Template Models For Surface Manipulation Of Musculoskeletal Extremity Regions

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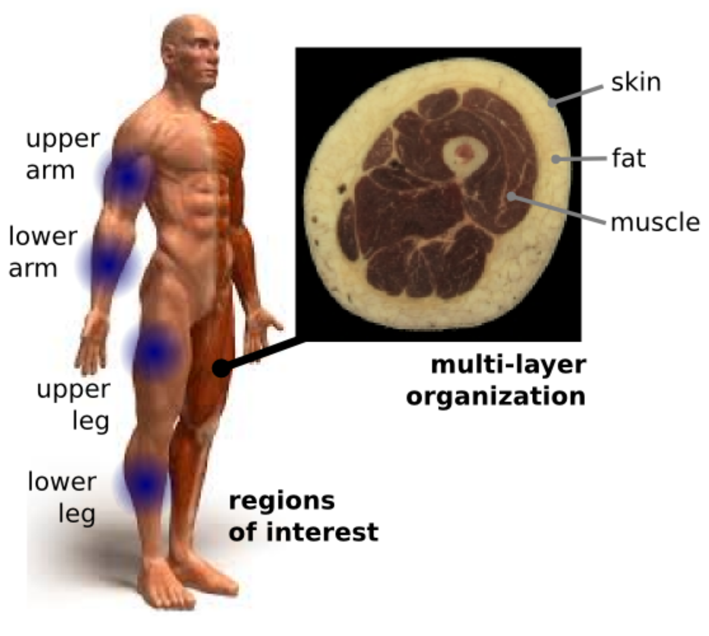
BACKGROUND

Almost **half of combat injuries** occur to the **musculoskeletal extremities**[1]. A need for models that can provide authentic haptic response and are built on a comprehensive dataset has arisen in the areas of:

- Surgical simulation
- Virtual prototyping of protective gear
- Medical training

Simplified models that merge the skin, muscle, and fat layers but capture authentic tissue surface response are important to improve computational efficiency.



The four regions of interest modeled as part of the study.

GOAL

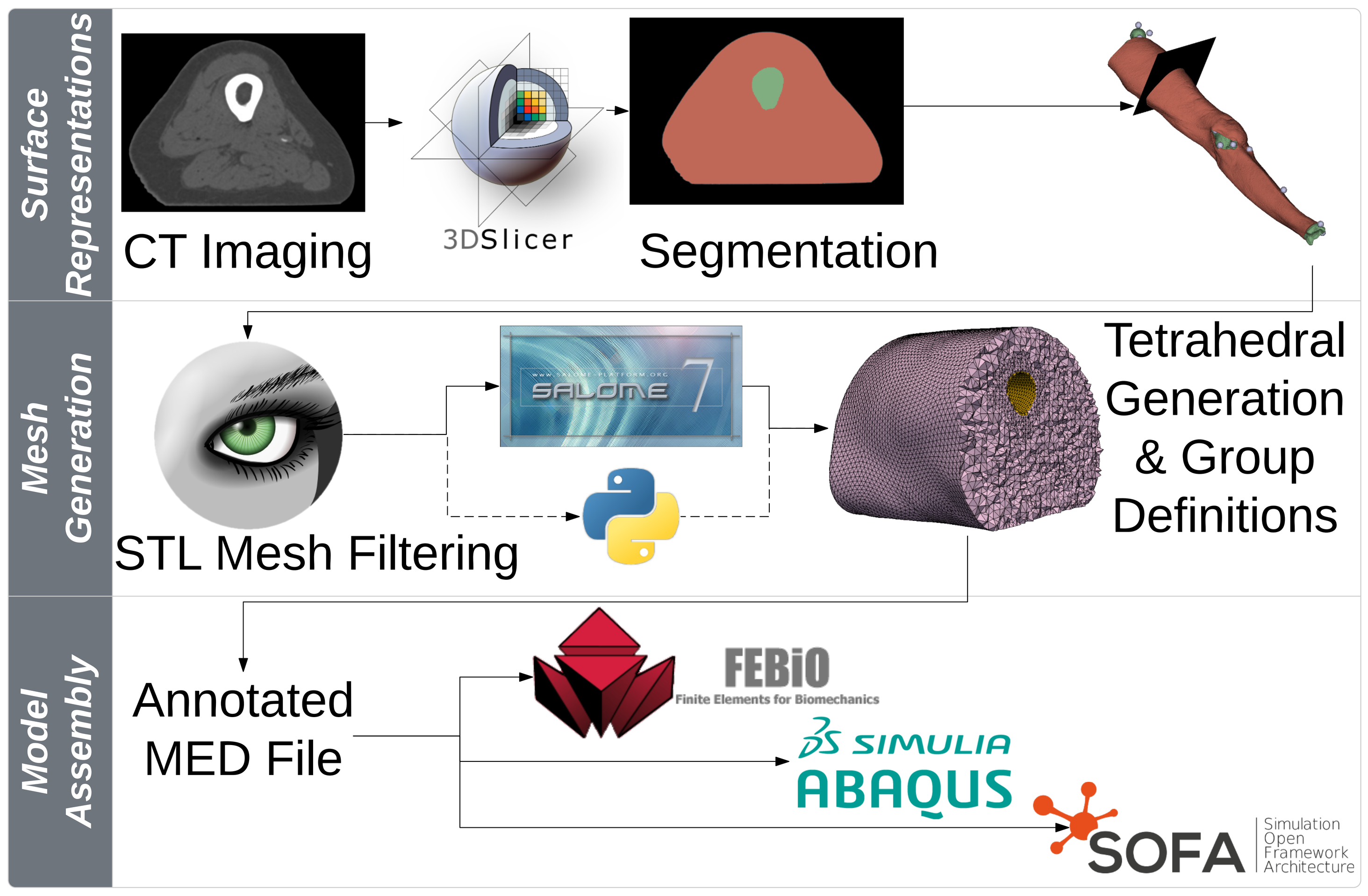
Develop **free and open source template models** for the musculoskeletal extremities that can faithfully replicate indentation and other surface interactions to inform haptic feedback.

METHODS

- CT images (0.5x0.5x0.6 mm^3) acquired on 4 cadaver musculoskeletal regions[2] of 2 donors were manually segmented.

Sex	Age (years)	Weight (kg)	Height (m)	BMI (kg/m²)
Male	65	77.1	1.78	24
Female	62	68.0	1.80	21

- **8 models** were used with **FEBio** 2.8.0 to simulate indentation with an ultrasound probe - frictionless penalty-based contact and a Neo-Hookean constitutive model (C_1 = .01 MPa, K = 1000* C_1^3). The pipeline for model development also supports **Abaqus and SOFA**.



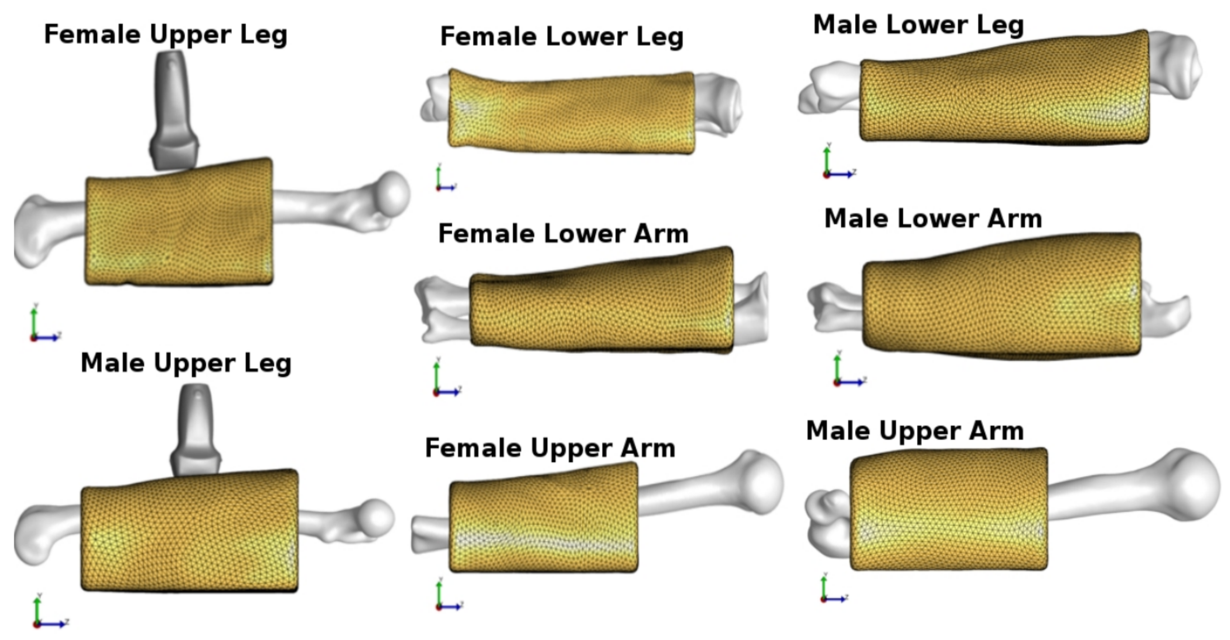
Stages of model development, automated with Python scripting and other open-source software.

- Previous work provided probe force-displacement data during indentation (2.9 to 9.1 mm, a 9.5 to 30.9% change in tissue thickness)[2,4]. Displacement data informed boundary conditions and an inverse finite element analysis calculated **specimen-specific tissue properties**. Linearized indentation stiffness of the model was matched to experiment during this analysis by using the ratio of these to scale C1 (and with it, K to keep K/C1 = 1000).

- A mesh convergence study was performed. Convergence was reached at less than 5% change in simulated reaction forces for consecutive densities. Converged level (bolded) corresponds to a mesh resampling rate of 5 in MeshLab.

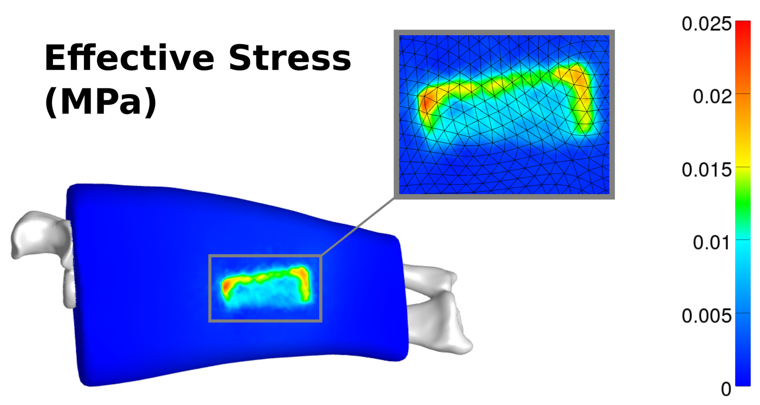
Node Count	Predicted Reaction Force (N)	Percent Difference
44968	20.8	-
72904	19.9	-4.3
113836	**18.1**	**-9.1**
173068	17.5	-3.0
244551	17.6	0.3

RESULTS

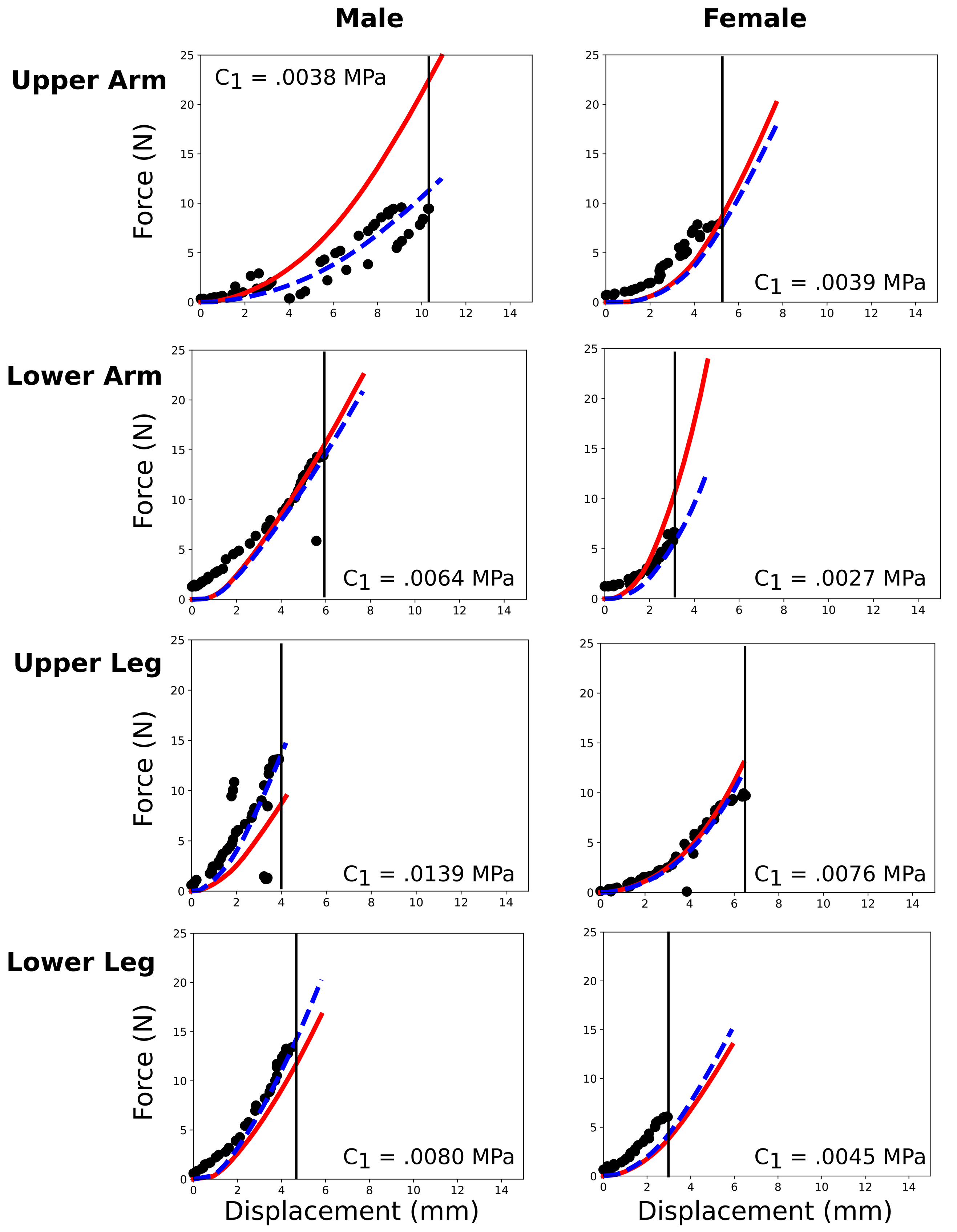


All eight lumped tissue models, with probe placement shown ony for the upper legs.

- Simpified inverse finite element analysis calibrated for specimen-and region- specific material properties usually in one iteration. Indentation response after calibrations matched measured surface mechanics more closely.
- Large variations in calibrated tissue properties were noted in comparison to literature value of C_1 = .01 MPa: C_1 = .0027 MPa to 0.0139 MPa.



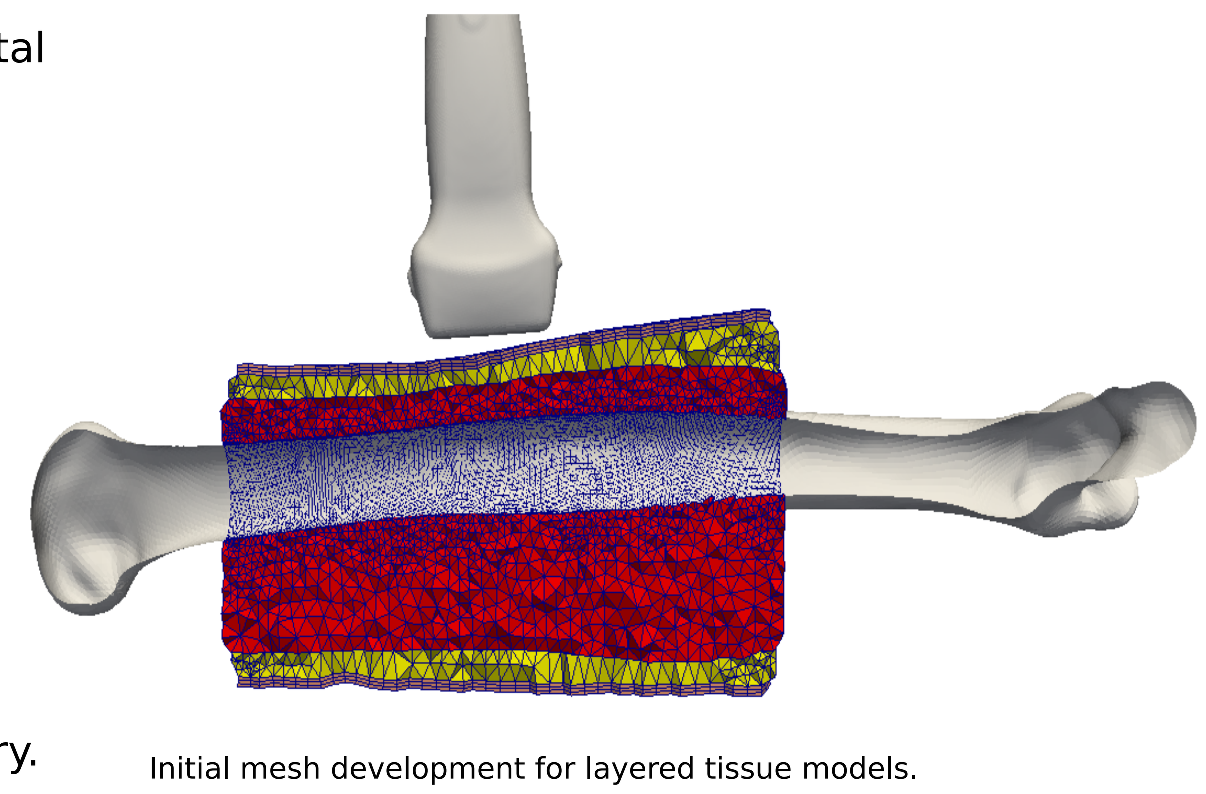
Concentration of effective stress at maximum indentation for the male lower arm. Other field metrics are also available, e.g., Lagrange strain, contact pressure, etc.



Indentation force and displacement: experimental (black dot), simulation with literature properties (red solid line) and after calibration (blue dotted line). Vertical lines indicate peak experimental indentation depth.

DISCUSSION

- Eight template models for surface manipulation of musculoskeletal extremity regions were built.
- Soft tissue properties are known to change with gender, age, and body region[5]. Using the same literature value for all 8 models demonstrated the need to accommodate this with inverse finite element analysis.
- Calibration with simplified inverse FEA provided a quick yet practically adequate method to represent specimen-specific indentation response for experimental range of displacements, achieving the goal of region-specific haptic feedback.
- These models will be the starting point for scientific and clinical simulations of extremity manipulation. Surgical simulations are also possible. Although further model reduction may be necessary.



Initial mesh development for layered tissue models.

Next steps:

- Implement **mesh morphing** for building models with only in vivo thickness measurements.
- Develop **layered models** with interactions between tissue layers.
- Port the current models to **surgical simulation software** (SOFA).

REFERENCES

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[5] Choi, A., et al. Med. & Biol. Eng. & Comp. 43.2 (2005): 258-264.

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OPERATION MULTiS

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Project Funding: USAMRMC, DoD (W81XWH-15-1-0232; PI: Erdemir)
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