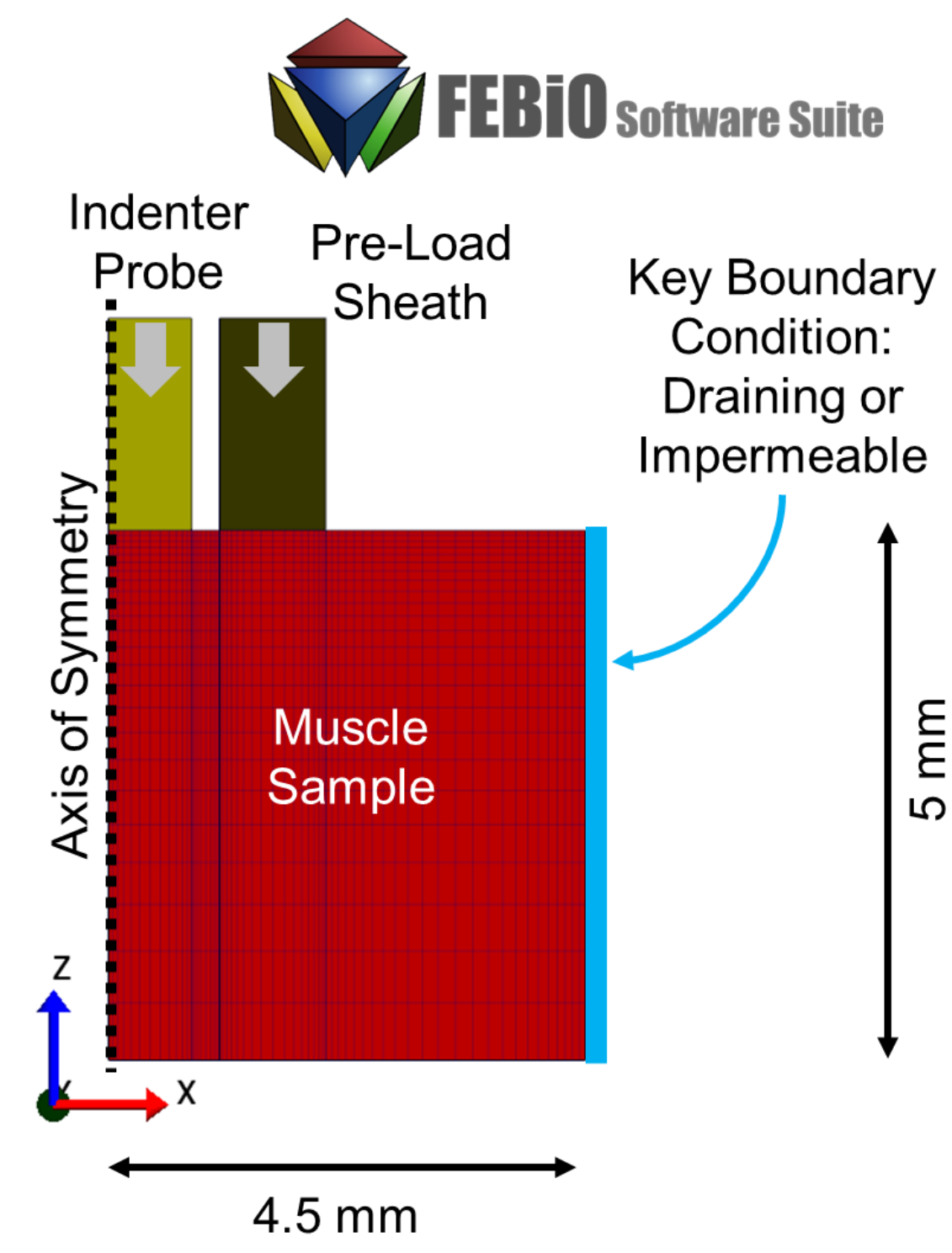


Figure 6. Microindentation modeling methods. Axisymmetric finite element model of sectioned sample, showing indentation sheath, indenter, axis of symmetry, and exterior boundary surface for either draining or impermeable conditions.

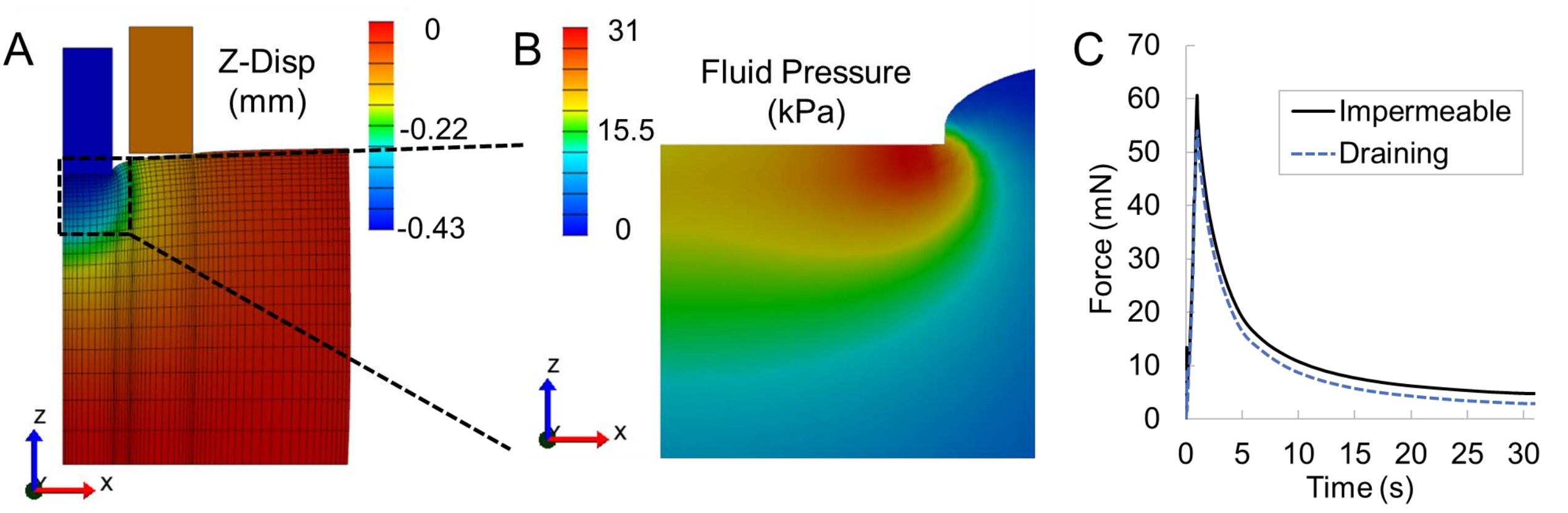


Figure 7. Microindentation modeling results. A) Model displacement in the Z-direction after pre-load and indentation, showing displacement of both pre-load sheath and indenter probe. Indentation is localized. B) Fluid pressure distribution near indentation probe. Pressurization is shown at indentation peak (prior to relaxation). C) Force-relaxation response of two indentation models: one with fully impermeable and one with fluid draining. Fluid draining shows a slight decrease in force, similar to experimental data of sectioned samples (Figure 5).

Variable Indentation Modeling

- Axisymmetric confined compression with variable indenter sizes (Figure 8) and two different constitutive models:
 - #1: same constitutive model as microindentation modeling
 - #2: reactive viscoelastic model only (no fluid)
- 5% nominal compression (0.5 mm of 10 mm sample)

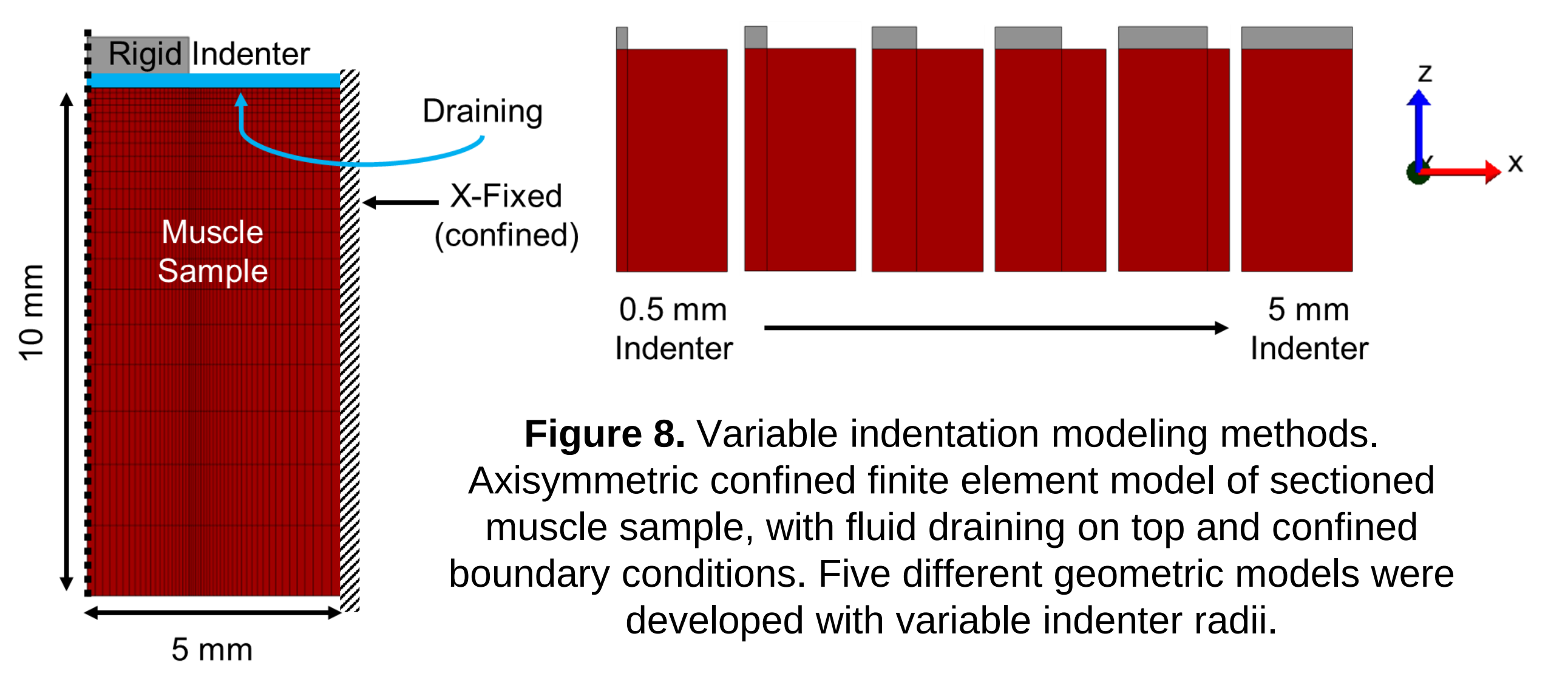


Figure 8. Variable indentation modeling methods. Axisymmetric confined finite element model of sectioned muscle sample, with fluid draining on top and confined boundary conditions. Five different geometric models were developed with variable indenter radii.

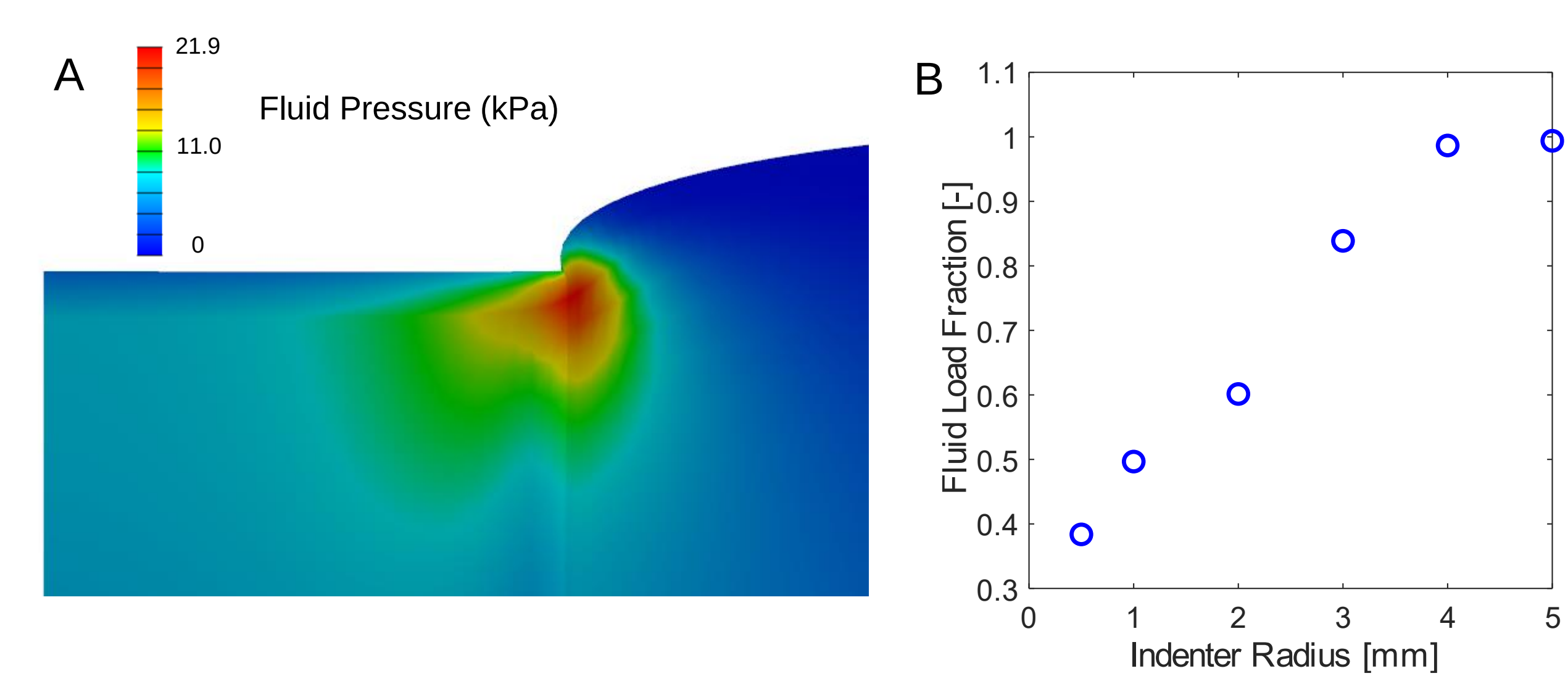


Figure 8. Variable indentation modeling results. A) Localized fluid pressurization for the 2 mm radius indenter model. B) Fluid load fraction (defined as 1 - the ratio between solid-only model and biphasic model indenter reaction forces) as a function of indenter radius. This increase in load fraction shows an increasing role of fluid-pressurization to muscle compressive stiffness with increasing volumetric strain.

Discussion

- Experimental microindentation data showed differences in tissue stiffness between sectioned and whole samples
- Modeling results I) suggests these differences could be due – in part – to fluid pressurization and fluid flow and II) show contributions to tissue stiffness by fluid pressurization increase from local to global strain
- These findings can help researchers develop and implement computational models for pressure ulcer prevention

Collectively, these results support the body of evidence that fluid pressurization plays a key role in compressive muscle stiffness [3-5], and that this role is increased in global volumetric compression compared to local compression.

References

[1] Padula, W., et al. *International Wound Journal*. (2019). [2] Tang, S. et. al. *Polymer Testing*. (2010). [3] Lavigne, T. et. al. *Clinical Biomechanics*. (2022). [4] Wheatley, B. et. al. *Computer Methods in Biomechanics and Biomedical Engineering*. (2017). [5] Wheatley, B. et. al. *Acta Biomaterialia*. (2025).