SIMON FRASER UNIVERSITY
ENGAGING THE WORLD

3D MODELLING OF MUSCLE MECHANICS USING FINITE ELEMENTS

CUMC/CCÉM Saskatoon 2018

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July 15, 2018

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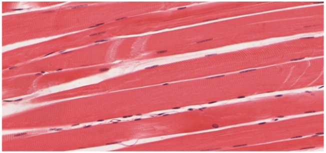
INTRODUCTION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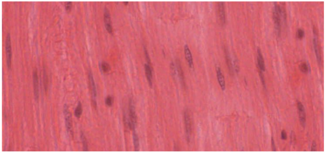
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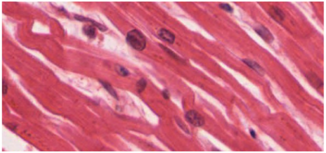
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Three broad types of muscle:

(a) **Skeletal** : most common, very large multi-nucleated cells.

(b) **Smooth** : contribute to the walls of blood vessels, and many visceral organs.

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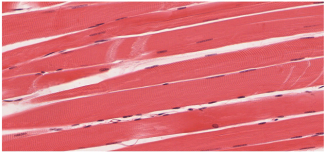

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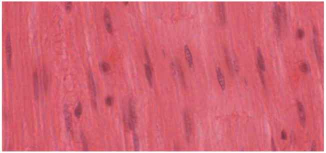

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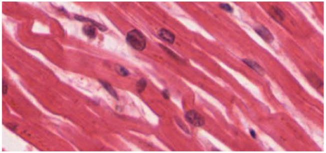

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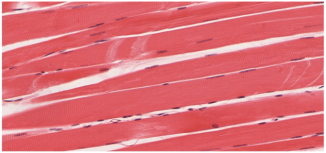

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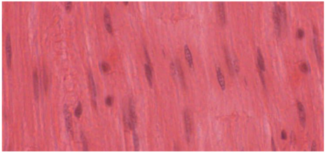

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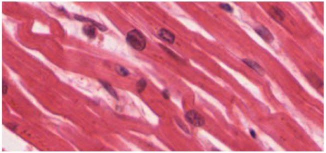

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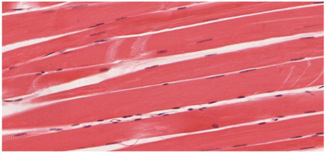
Muscle Architecture and Physiology



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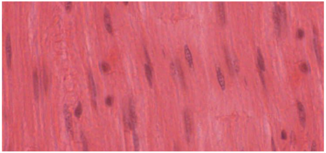

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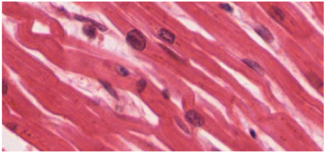

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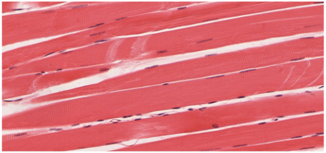

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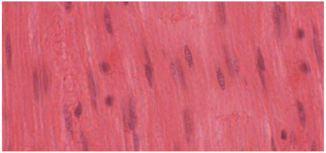

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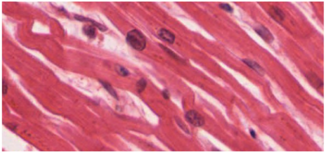

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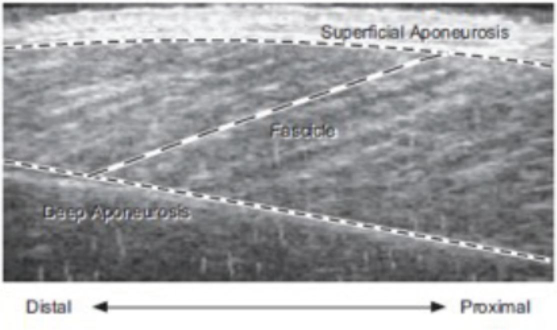
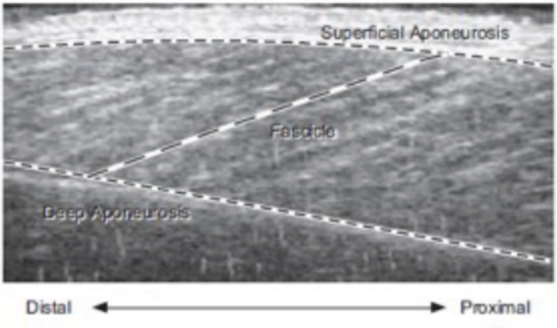
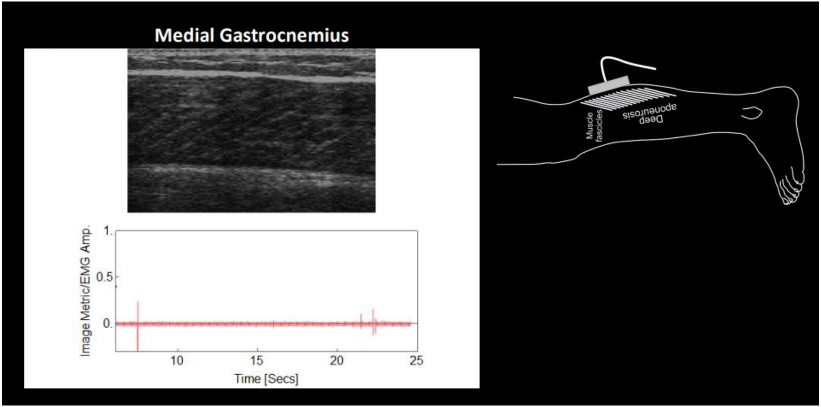
A **motor unit** consists of a motor neuron (located in the spinal cord), its axon, and the muscle fibers it innervates.

aponeurosis: white fibrous tissue that connects muscle and tendon to bone or other muscles.



pennation angle: angle of the fascicles within the muscle with respect to the aponeurosis.





Ultrasound of the medial gastrocnemius showing the pennate muscle fibres and aponeurosis. The medial gastrocnemius is one of the most popular muscles for study because of the easy access.

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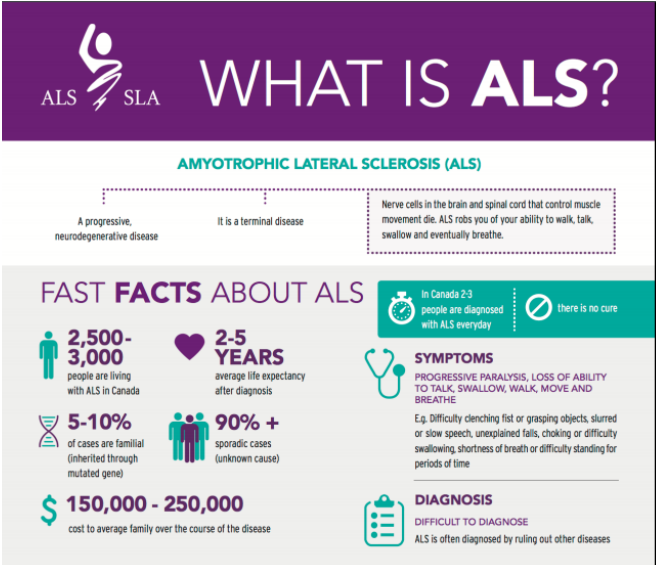

Muscle Architecture and Physiology

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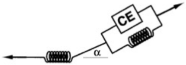

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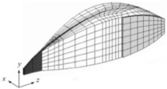

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2-dimensional models treat muscle as a panel with springs to either side, springs deform but area remains constant

3-dimensional continuum models hope to more accurately capture the complexity of biological tissue

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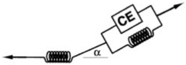

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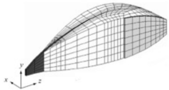
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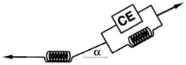

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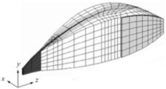

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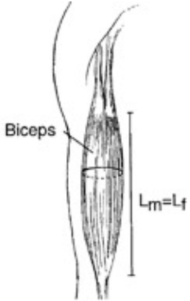
THE MATHEMATICAL PROBLEM

Modelling Assumptions

GOAL: Design a robust and accurate mathematical framework to answer fundamental questions about muscle mechanics

Features of biological tissue:

- Nearly incompressible
- Capable of finite, non-linear deformations
- Comprised of many materials
- Fibres can be activated



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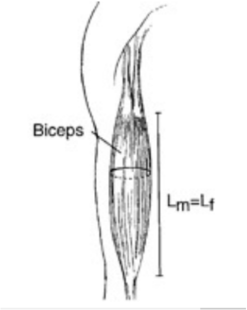

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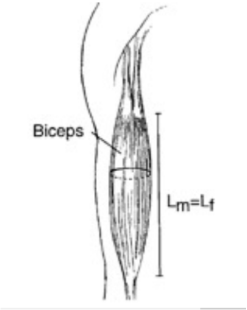

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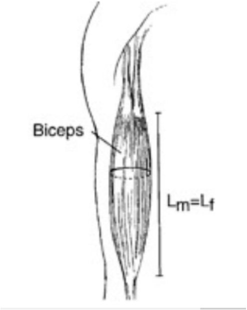

Problem: Partial Differential Equation

Want to find displacement $u(x, t)$ so that:

$$\nabla \cdot \sigma(u(x, t)) + F(x, t) = \rho(x) \frac{\partial^2 u}{\partial t^2}$$

All of the "biology" goes into σ

In the first term, σ is the stress function. It describes the forces within the muscle (active, passive, elastic).

The second term F describes any external forces.

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IDEA: discretize the given continuous problem with infinitely many degrees of freedom, to obtain a discrete problem. (finitely many degrees of freedom)

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Steps:

1. Reformulate the differential equation as an equivalent variational problem. (subject to constraints of different kinds)
2. In order for the problem to be solved exactly, replace the set of admissible functions V (infinite dimension) by a set V_h of simple functions dependent on finitely many parameters
3. We end up with a non-linear system of equations.
4. Solution of the discrete problem, and computer implementation

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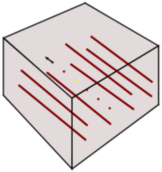
Tools: Differential Equations Analysis Library



dealii is an open source finite element library

C++ program library targeted at the computational solution of partial differential equations using adaptive finite elements.

Current model based on the step 44 tutorial on nonlinear solid mechanics

Information stored in quadrature points

Within each sub-grid lie a finite number of quadrature points, at which we store $\approx$27 important values such as:

- location in space (x,y,z) coordinates
- components of velocity in the (x,y,z) directions
- type of tissue (muscle or tendon)
- activation level
- modulus of compression (tells us how the compressive force is changing the volume per unit)
- constants related to tissue mechanical properties (e.g. bulk modulus)
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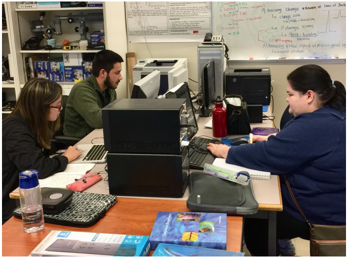
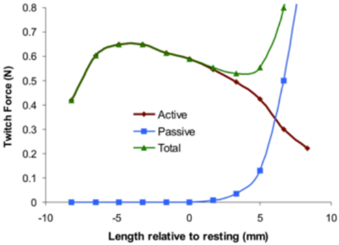
CURRENT EXPERIMENTS AND PROBLEMS

What the NSERC kids are up to!





Alice: Generating a force-length curve. Pulling the muscle to different lengths, then activating. [0.6, 1.6] of normalized length.

Ryan: Adapting code to simulate an external weight on the muscle, changing length and then activating.

Cassidy: Adapting code to apply pressure to the "top" of the muscle, observing how compression effects force output.

Megan: Activation of ≈5 percent of muscle fibres to simulate the firing of a single motor neuron - "twitch". Want to look at visual output!

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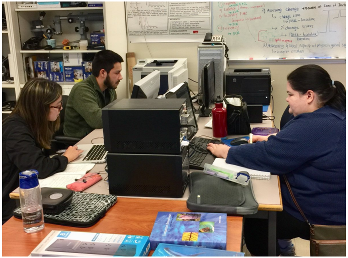

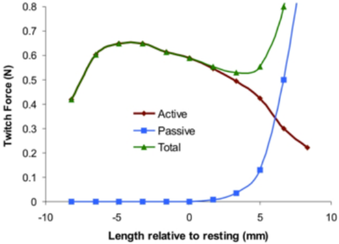

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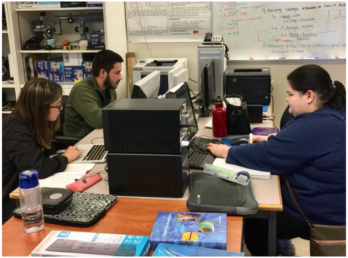

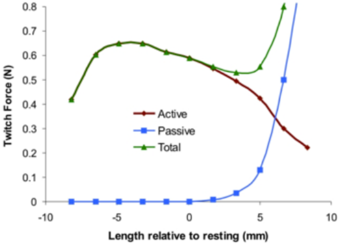

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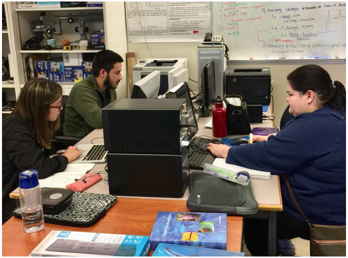

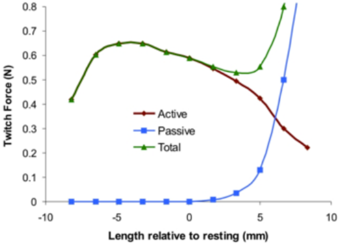

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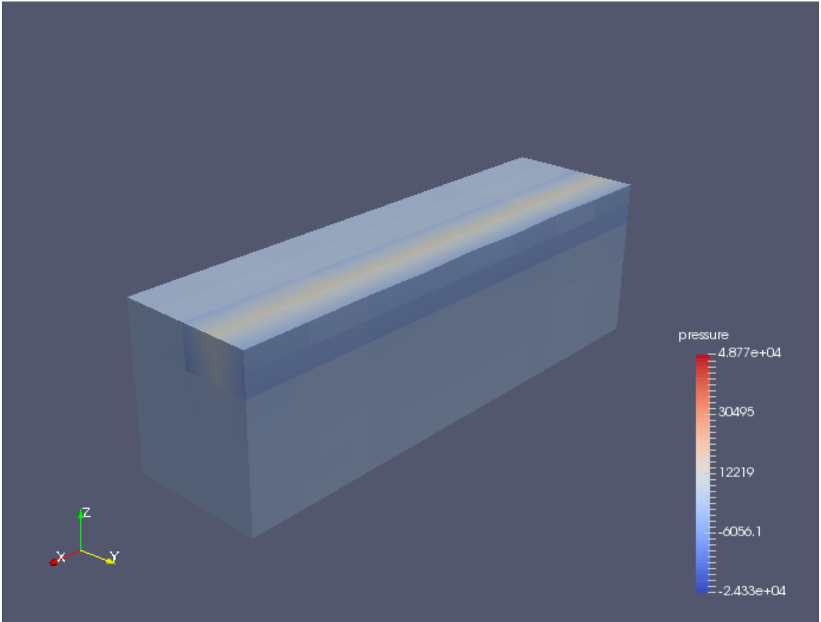
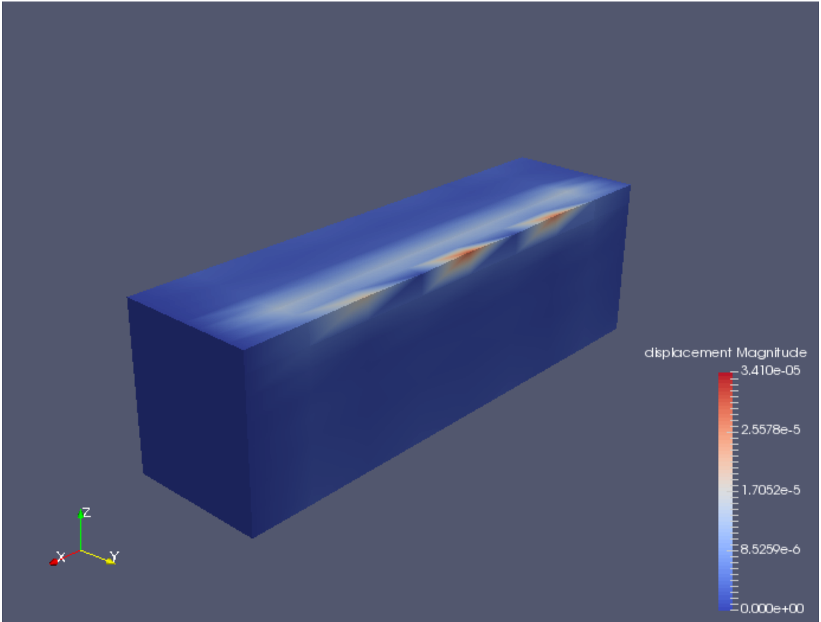
RESULTS

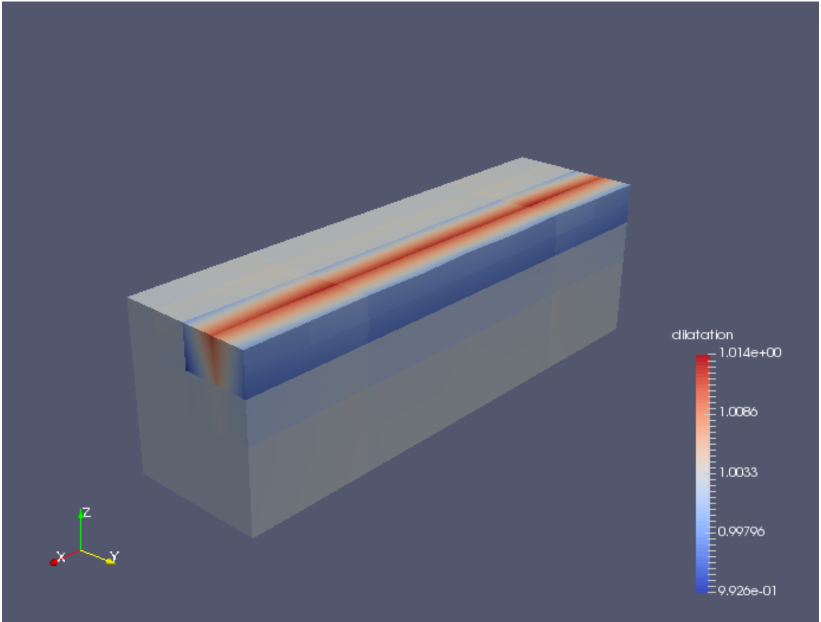
Example 1: Pressure output



Example 1: Displacement output



Example 1: Dilation output



Example 2: Displacement Movie!

In this simulation, we are activating the top 5 percent of fibres in the z-direction.

FINAL REMARKS

Further Questions and Adaptations

For ALS, can we simulate motor neuron death? This would change the base properties of the material, as fibres degenerate into fat and other substances.

Time delay between activation of fibres within a single motor unit. i.e. "jitters"

Changing the function used to ramp up activation. (generalized normal distribution)

How does not being at optimal length affect "twitches"?

Create more realistic, curved geometries

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Further Questions and Adaptations

We want to add the aponeurosis tissue, and observe how the visual output of ”twitches” changes.

ALS probes are most commonly used in the bicep and gastrocnemius muscles. The bicep has parallel fibres, while the gastrocnemius is pennate. Adapt geometries to these two specific muscles for most accurate and helpful results.

How does the distribution of the muscle fibres associated with a single motor unit effect the result? (i.e. clumped close together, spread across mesh)

Multiple neurons firing simultaneously, likely with delay.

Reinnervation: When a motor unit ”saves” the fibres of another that has died. The result is a larger unit, with more potential force. This process breaks down in ALS. Can we account for this?

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THANK YOU!