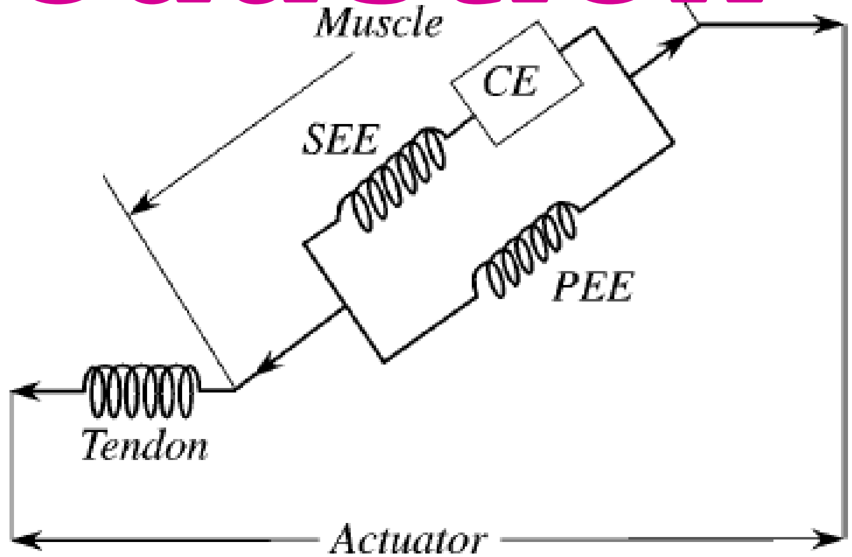
Computer Modeling And Simulation of Skeletal Muscle: An Introduction

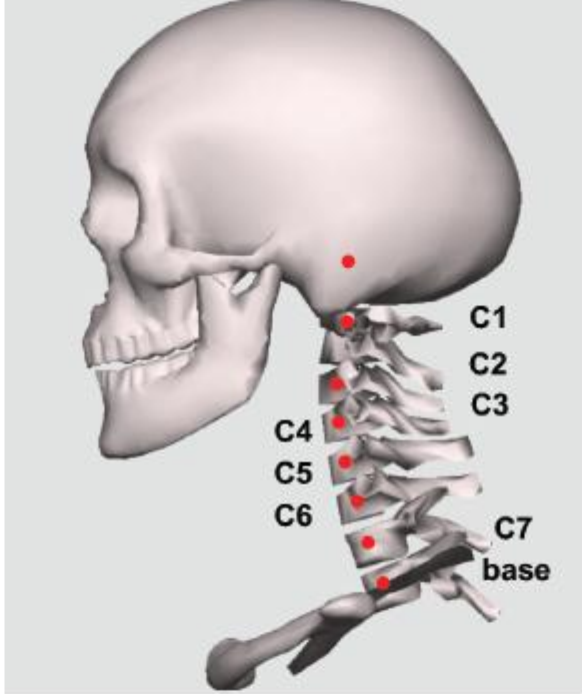


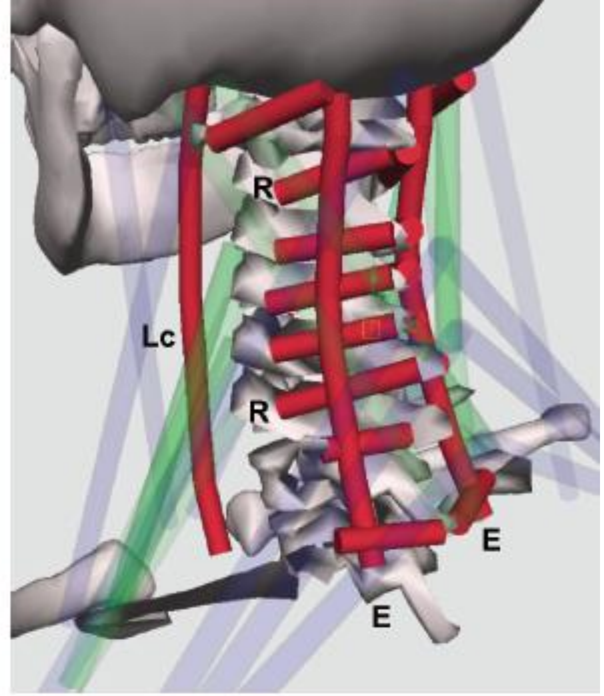
Enja Schenck

April 30th, 2014

Introduction/
What Muscle modeling is NOT

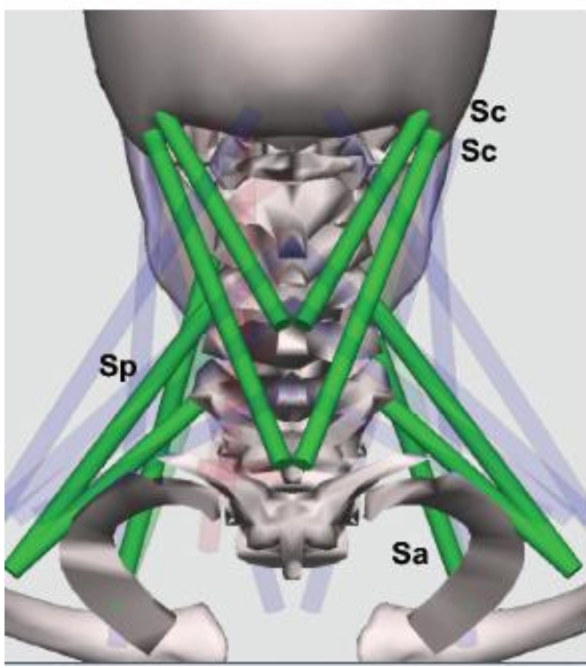
- ❖ Not just object creation as in architectural 3D software
- ❖ Not just key-framing as in 3D animation programs
- ❖ It uses sarcomere-level forces that have been translated into mathematical functions
- ❖ Movement is not pre-programmed but based on interaction and feedback loops

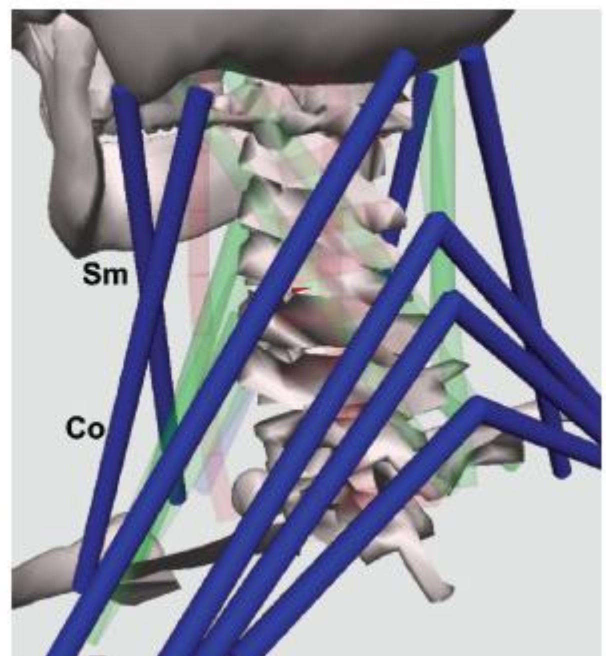


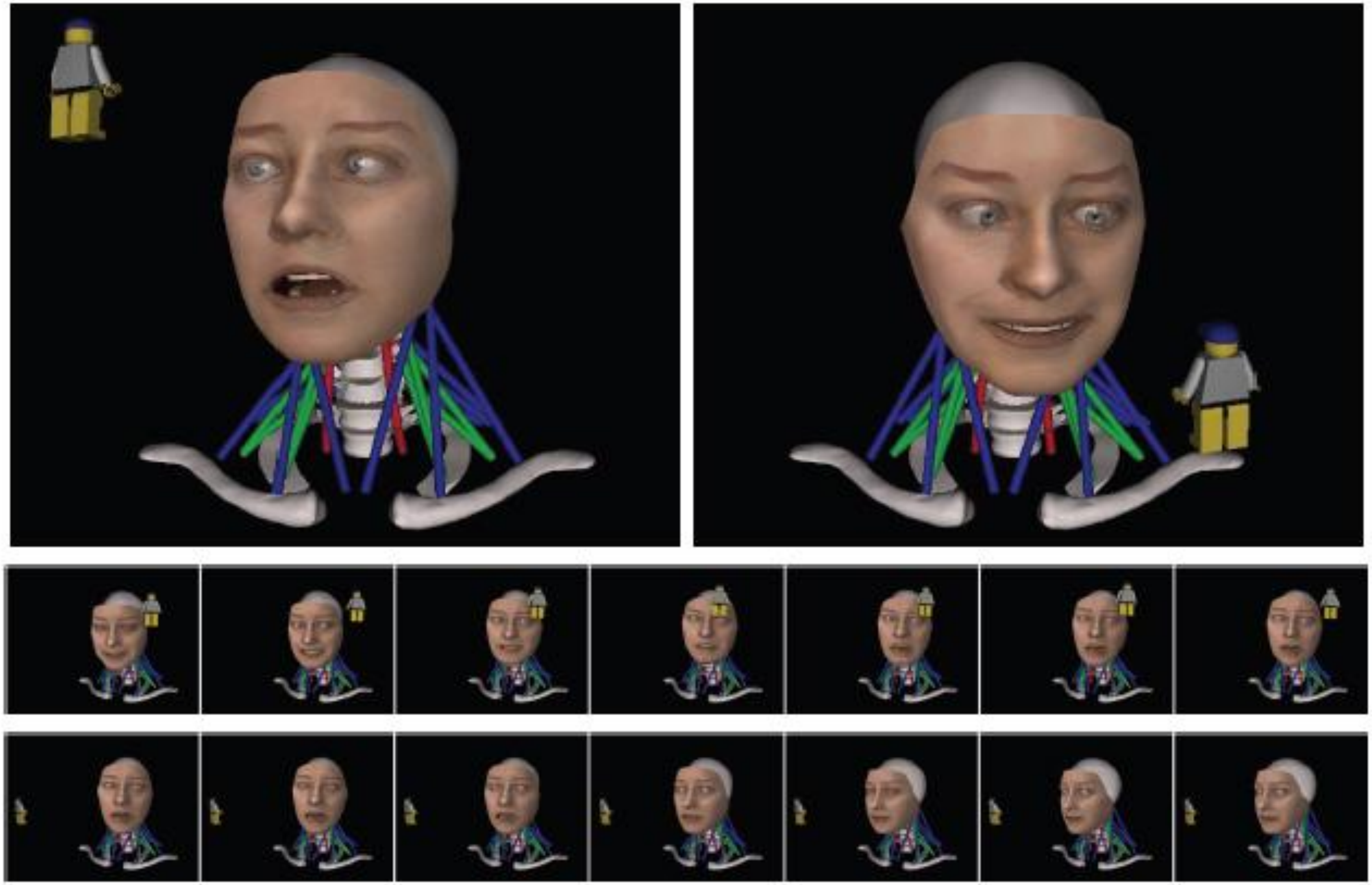


(a) Skeleton model.

(b) Deep muscles.







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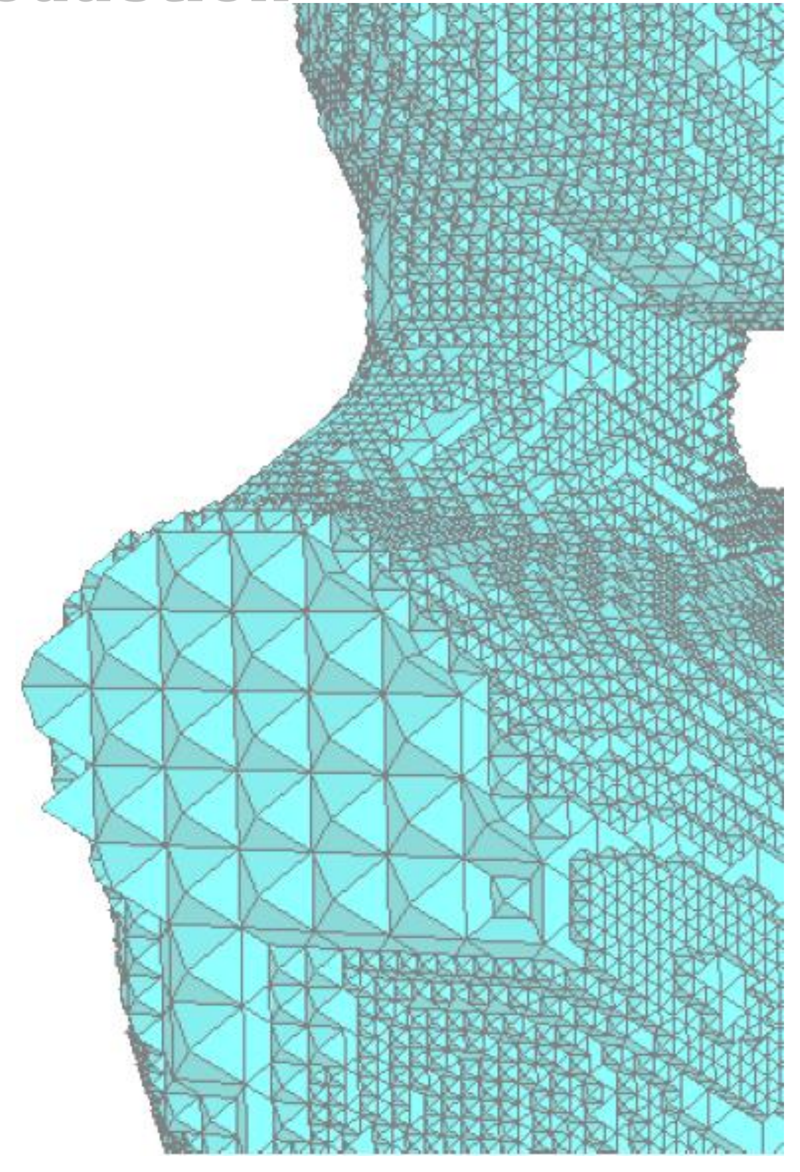
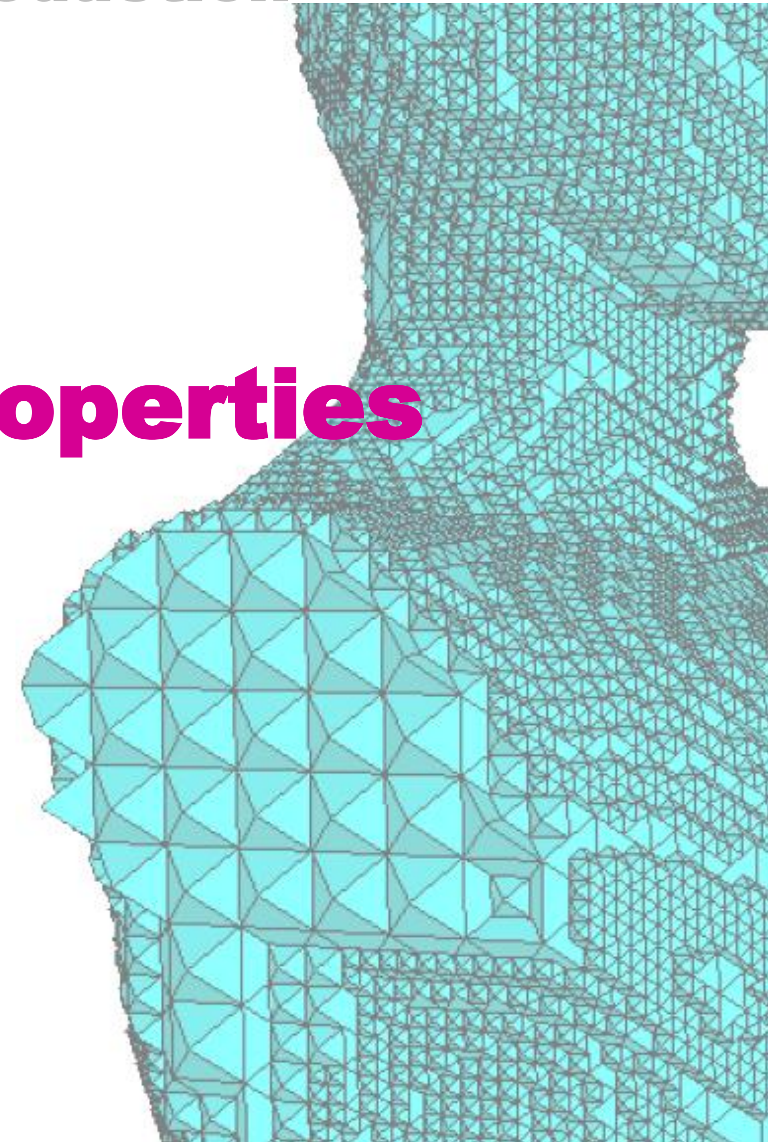


Introduction/ Applications

- Biomechanics
- Ergonomics
- Medicine
- Biomedical engineering
- Computer graphics

Introduction/
Relevant muscle properties

- ❖ Myofibril architecture
- ❖ Tendons and force transmission
- ❖ Muscle architecture
- ❖ Sliding filament theory
- ❖ Force-length, force-velocity and stimulus-tension curves



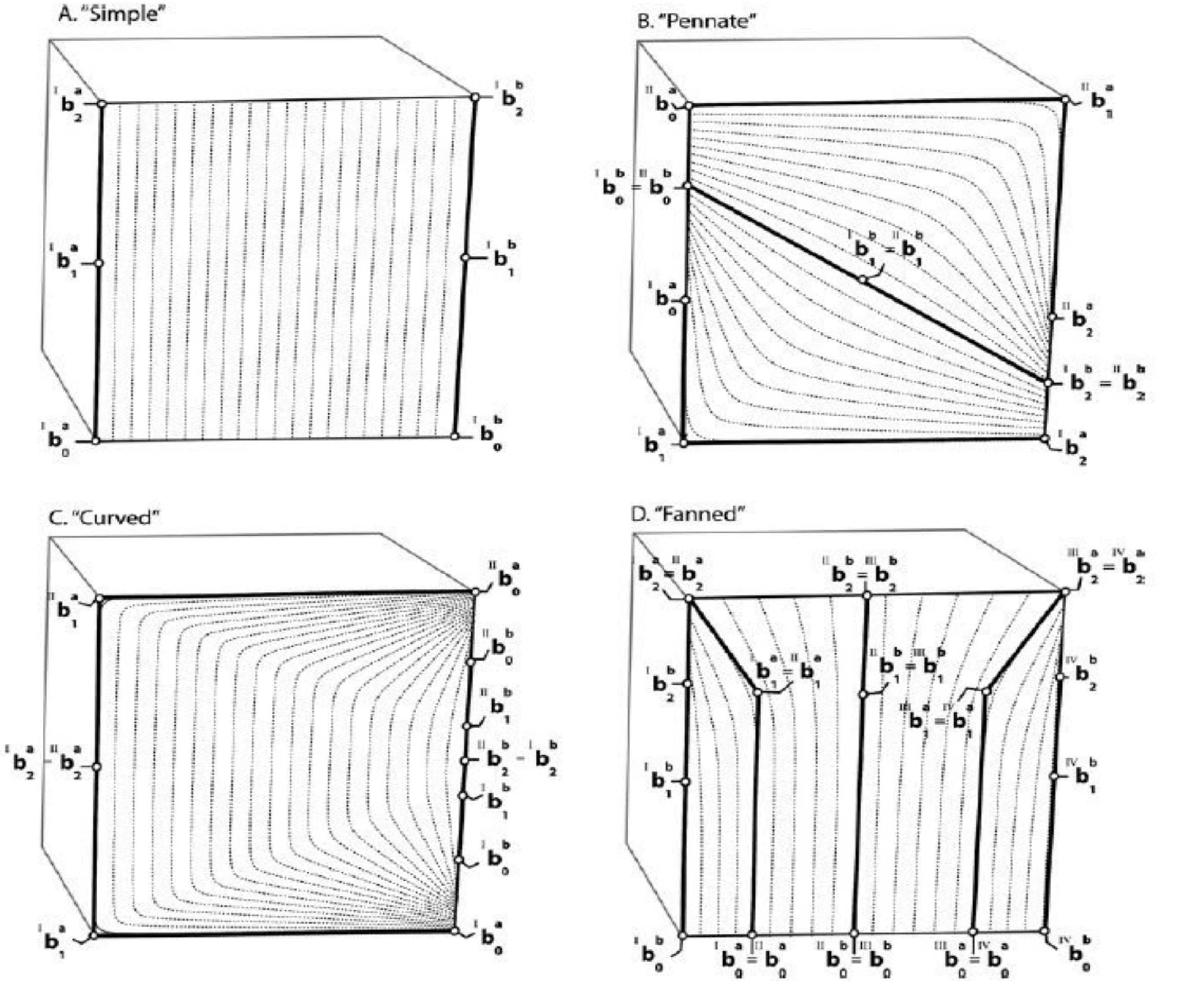
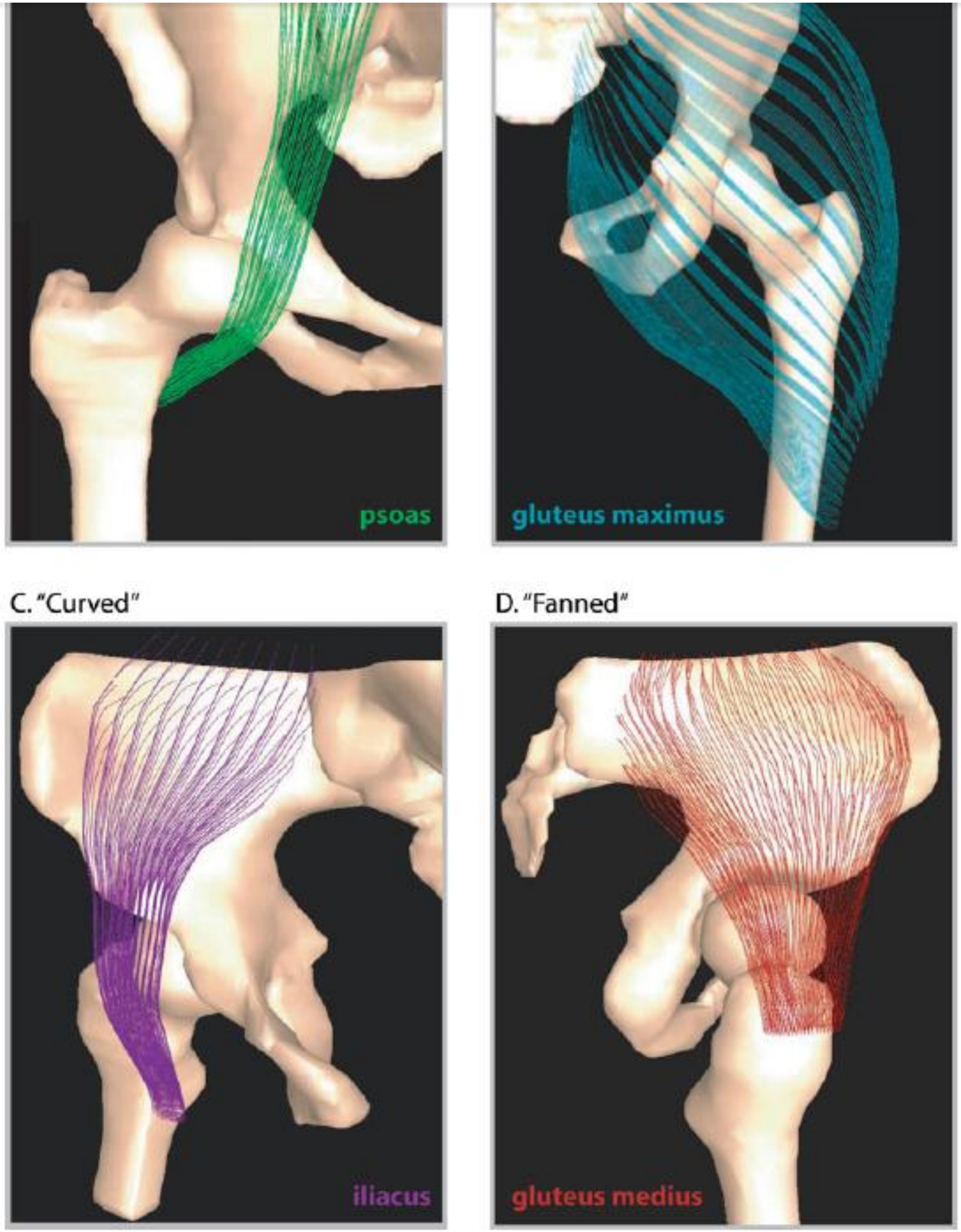
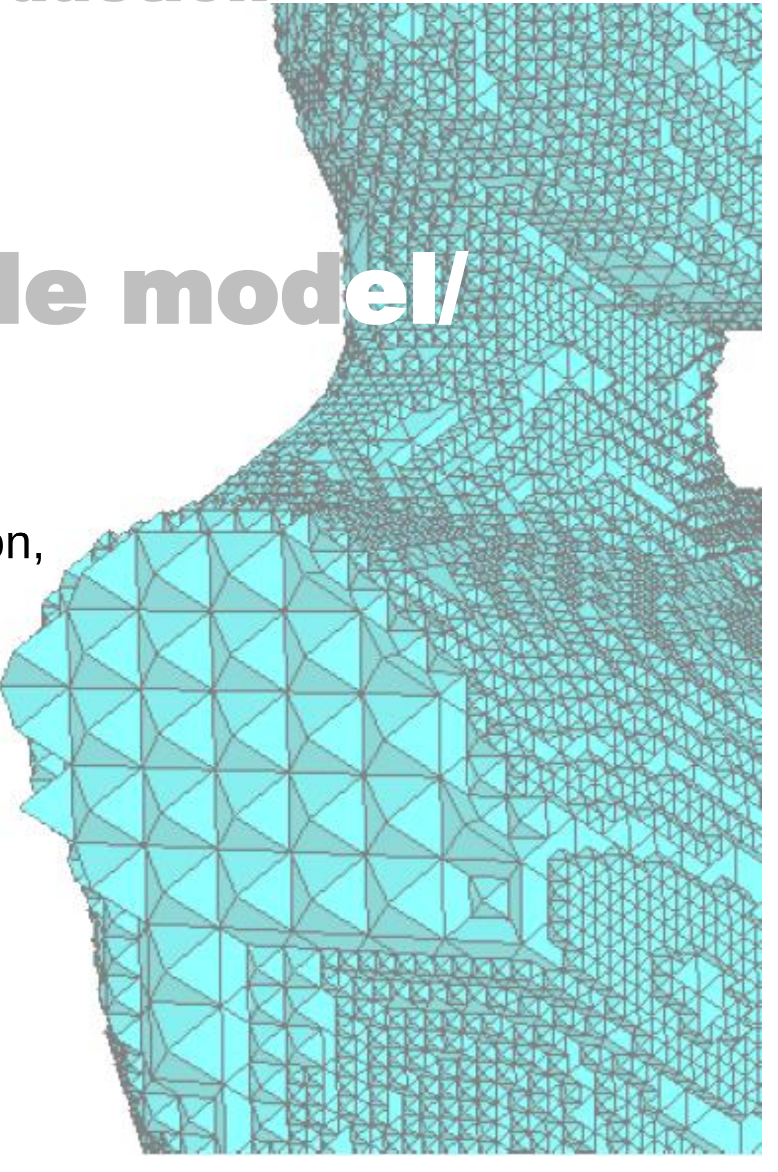


FIGURE 4. Fiber geometry templates used for parallel muscles (A), pennate muscles (B), curved muscles (C), and fanned muscles (D). The templates consist of interpolated rational Bezier spline curves. In the simplest case (A), only one set of spline curves are the basis for the interpolation. In the most complex case (D), four sets of spline curves are the basis for the interpolation.

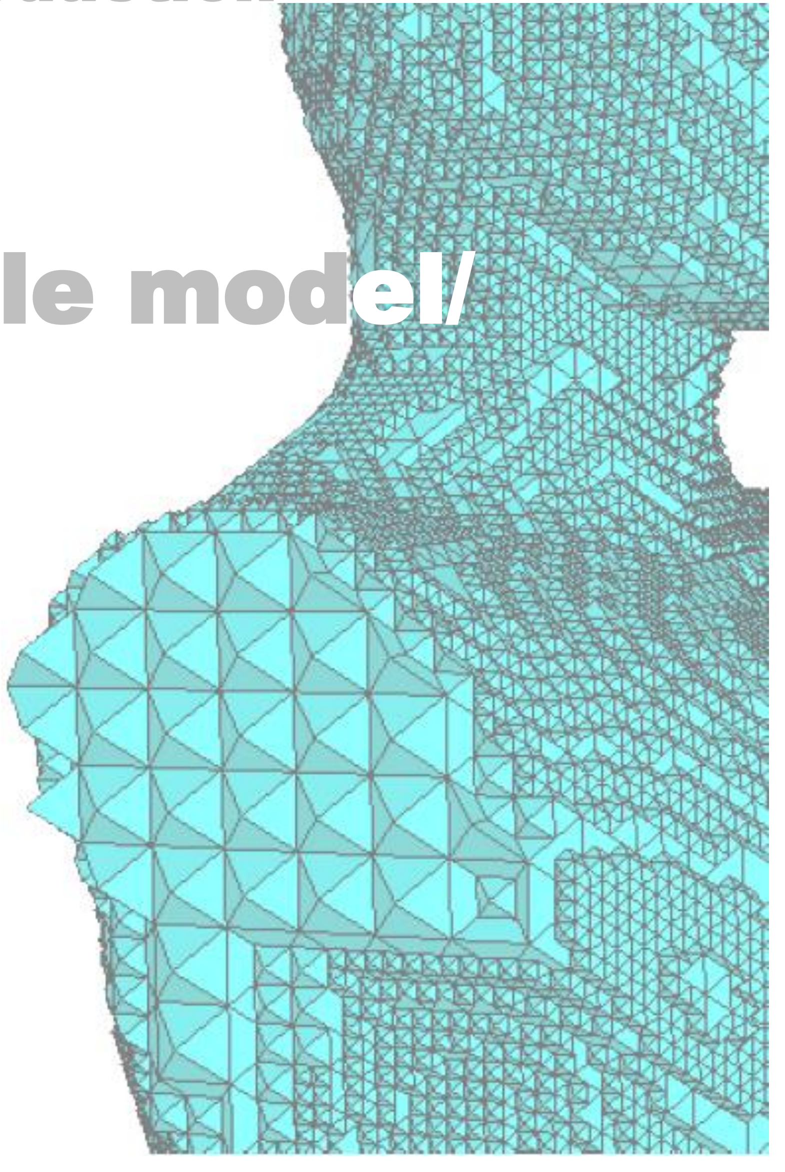

psoas
gluteus maximus
C. "Curved"
D. "Fanned"
iliacus
gluteus medius

Elements of a muscle model/
Muscle creation



- Dissected muscle: Digitization, 3D conversion,
  spline creation
- Visible Human Project®
- The Human

Computer Modeling and Simulation of Skeletal Muscle: An Introduction



Elements of a muscle model/ Mechanical models

❖ Hill-type and Huxley (force) models

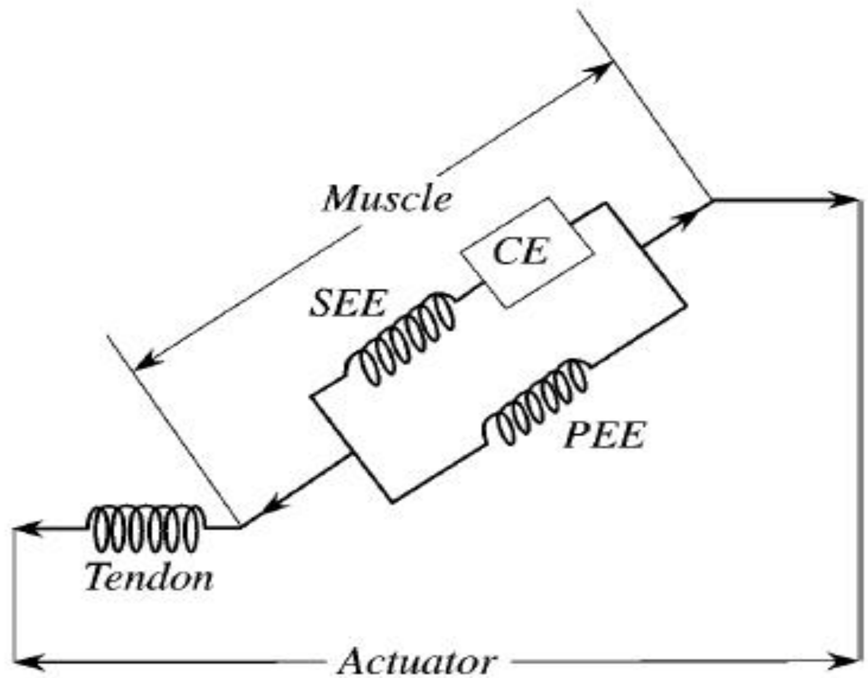


Figure 6 Schematic diagram of a model commonly used to simulate musculotendon actuation. Each musculotendon actuator is represented as a 3-element muscle in series with an elastic tendon. The mechanical behavior of muscle is described by a Hill-type contractile element (CE) that models muscle's force-length-velocity property, a series-elastic element (SEE) that models muscle's active stiffness, and a parallel-elastic element (PEE) that models muscle's passive stiffness. The instantaneous length of the actuator is determined by the length of the muscle, the length of the tendon, and the pennation angle of the muscle. In this model, the width of the muscle is assumed to remain constant as muscle length changes. (Modified from References 5, 57.)

muscle power stroke (Stålhand et al., 2011). Taking into account Eqs. (7), (8) and (13), Eq. (18) reduces to

$$\left(\frac{1}{2}\mathbf{S}-\frac{\partial\Psi}{\partial\mathbf{C}}\right):\dot{\mathbf{C}}-\frac{\partial\Psi}{\partial\mathbf{C}_e}:\dot{\mathbf{C}}_e+\left(\frac{1}{2}\mathbf{S}_a-\frac{\partial\Psi}{\partial\mathbf{C}_a}\right):\dot{\mathbf{C}}_a\geq 0. \quad (19)$$

Eq. (6) allows to eliminate the explicit dependance on $\dot{\mathbf{C}}_e$:

$$\left(\frac{1}{2}\mathbf{S}-\frac{\partial\Psi}{\partial\mathbf{C}}-\mathbf{F}_a^{-1}\frac{\partial\Psi}{\partial\mathbf{C}_e}\mathbf{F}_a^{-T}\right):\dot{\mathbf{C}}+\left(\mathbf{F}_a\mathbf{S}_a-2\mathbf{F}_a\frac{\partial\Psi}{\partial\mathbf{C}_a}+2\mathbf{C}_e\frac{\partial\Psi}{\partial\mathbf{C}_e}\mathbf{F}_a^{-T}\right):\dot{\mathbf{F}}_a\geq 0. \quad (20)$$

Hence, in order to satisfy Eq. (20), the following constitutive relations are obtained:

$$\mathbf{S}=2\frac{\partial\Psi}{\partial\mathbf{C}}+\mathbf{F}_a^{-1}\left(2\frac{\partial\Psi}{\partial\mathbf{C}_e}\right)\mathbf{F}_a^{-T} \quad (21)$$

$$\left(\mathbf{P}_a-2\mathbf{F}_a\frac{\partial\Psi}{\partial\mathbf{C}_a}+2\mathbf{C}_e\frac{\partial\Psi}{\partial\mathbf{C}_e}\mathbf{F}_a^{-T}\right):\dot{\mathbf{F}}_a\geq 0, \quad (22)$$

where $\mathbf{P}_a$ is the first Piola–Kirchoff active stress.

2.4. Stress tensors and elasticity tensor

Substituting Eq. (14) into Eq. (21), the second Piola–Kirchhoff stress tensor is found to be

$$\mathbf{S}=\mathbf{S}_{vol}+\overline{\mathbf{S}}_p+\overline{\mathbf{S}}_a, \quad (23)$$

with

$$\mathbf{S}_{vol}=J\frac{d\Psi_{vol}}{dJ}\mathbf{C}^{-1}=Jp\mathbf{C}^{-1}, \quad (24)$$

$$\overline{\mathbf{S}}_p=J^{-2/3}DEV\left[2\frac{\partial\Psi}{\partial\overline{\mathbf{C}}}\right]=J^{-2/3}DEV[\tilde{\mathbf{S}}_p], \quad (25)$$

$$\overline{\mathbf{S}}_a=J^{-2/3}\overline{\mathbf{F}}_a^{-1}DEV_{C_e}\left[2\frac{\partial\Psi}{\partial\overline{\mathbf{C}}_e}\right]\overline{\mathbf{F}}_a^{-T}=J^{-2/3}\overline{\mathbf{F}}_a^{-1}DEV_{C_e}\left[\tilde{\mathbf{S}}_e\right]\overline{\mathbf{F}}_a^{-T}, \quad (26)$$

$$\mathbb{C}=\mathbb{C}_{vol}+\overline{\mathbb{C}}_p+\overline{\mathbb{C}}_a=2\frac{\partial\mathbf{S}_{vol}}{\partial\mathbf{C}}+2\frac{\partial\overline{\mathbf{S}}_p}{\partial\mathbf{C}}+2\frac{\partial\overline{\mathbf{S}}_a}{\partial\mathbf{C}}, \quad (3$$

where

$$\mathbb{C}_{vol}=2\mathbf{C}^{-1}\otimes\left(p\frac{\partial J}{\partial\mathbf{C}}+J\frac{\partial p}{\partial\mathbf{C}}+2Jp\frac{\partial\mathbf{C}^{-1}}{\partial\mathbf{C}}\right)=J\tilde{p}\mathbf{C}^{-1}\otimes\mathbf{C}^{-1}-2J\mathbb{I}_{C^{-1}}, \quad (3$$

with

$$(\mathbb{I}_{C^{-1}})_{IJKL}=-(\mathbf{C}^{-1}\odot\mathbf{C}^{-1})_{IJKL}=-\frac{1}{2}(C_{IK}^{-1}C_{JL}^{-1}+C_{IL}^{-1}C_{JK}^{-1}), \quad (3$$

and

$$\tilde{p}=p+J\frac{dp}{dJ}. \quad (3$$

The term $\overline{\mathbb{C}}_p$ corresponding to the passive response is given

$$\overline{\mathbb{C}}_p=-\frac{4}{3}J^{-4/3}\left(\frac{\partial\overline{\Psi}_p}{\partial\overline{\mathbf{C}}}\otimes\overline{\mathbf{C}}^{-1}+\overline{\mathbf{C}}^{-1}\otimes\frac{\partial\overline{\Psi}_p}{\partial\overline{\mathbf{C}}}\right)+\frac{4}{3}J^{-4/3}\left(\frac{\partial\overline{\Psi}_p}{\partial\overline{\mathbf{C}}}:\overline{\mathbf{C}}\right)\left(\mathbb{I}_{\overline{C}^{-1}}-\frac{1}{3}\overline{\mathbf{C}}^{-1}\otimes\overline{\mathbf{C}}^{-1}\right)+J^{-4/3}\overline{\mathbb{C}}_{\overline{w}}^{p}, \quad (3$$

where term $\overline{\mathbb{C}}_{\overline{w}}^{p}$ is defined as

$$\overline{\mathbb{C}}_{\overline{w}}^{p}=4\frac{\partial^2\overline{\Psi}_p}{\partial\overline{\mathbf{C}}\partial\overline{\mathbf{C}}}-\frac{4}{3}\left[\left(\frac{\partial^2\overline{\Psi}_p}{\partial\overline{\mathbf{C}}\partial\overline{\mathbf{C}}}:\overline{\mathbf{C}}\right)\otimes\overline{\mathbf{C}}^{-1}+\overline{\mathbf{C}}^{-1}\otimes\left(\frac{\partial^2\overline{\Psi}_p}{\partial\overline{\mathbf{C}}\partial\overline{\mathbf{C}}}:\overline{\mathbf{C}}\right)\right]+\frac{4}{9}\left(\overline{\mathbf{C}}:\frac{\partial^2\overline{\Psi}_p}{\partial\overline{\mathbf{C}}\partial\overline{\mathbf{C}}}:\overline{\mathbf{C}}\right)\overline{\mathbf{C}}^{-1}\otimes\overline{\mathbf{C}}^{-1}. \quad (3$$

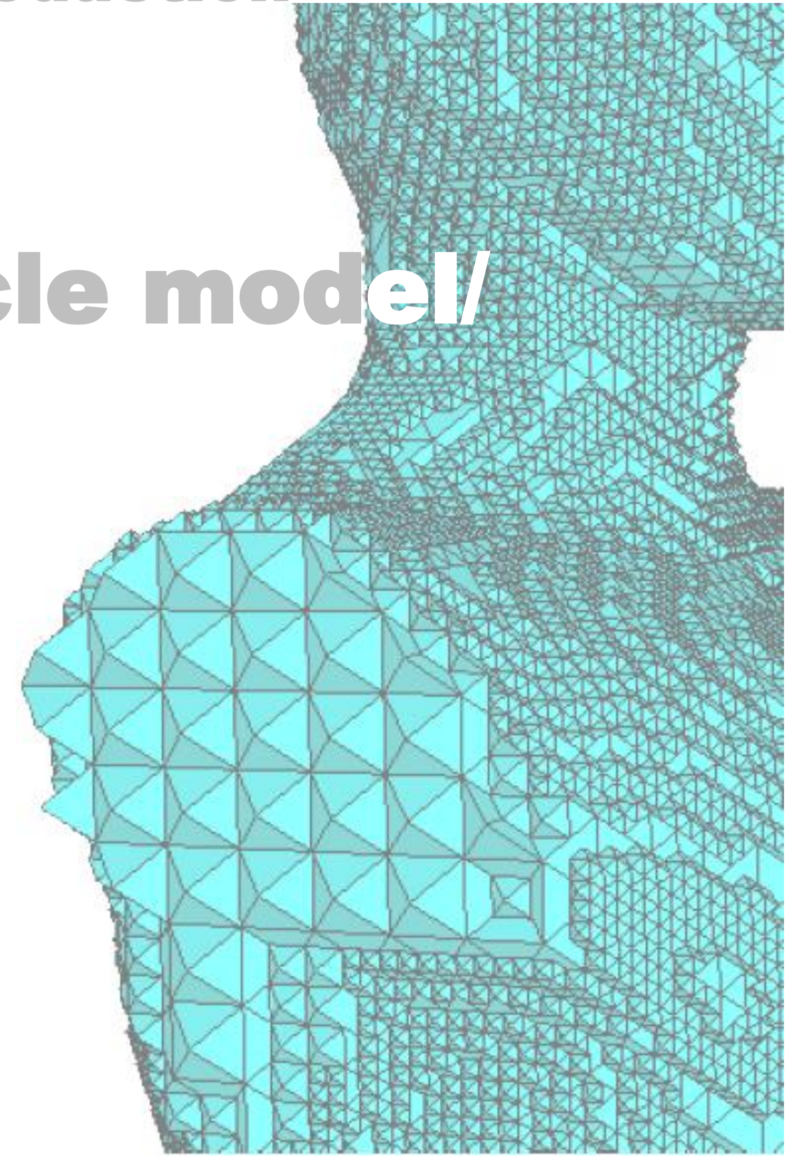
The last term in Eq. (32), $\overline{\mathbb{C}}_a$, is given by

$$\overline{\mathbb{C}}_a=\overline{\mathbf{F}}_a^{-1}\odot\overline{\mathbf{F}}_a^{-1}\left[-\frac{4}{3}J^{-4/3}\left(\frac{\partial\overline{\Psi}_a}{\partial\overline{\mathbf{C}}_e}\otimes\overline{\mathbf{C}}_e^{-1}+\overline{\mathbf{C}}_e^{-1}\otimes\frac{\partial\overline{\Psi}_a}{\partial\overline{\mathbf{C}}_e}\right)+\frac{4}{3}J^{-4/3}\left(\frac{\partial\overline{\Psi}_a}{\partial\overline{\mathbf{C}}_e}:\overline{\mathbf{C}}_e\right)\left(\mathbb{I}_{\overline{C}_e^{-1}}-\frac{1}{3}\overline{\mathbf{C}}_e^{-1}\otimes\overline{\mathbf{C}}_e^{-1}\right)+J^{-4/3}\overline{\mathbb{C}}_{\overline{w}}^{a}\right]\overline{\mathbf{F}}_a^{-T}\odot\overline{\mathbf{F}}_a^{-T}, \quad (3$$

where

Elements of a muscle model/ Deformation

- ❖ Geometrically based approaches
- ❖ Physically-based approaches
  - Mass-spring systems
  - FEM (Finite Element Method)
  - FVM (Finite Volume Method)
- ❖ Data-driven approaches



IV. Finite Volume Method

A. Force Computation

The Finite Volume Method provides a simple and geometrically intuitive way of integrating the equations of motion, with an interpretation that rivals the simplicity of mass-spring systems. However, unlike masses and springs, an arbitrary constitutive model can be incorporated into the FVM.

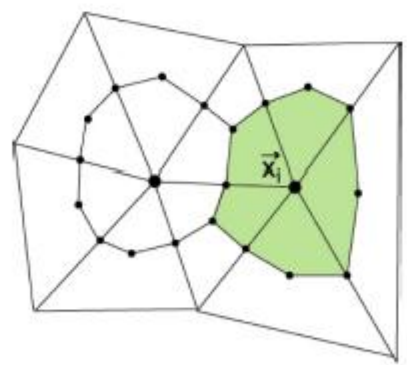


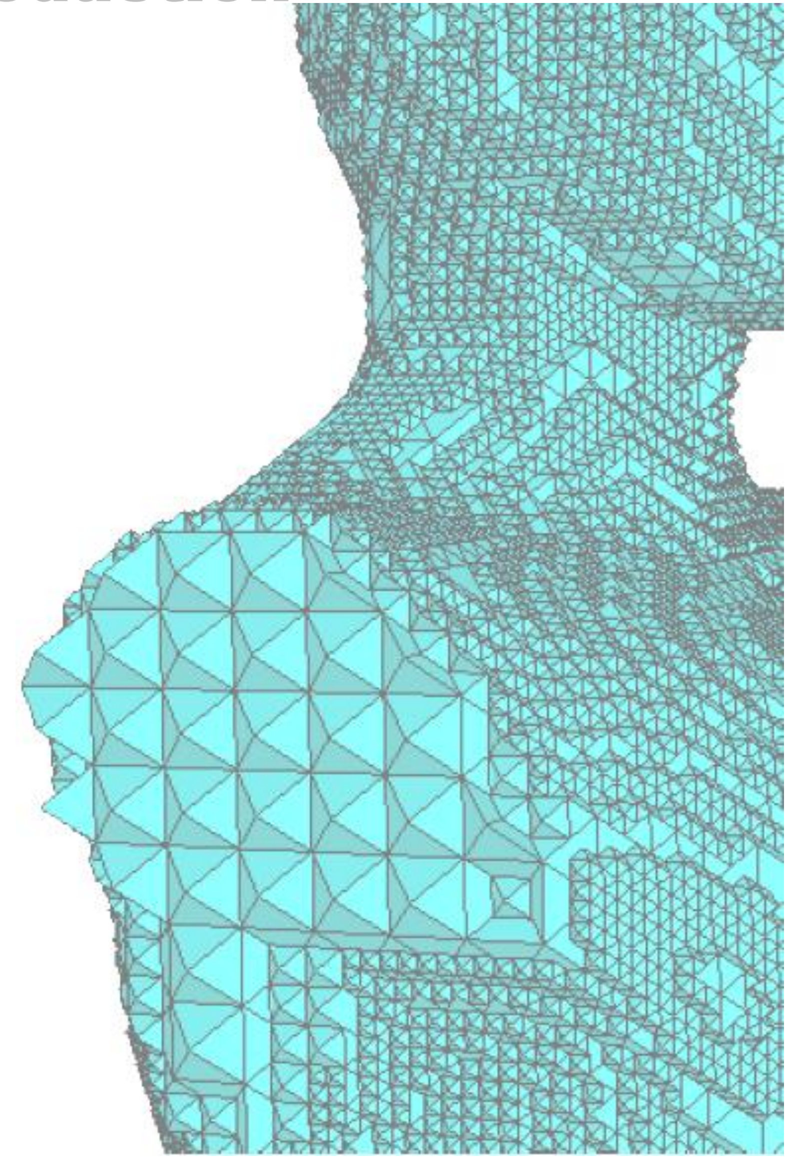
Fig. 5. FVM integration regions.

In the deformed configuration, consider dividing up the continuum into a number of discrete regions each surrounding a particular node. Figure 5 depicts two nodes each surrounded by a region. Suppose that we wish to determine the force on the node $\mathbf{x}_i$ surrounded by the shaded region Ω. Ignoring body forces for brevity, the force can be calculated as

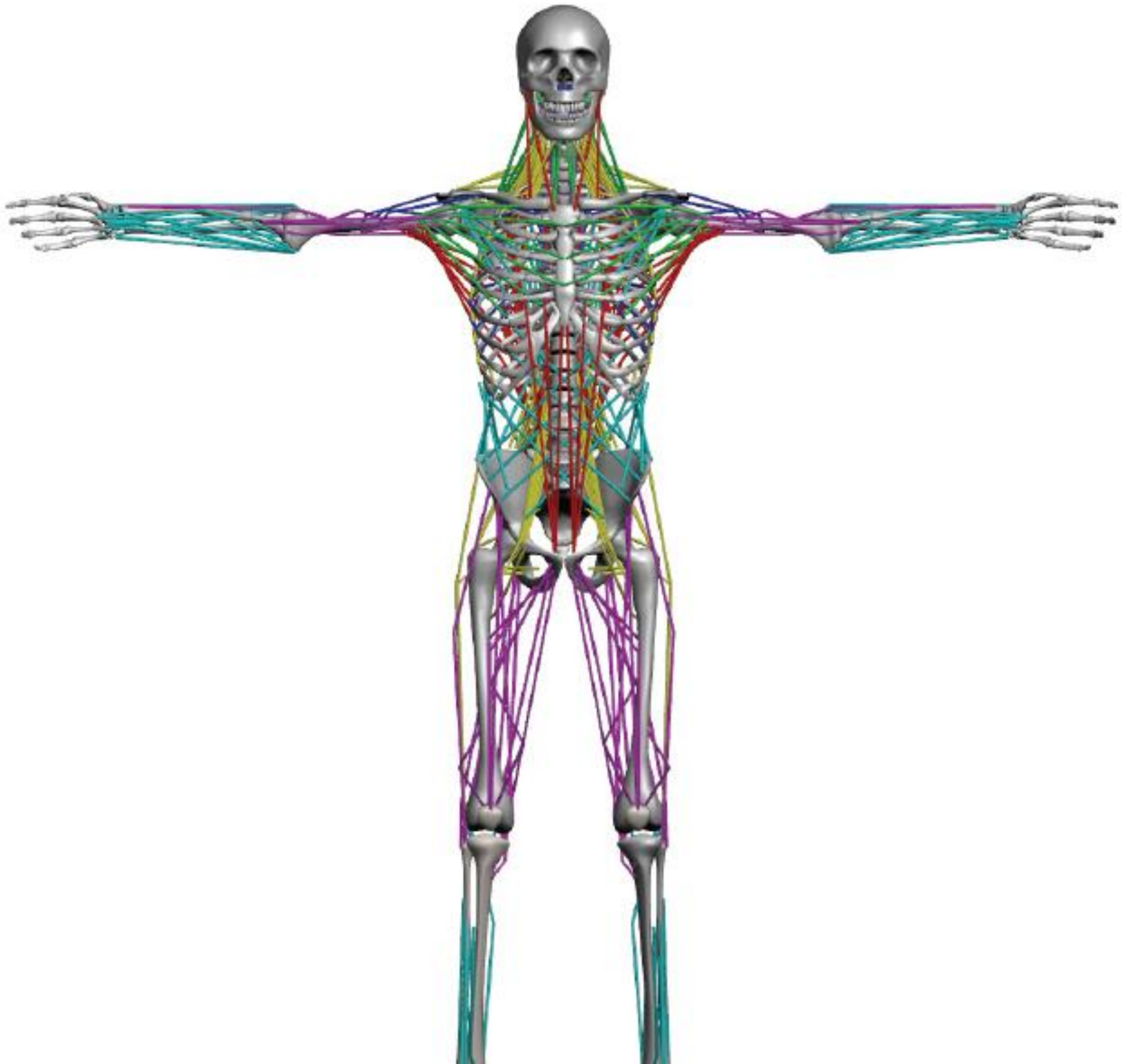
$$\mathbf{f}_i = \frac{D}{Dt}\int_{\Omega} \rho \mathbf{v} d\mathbf{x} = \oint_{\partial\Omega} \mathbf{t} dS = \oint_{\partial\Omega} \sigma \mathbf{n} dS$$

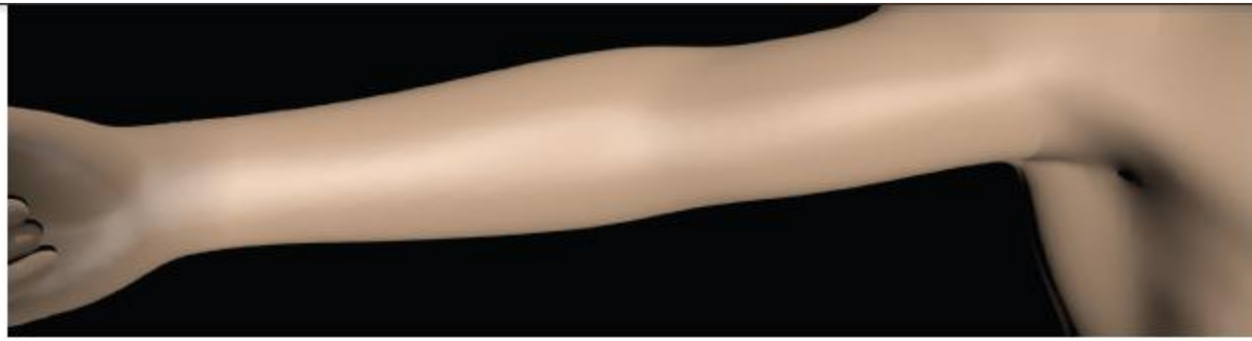
Model creation/
A sample process

- ❖ Creation of dynamic skeletal model
- ❖ Creation of muscles
- ❖ Hill-type muscle actuation model
- ❖ FEM (Finite Element Method) model
- ❖ Integration
- ❖ Motion control and kinematics

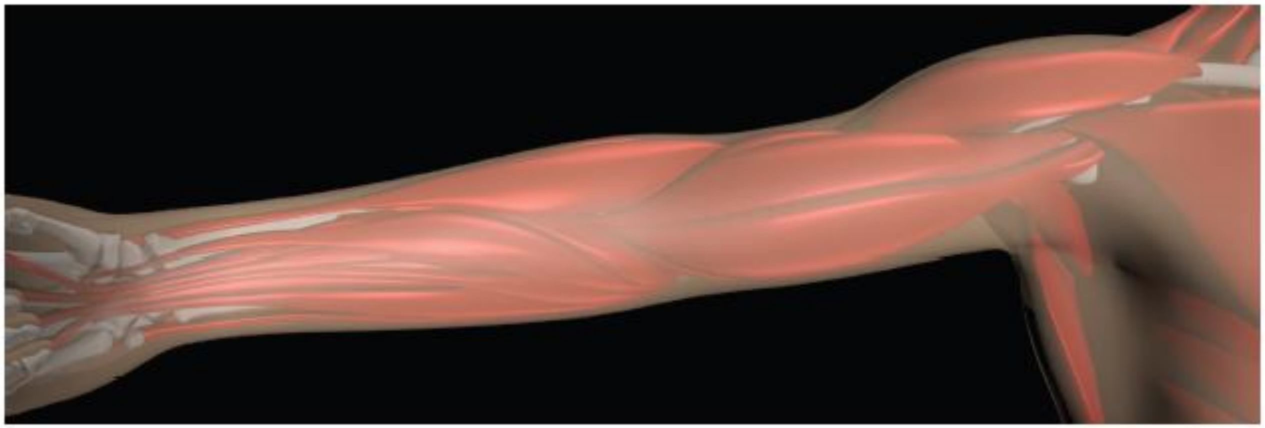


(a) (b) (c)

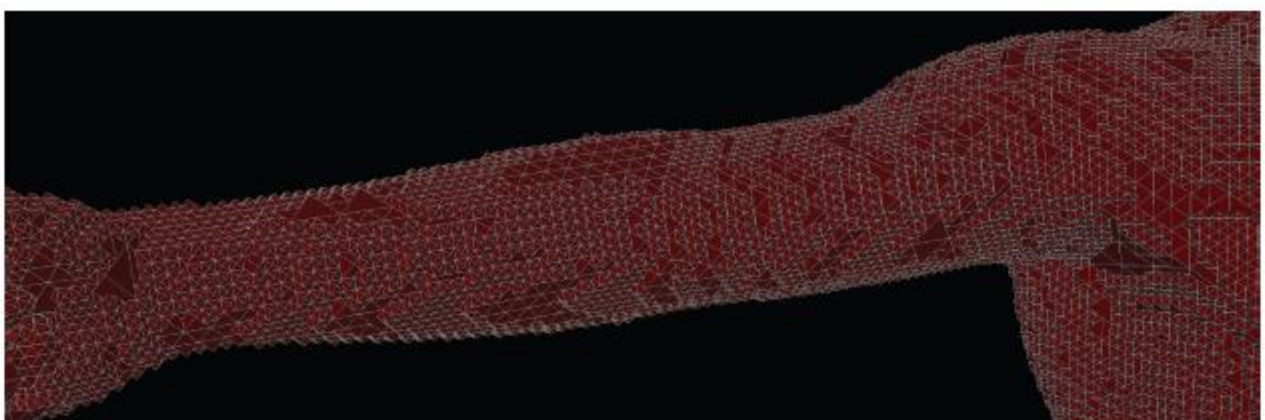




(a) Skin Visualization Geometry



(b) Anatomical Bone and Soft Tissue Geometry



(c) Simulation Mesh

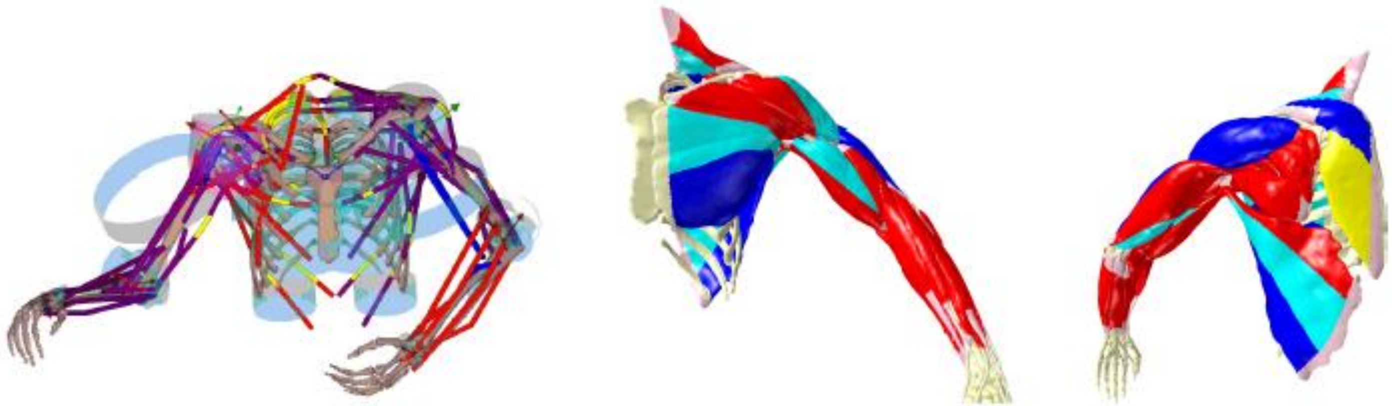


Fig. 4. The leftmost figure shows the piecewise linear muscle models with wrapping surfaces to model muscle contact in inverse dynamics calculations. Larger muscles have multiple contractile regions with individual activations and these must be embedded in the tetrahedron meshes for simulation (rightmost figures).

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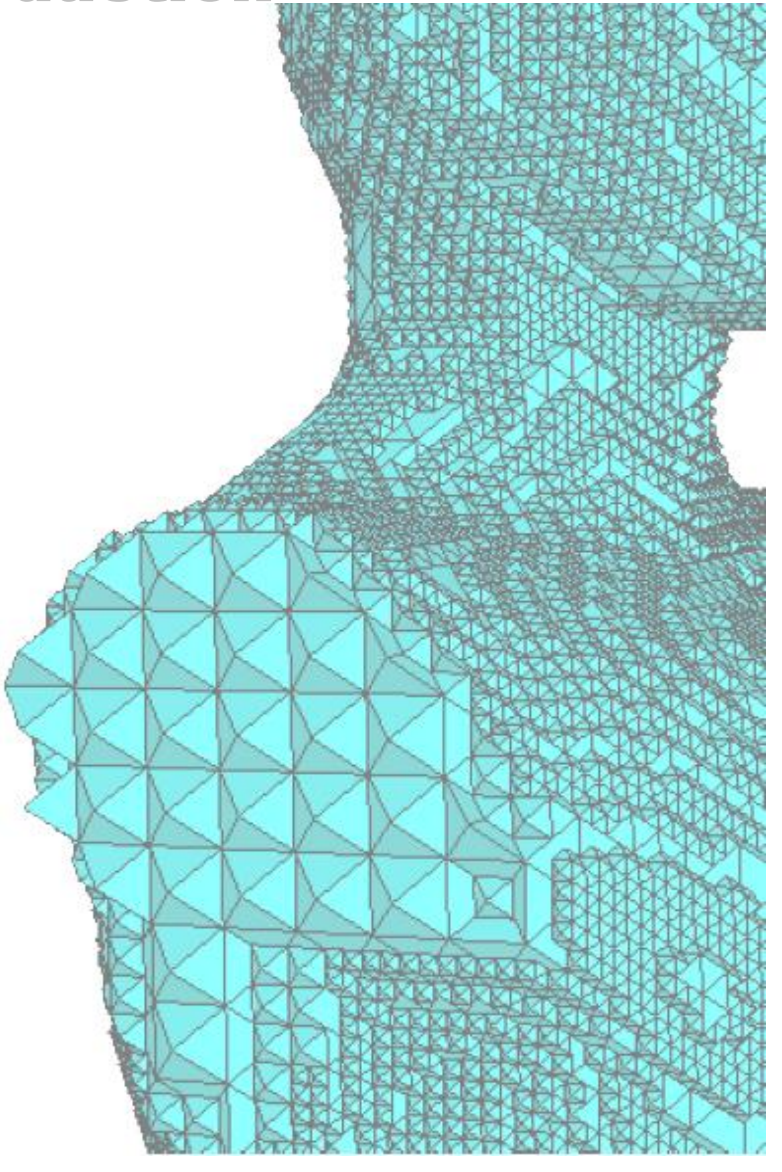
Challenges

- Motor-unit level research
- Mechanical muscle behavior
- Voluntary Control
- Learning



Outlook

Flexible Muscle-Based Locomotion

for Bipedal Creatures:

http://vimeo.com/79098420