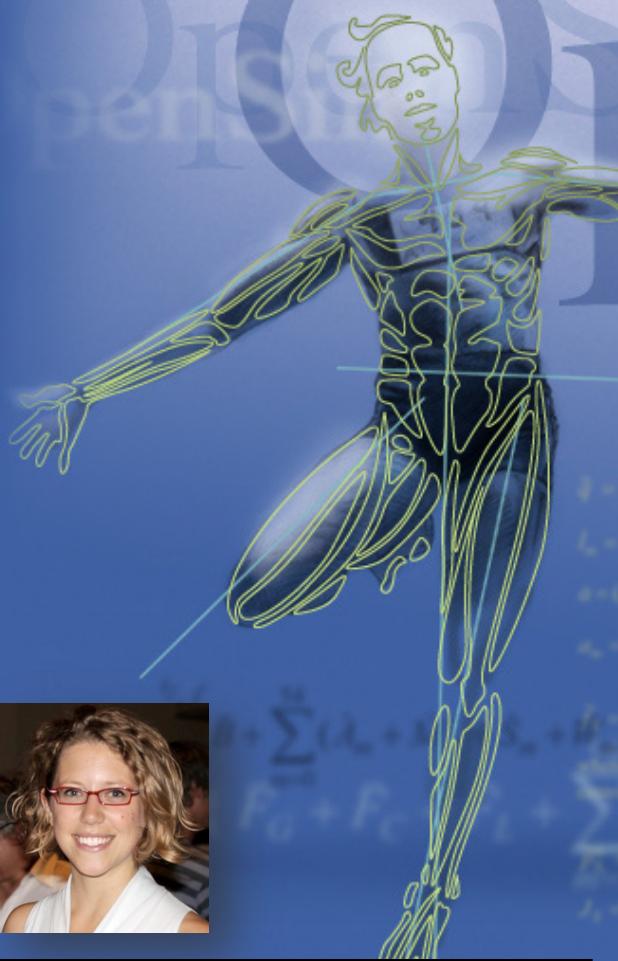


# Musculoskeletal Models Deconstructed

**Presenter:**  
**Apoorva Rajagopal**



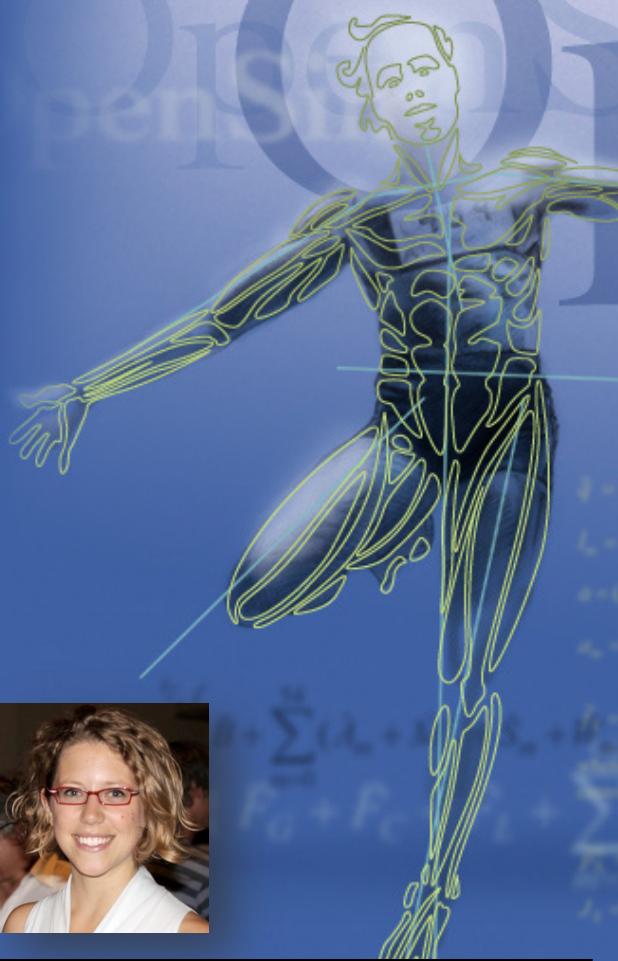
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## *Goals of the OpenSim Webinar Series:*

- **Showcase cutting-edge research and insights on OpenSim**
- **Communicate with our growing, geographically diverse user base**
- **Promote discussion and community-building**

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**Questions will be addressed at the end of  
the presentation via the text-based Q&A  
panel**

**For more help, consult the “Participating in  
OpenSim Webinars” guide available at:**

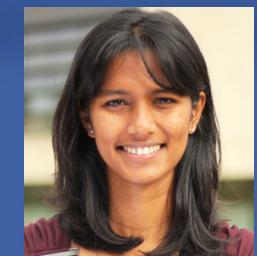
**<http://opensim.stanford.edu/webinarguide.pdf>**

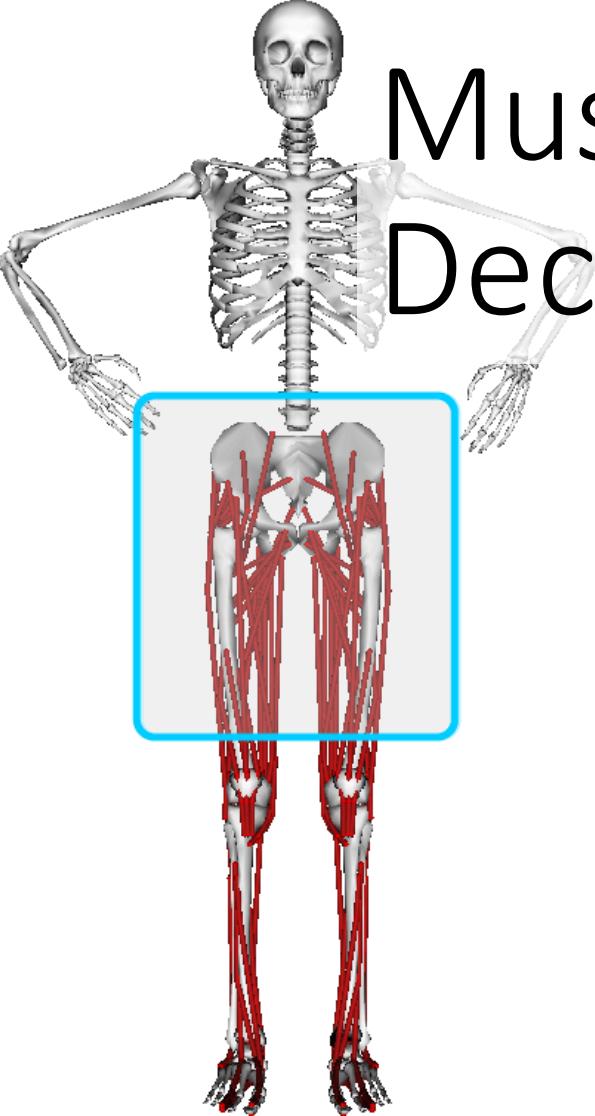


# Musculoskeletal Models Deconstructed

**Apoorva Rajagopal**  
**Stanford University**

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# Musculoskeletal Models Deconstructed

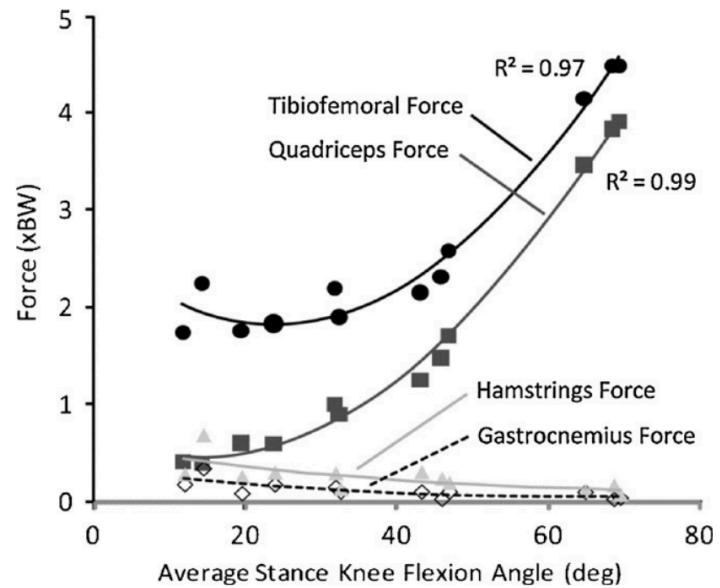
Apoorva Rajagopal

Neuromuscular Biomechanics Lab

Stanford University

# Introduction

- Musculoskeletal simulations allow us to, e.g.,
  - Measure relationship between muscle force and joint contact force in healthy and impaired subjects



<sup>1</sup>Steele *et al.* 2012

# Introduction

- Musculoskeletal simulations allow us to, e.g.,
  - Measure relationship between muscle force and joint contact force in healthy and impaired subjects<sup>1</sup>
  - Design assistive devices to increase human performance<sup>2</sup>



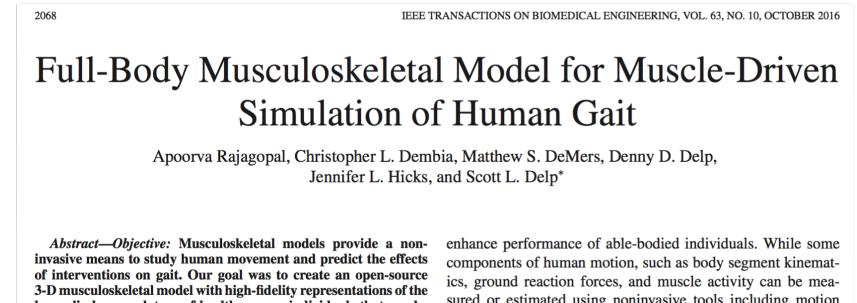
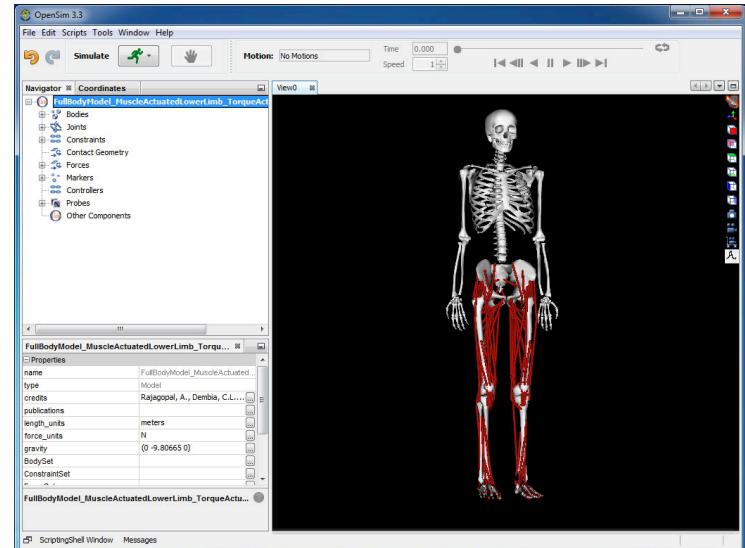
<sup>2</sup>Ekso Bionics

<sup>1</sup>Steele KM, et al. Compressive tibiofemoral force during crouch gait. Gait Posture (2011), doi:10.1016/ j.gaitpost.2011.11.023

<sup>2</sup>Ekso Bionics, <http://eksobionics.com/>

# Introduction: Goals

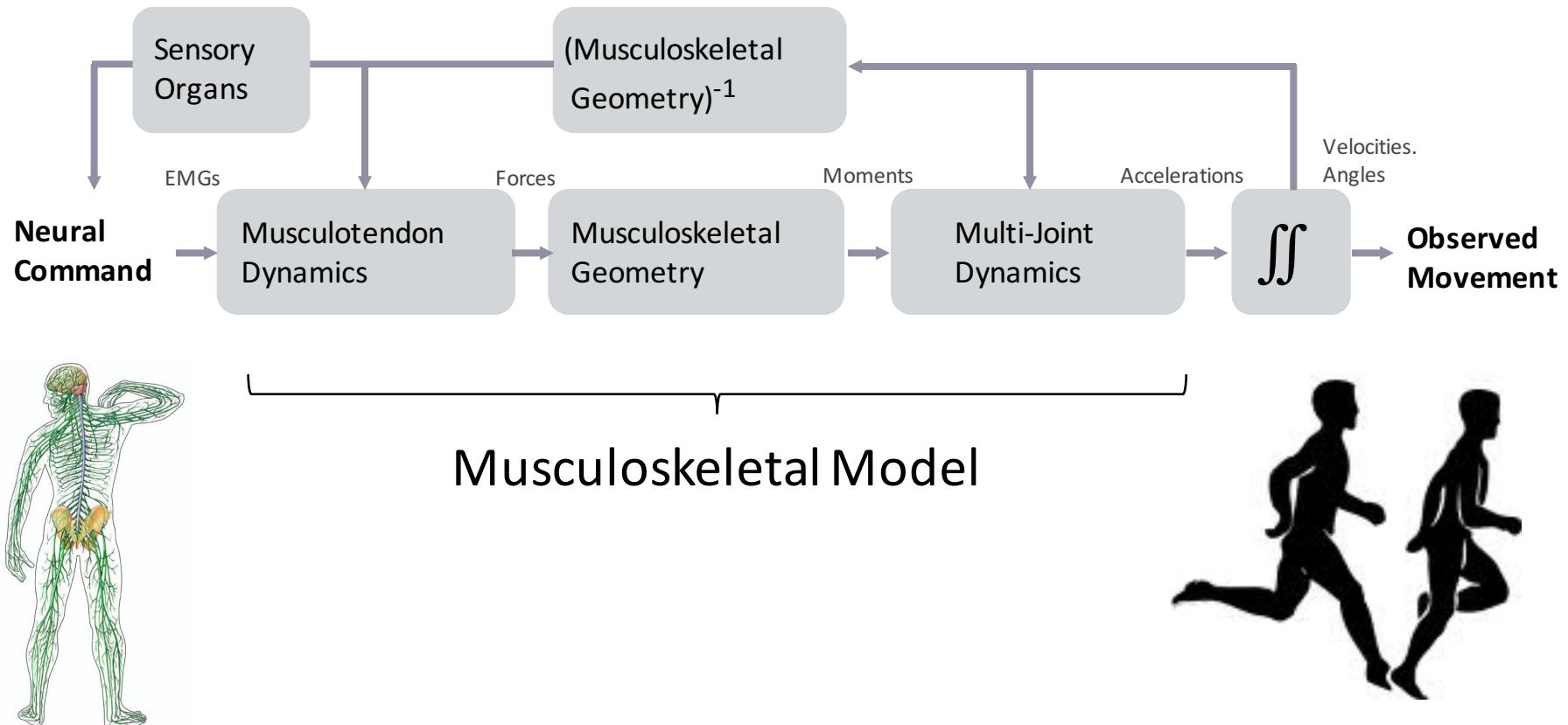
- Introduce the major components of a musculoskeletal model in OpenSim
- Validate a model in context of its intended use



<sup>3</sup>Delp, Scott L., et al. "OpenSim: open-source software to create and analyze dynamic simulations of movement." *IEEE transactions on biomedical engineering* 54.11 (2007): 1940-1950.

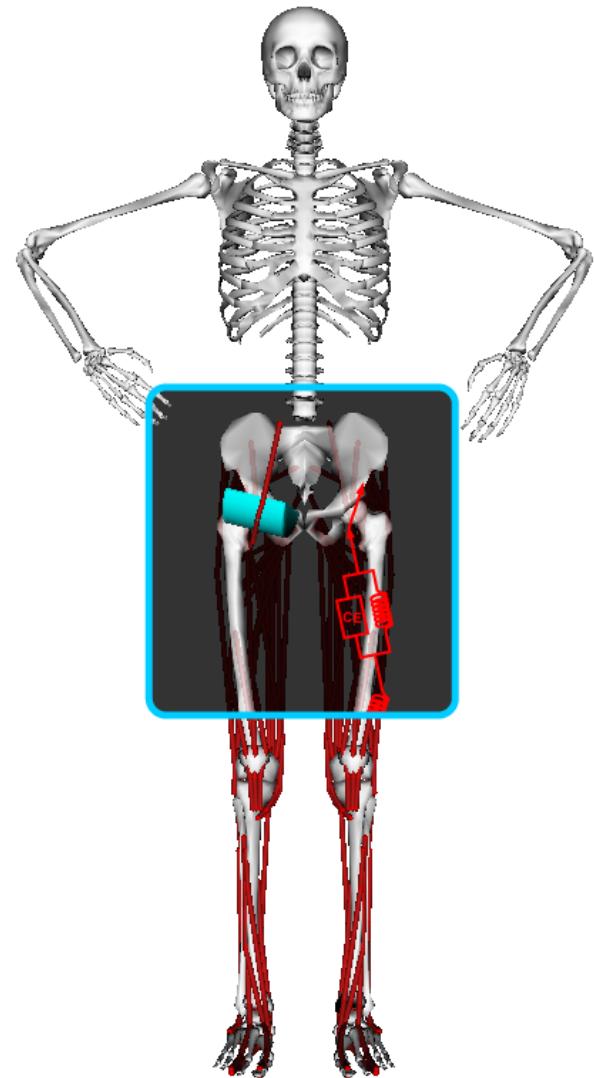
<sup>4</sup>Rajagopal, Apoorva, et al. "Full-Body Musculoskeletal Model for Muscle-Driven Simulation of Human Gait." *IEEE Transactions on Biomedical Engineering* 63.10 (2016): 2068-2079.

# Introduction: Simulating Movement



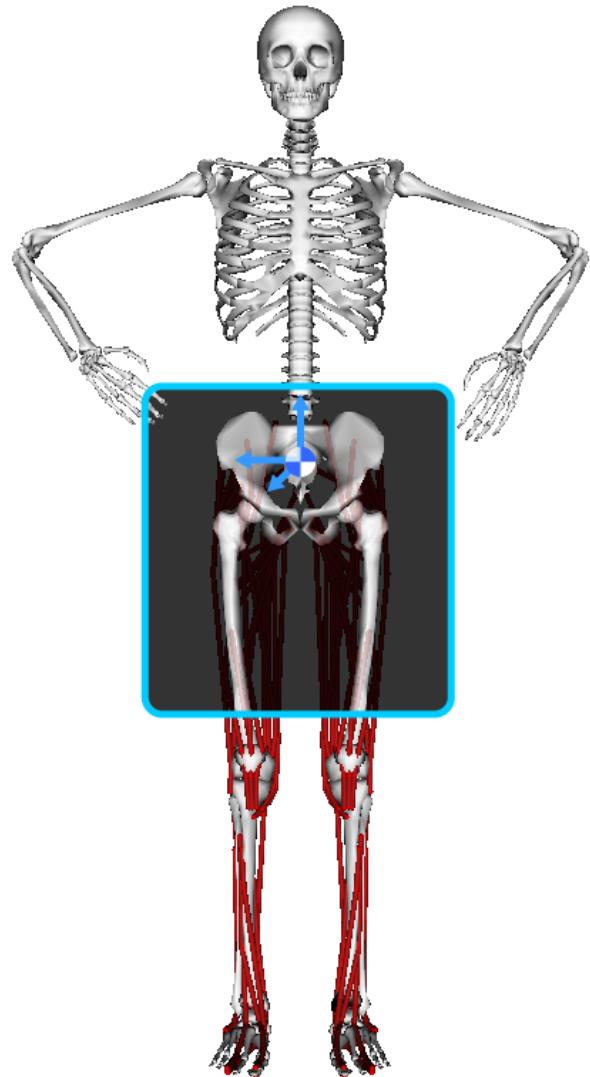
# Outline

- Components of a model
  - Rigid Bodies  
(e.g., pelvis)
  - Joints  
(e.g., hip)
  - Force-generating elements  
(e.g., muscles)
- Validating a model in context of its intended use



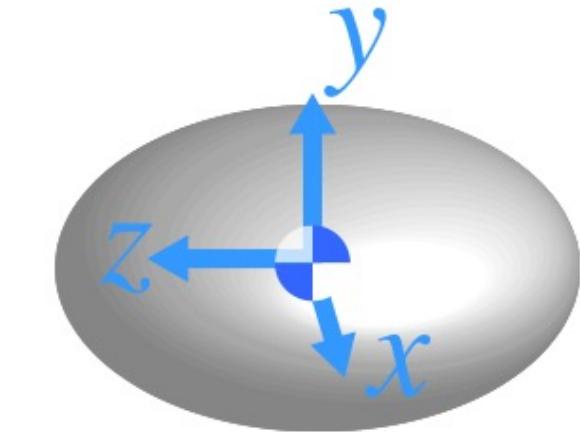
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# Rigid Bodies

- Defining properties:  
“Force = **mass** × acceleration”
  - Mass
  - Inertia tensor about center of mass
- Coordinate system
- Center of mass location



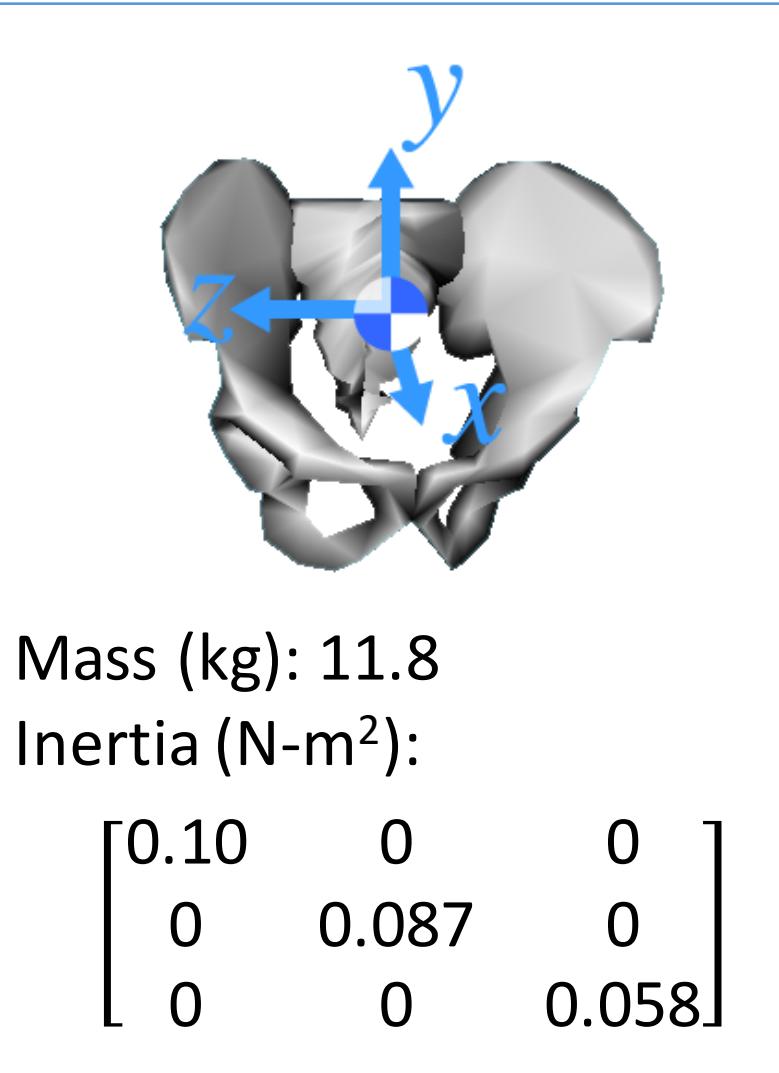
Mass (kg): 11.8

Inertia (N-m<sup>2</sup>):

$$\begin{bmatrix} 0.10 & 0 & 0 \\ 0 & 0.087 & 0 \\ 0 & 0 & 0.058 \end{bmatrix}$$

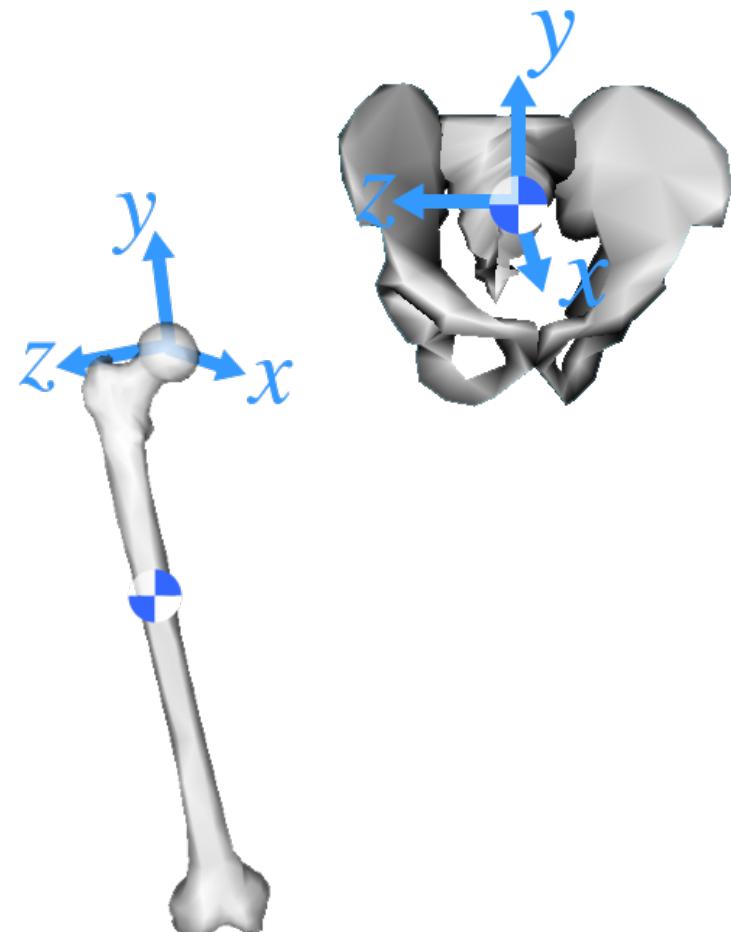
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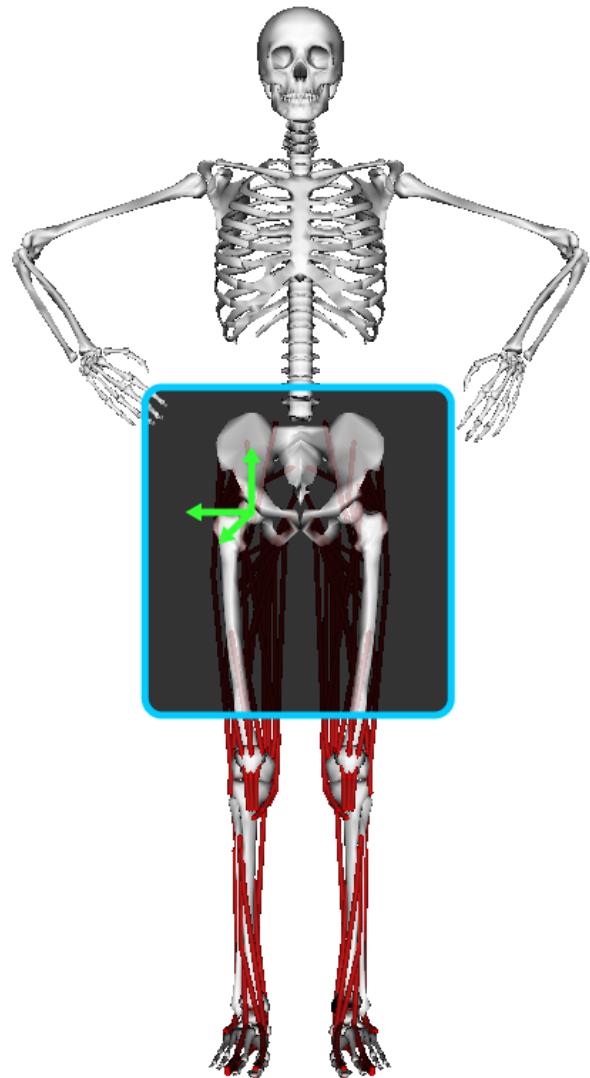
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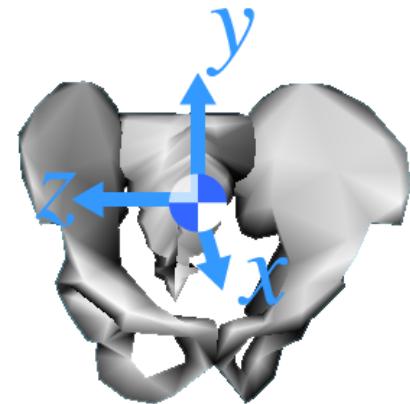
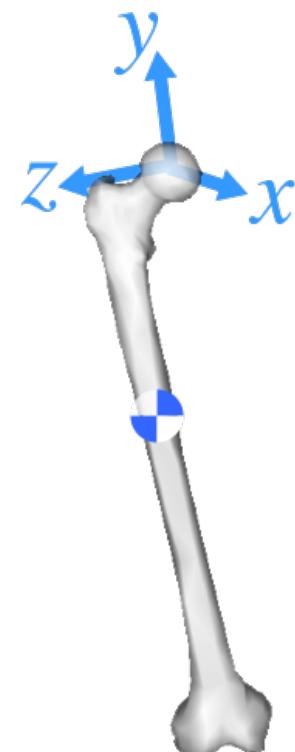
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# Joints: Defining Properties

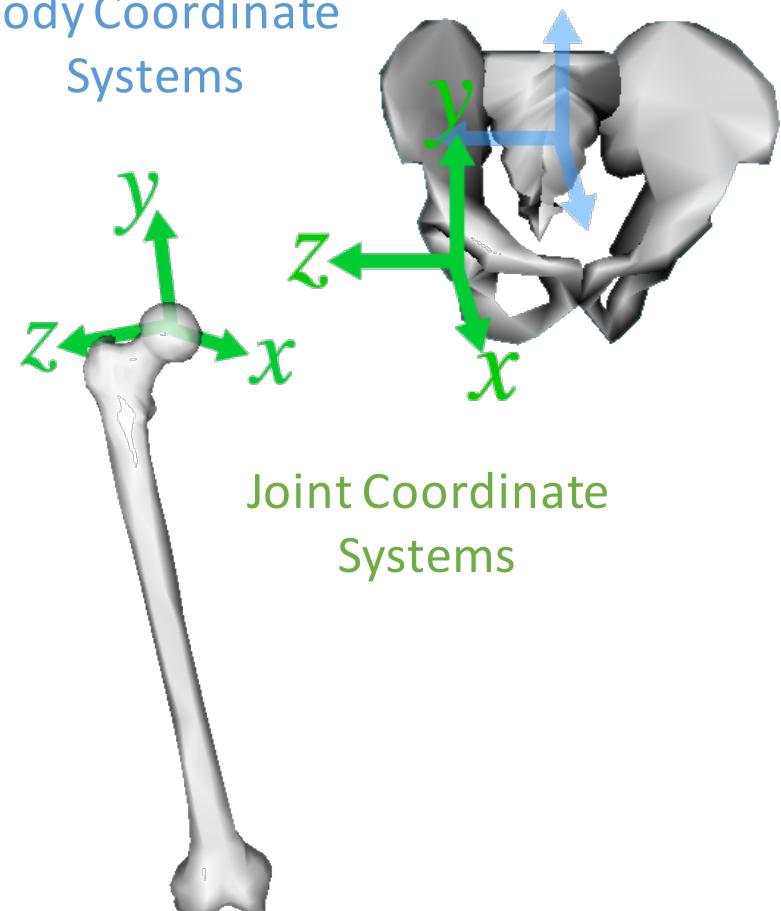
Body Coordinate Systems



# Joints: Defining Properties

- Joint Coordinate Frame

Body Coordinate  
Systems

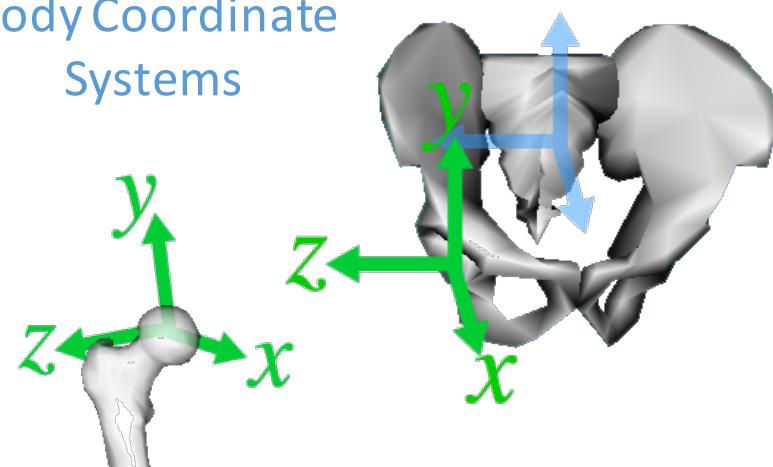


Joint Coordinate  
Systems

# Joints: Defining Properties

- Joint Coordinate Frame
  - Parent (e.g., pelvis)
  - Child (e.g., femur)

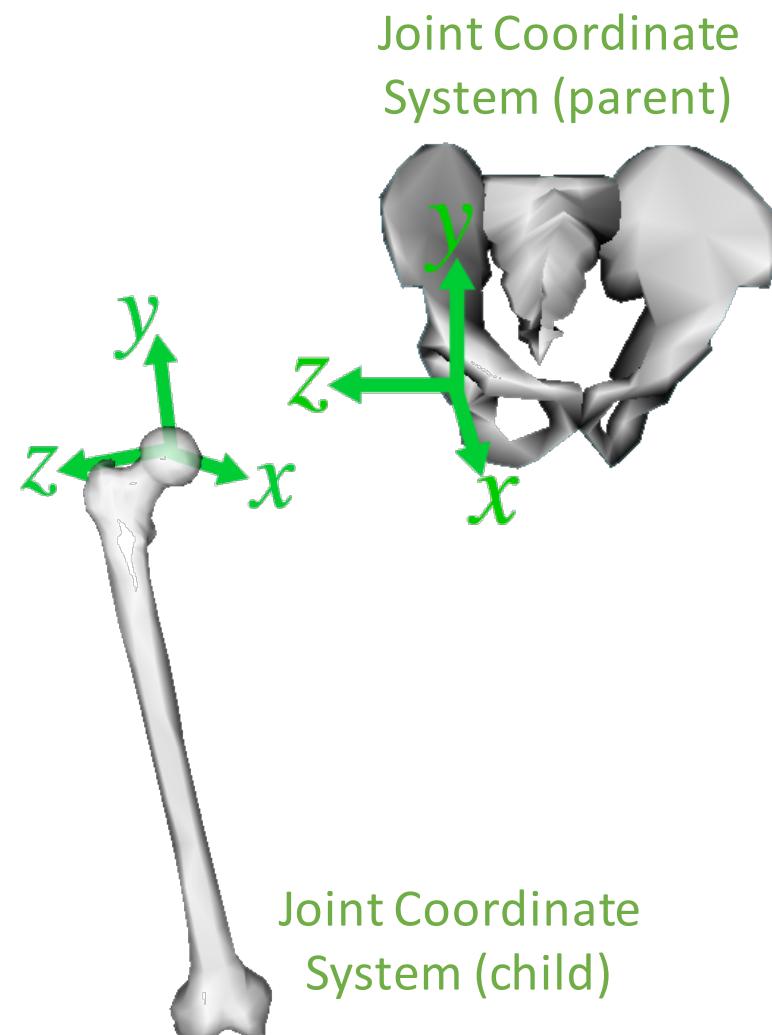
Body Coordinate Systems



Joint Coordinate Systems

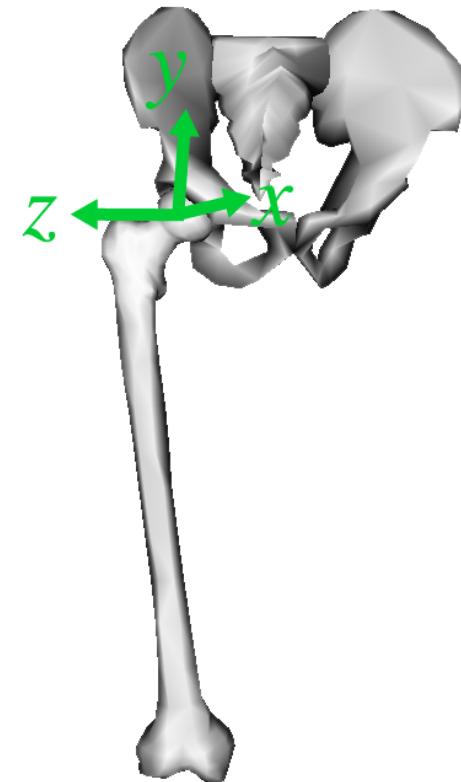
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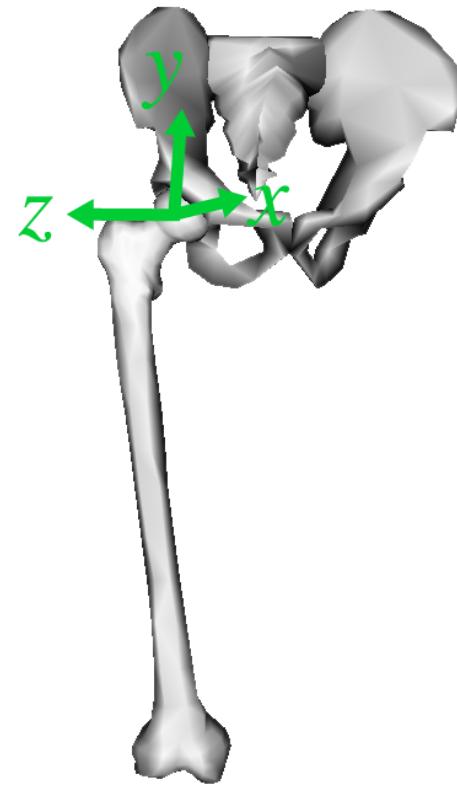
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# Joints: Defining Properties

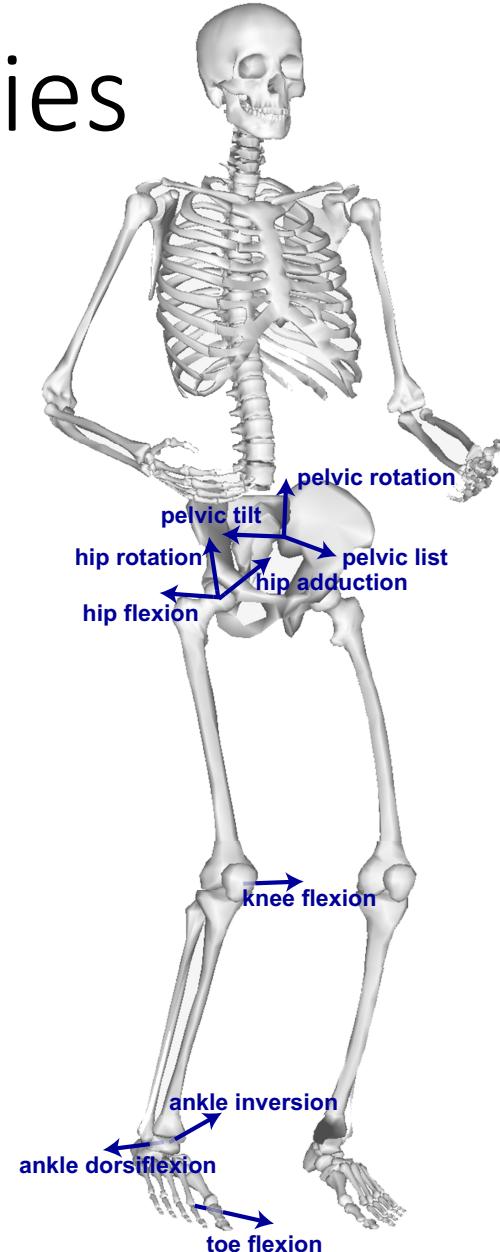
- Joint Coordinate Frame
  - Parent (e.g., pelvis)
  - Child (e.g., femur)
- Degrees of Freedom (coordinates)
  - e.g., hip flexion, hip adduction, hip rotation

$$\text{Child}_T^{\text{Parent}} = f(\text{degrees of freedom})$$



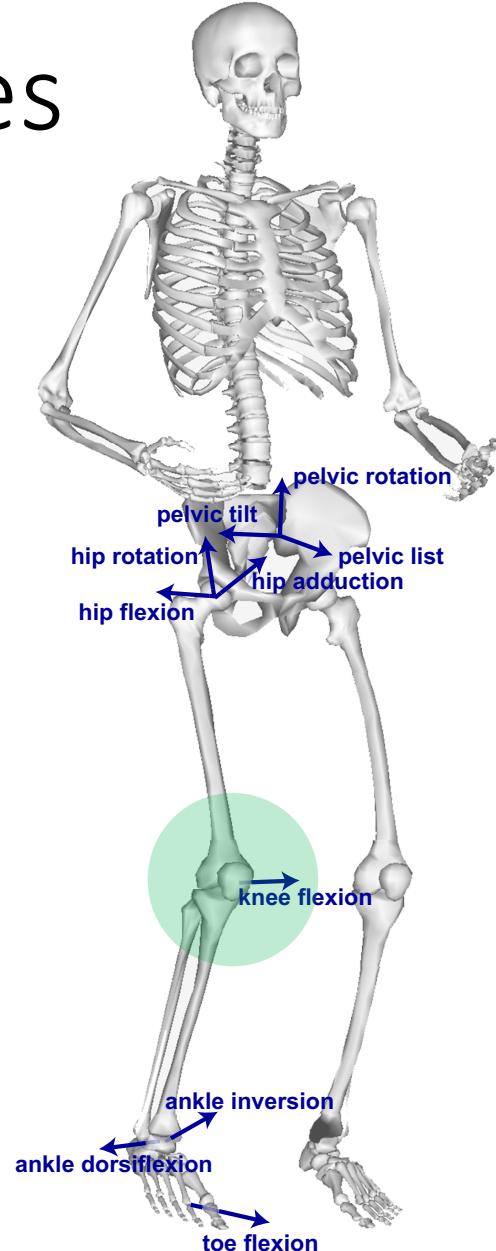
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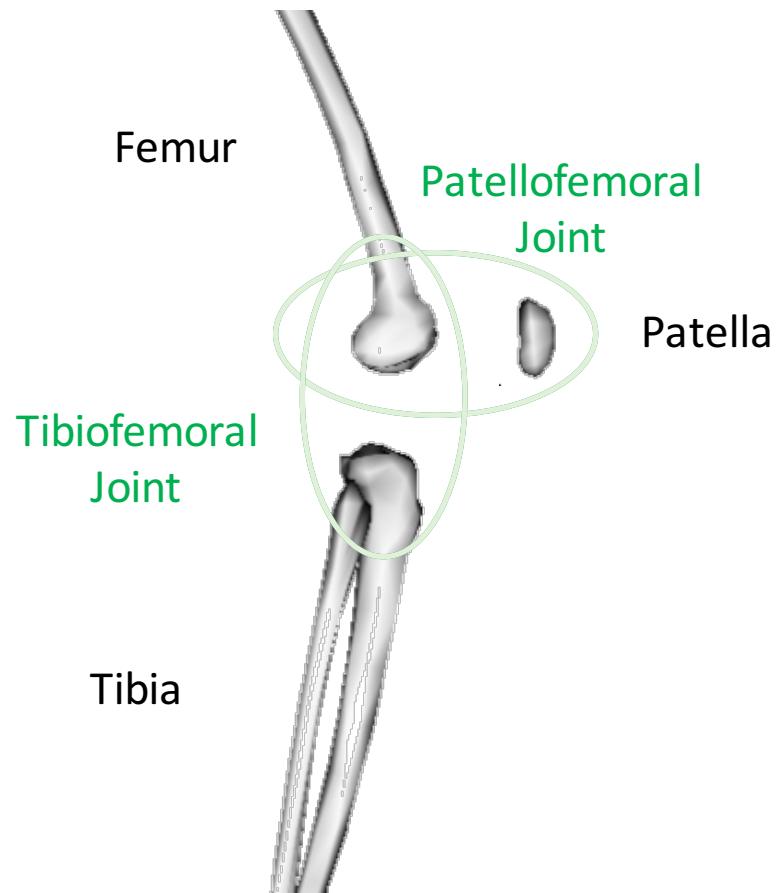
# Joints: Modeling Choices

- Degrees of freedom to enable



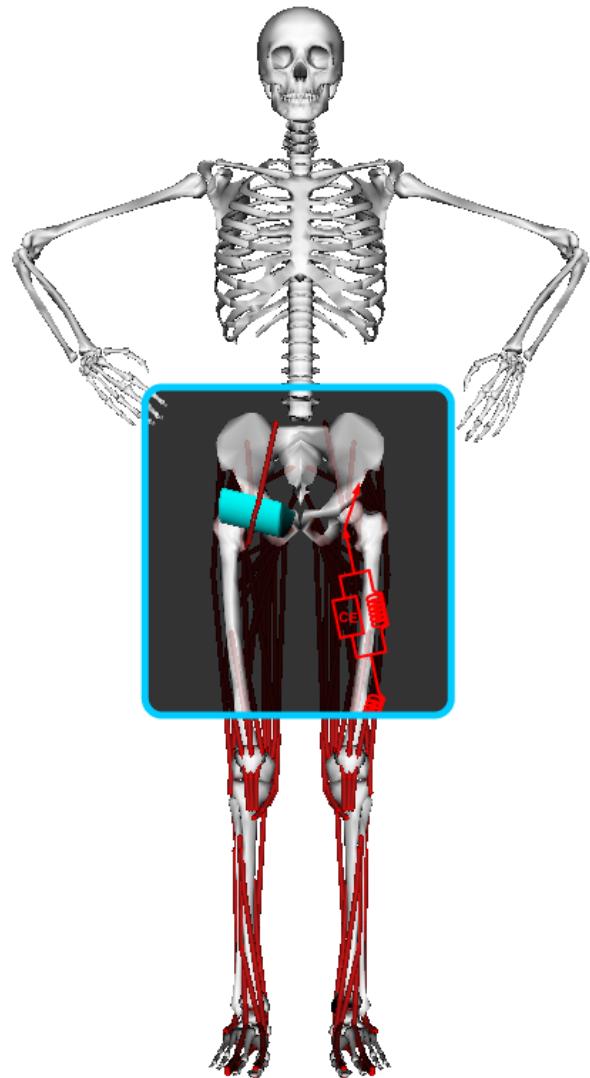
# Joints: Modeling Choices

- Degrees of freedom to enable
  - “Maximal” formulation
    - 6-DOF patellofemoral joint
    - 6-DOF tibiofemoral joint
  - “Minimal” formulation
    - 1 DOF: knee flexion
    - All other motions parameterized by knee flexion angle



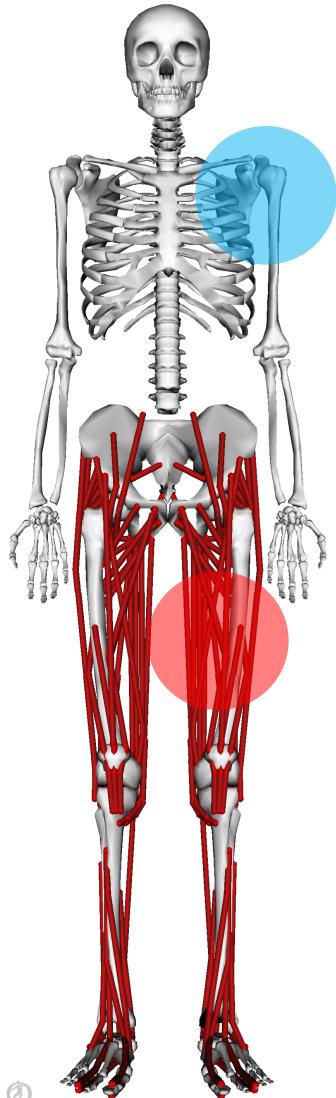
# Outline

- Components of a model
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  - Joints  
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  - **Force-generating elements**  
(e.g., muscles)
- Validating a model in context of its intended use



# Force-generating Elements

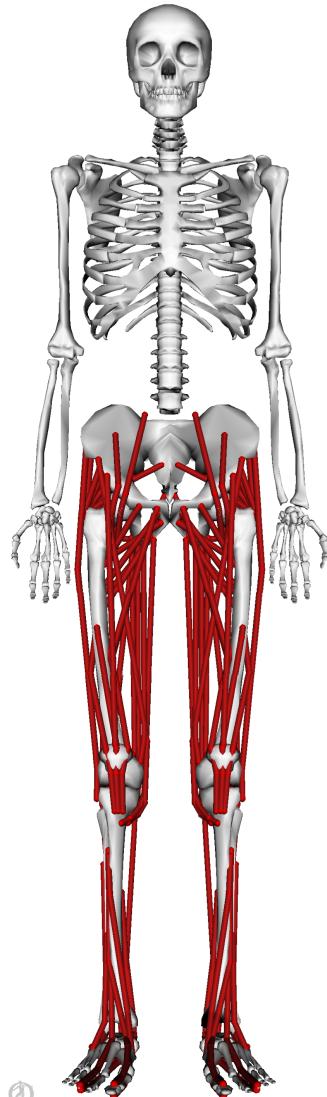
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- Muscles
- Torque motors
- Passive structures, e.g.
  - Ligaments
  - Coordinate limit forces
  - Springs, bushings
- Contact geometry
- ... and more

# Force-generating Elements

---



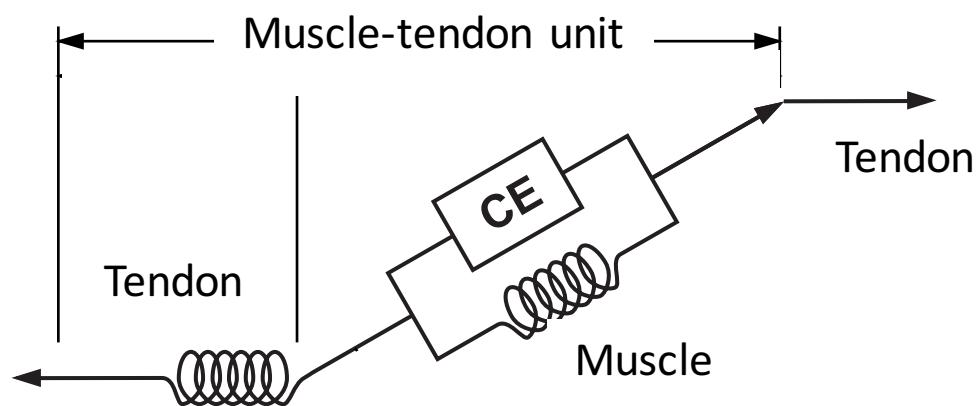
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# Muscle Model Components

Muscle Path



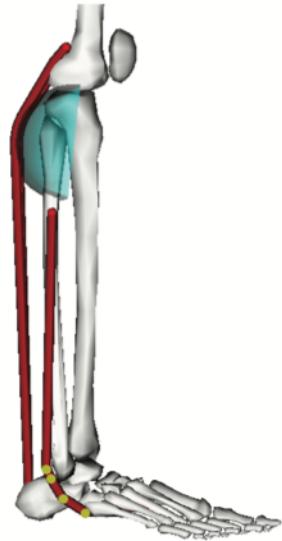
Force Generating Capacity



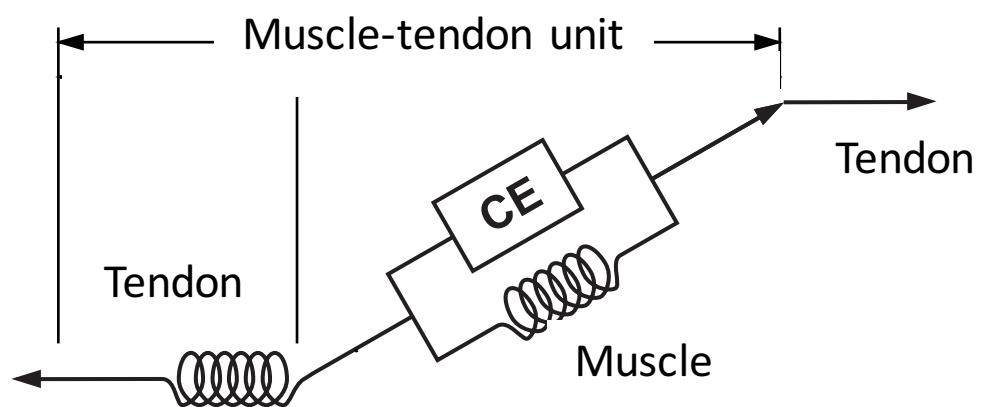
1. Model and inherent assumptions
2. Choosing and validating parameters
3. Consequences of modeling assumptions in simulation

# Muscle Model Components

Muscle Path



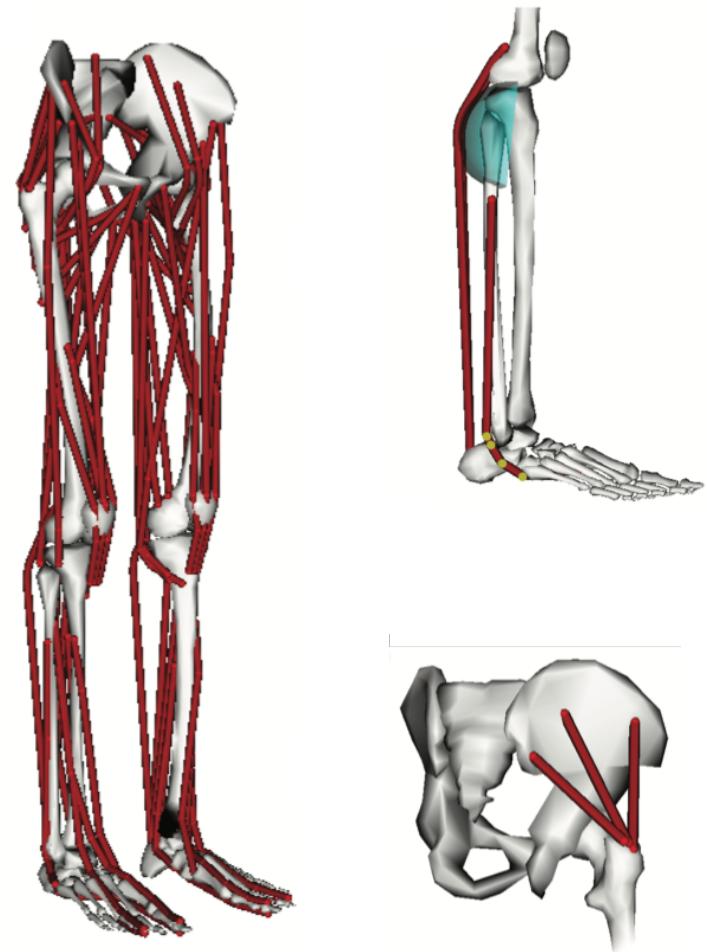
Force Generating Capacity



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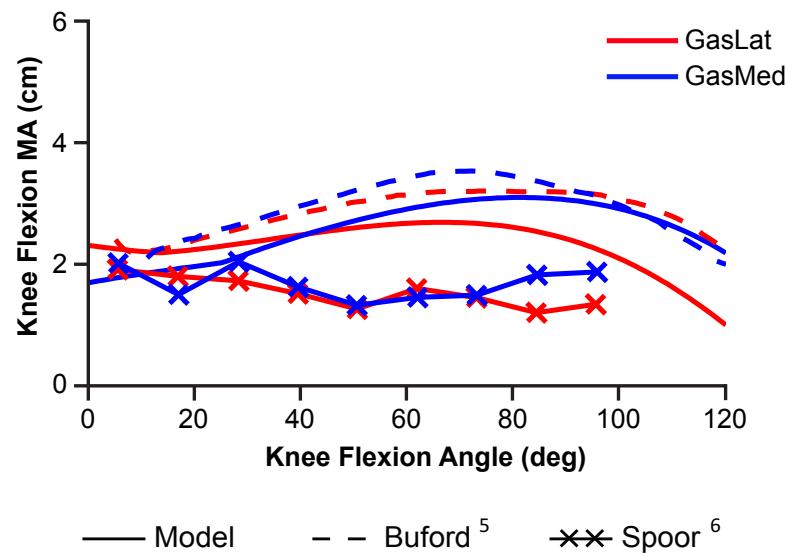
# Muscles: Geometry

- Constructing a muscle
  - Lines representing path through centroid of muscle cross-section
  - Path specified through fixed points and wrapping surfaces
  - Multiple lines of action to represent muscles with broad attachments



# Muscles: Geometry

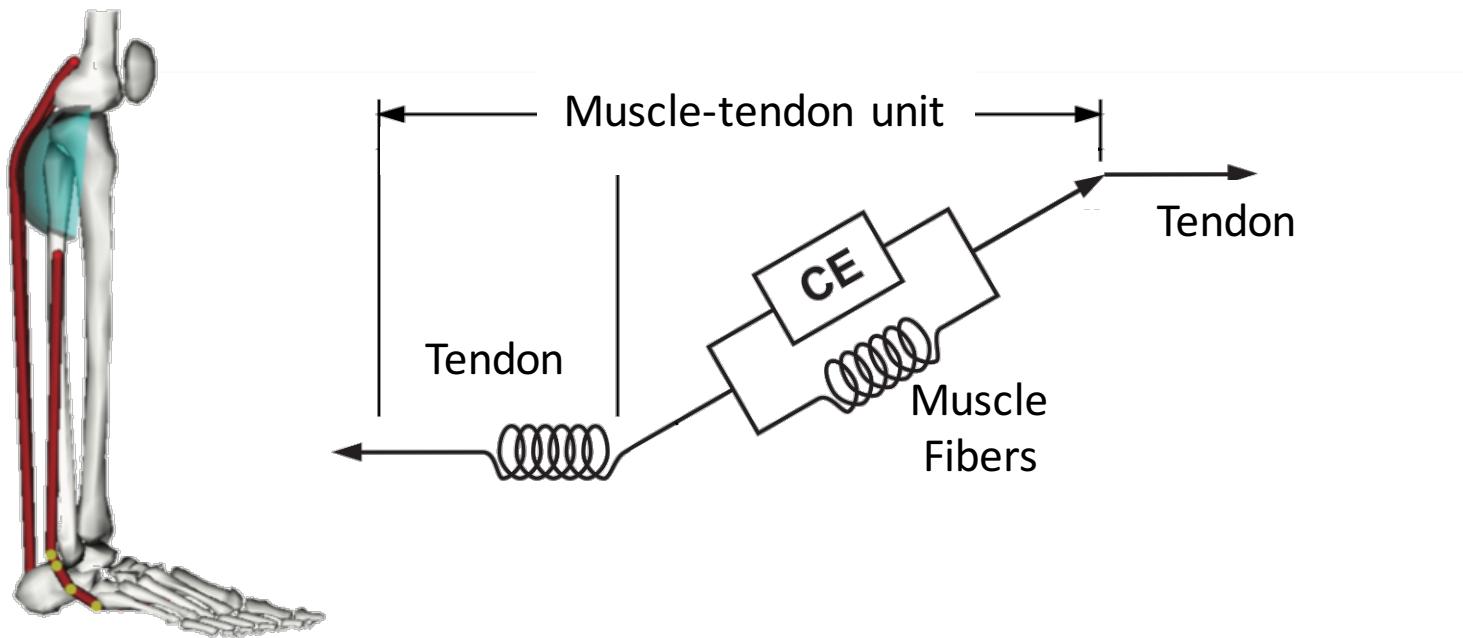
- Validating geometry
  - Joint moment = Muscle force  $\times$  **Muscle moment arm**
  - Compare model moment arms to experimental data



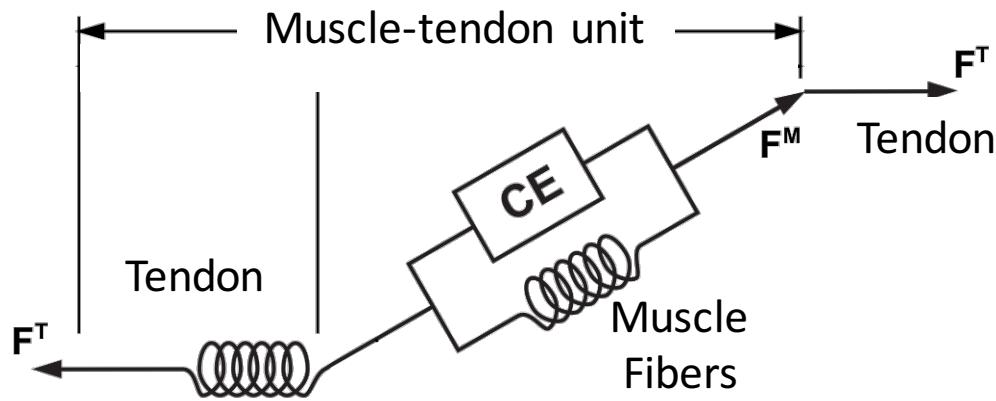
<sup>5</sup>W. L. Buford Jr. et al., "Muscle balance at the knee--moment arms for the normal knee and the ACL-minus knee," IEEE Trans Rehabil Eng, vol. 5, no. 4, pp. 367–379, 1997.

<sup>6</sup>C. W. Spoor and J. L. van Leeuwen, "Knee muscle moment arms from MRI and from tendon travel," J. Biomech., vol. 25, no. 2, pp. 201–6, Feb. 1992.

# Muscles: Force Generation Model

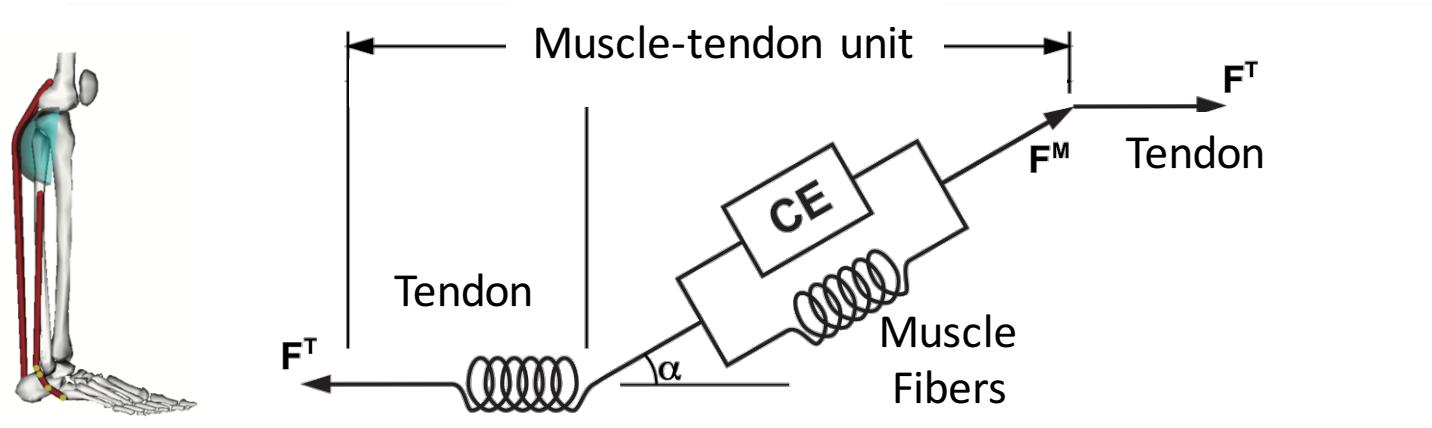


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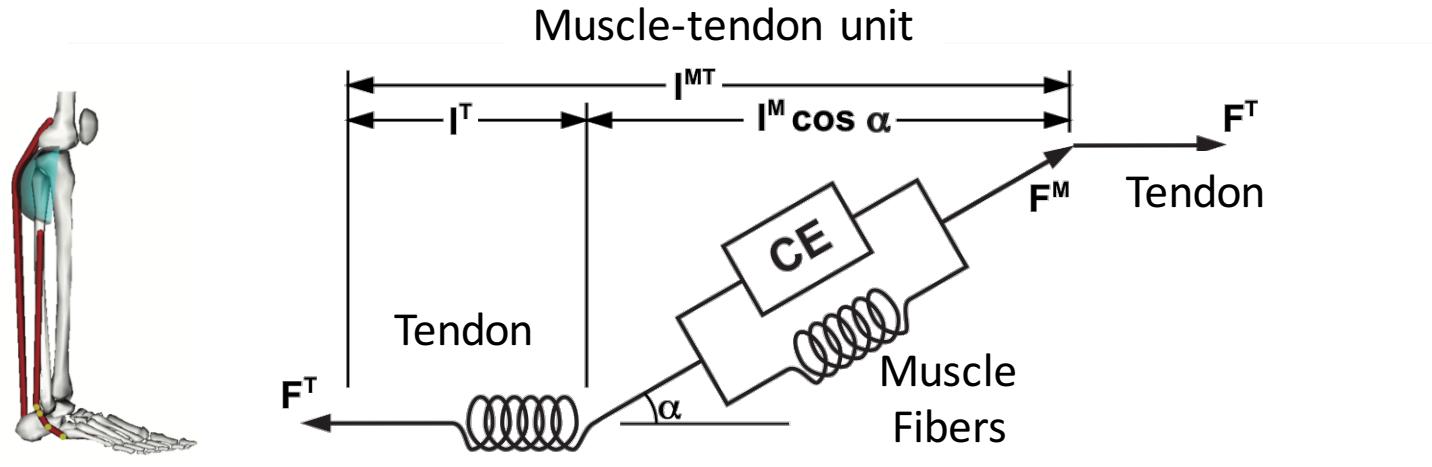
$F^M, F^T$  : force in muscle fiber and tendon

# Muscles: Force Generation Model



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 $\alpha$  : pennation angle of muscle fibers

# Muscles: Force Generation Model



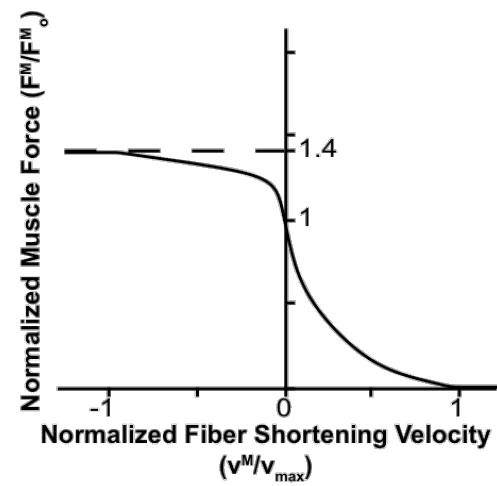
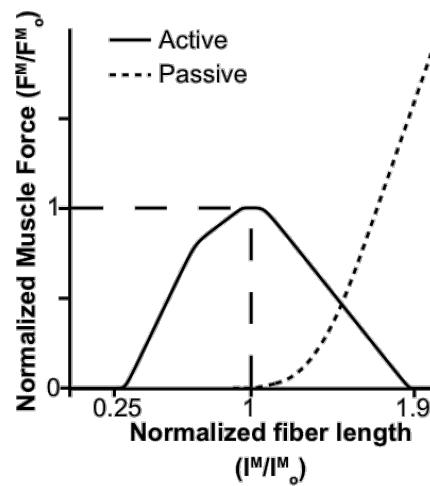
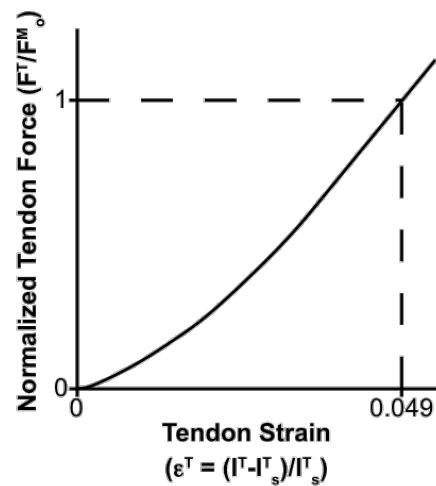
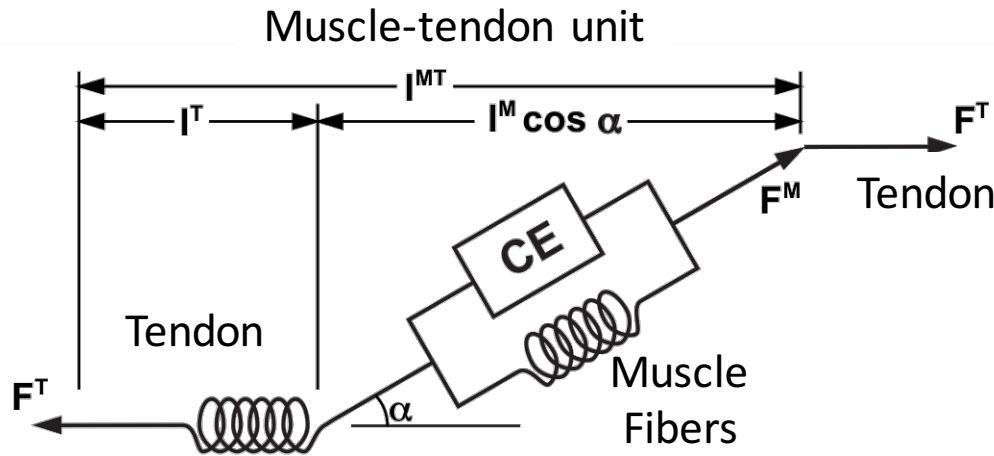
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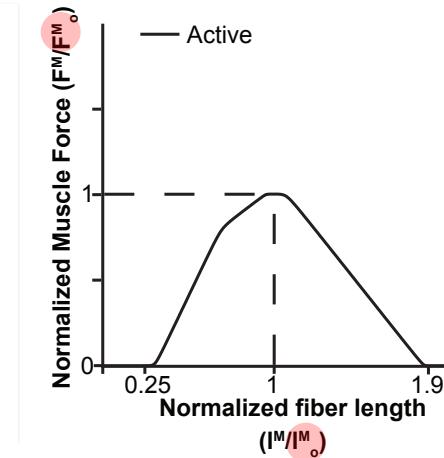
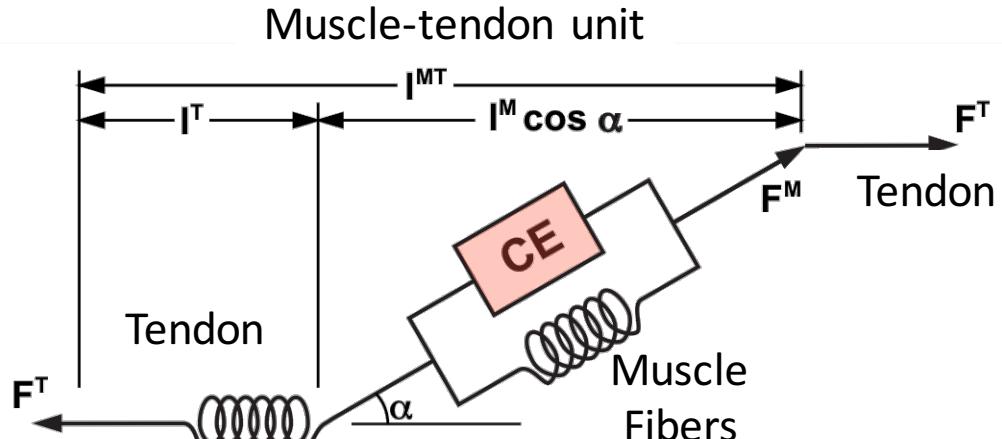
$|MT|$  : length of muscle-tendon unit

$|M|, |T|$  : length of muscle fiber and tendon

# Muscles: Force Generation Model



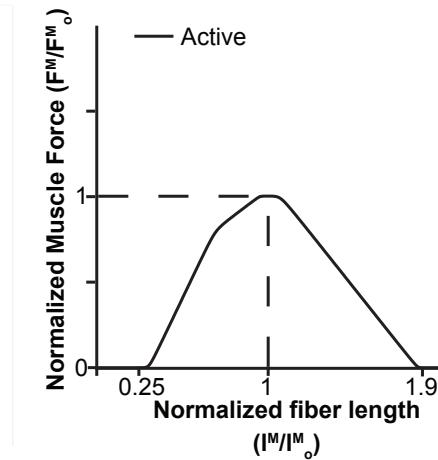
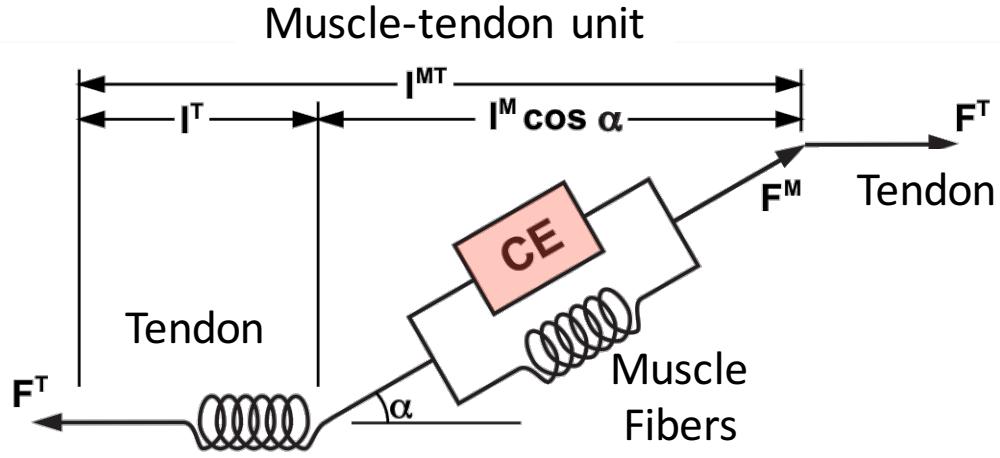
# Muscles: Force Generation Model



## Parameters

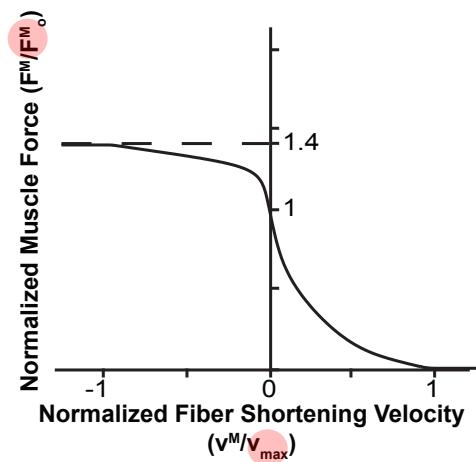
- $F_o^M$  : maximum active muscle isometric force  
 $l_o^M$  : optimal fiber length

# Muscles: Force Generation Model

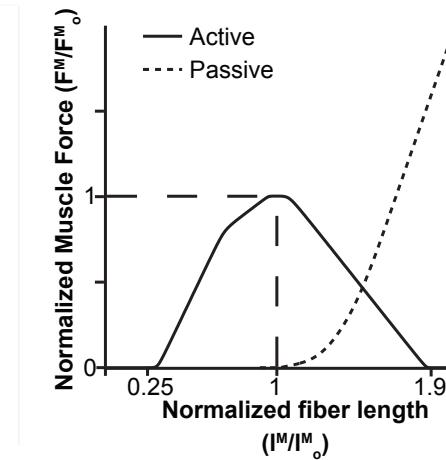
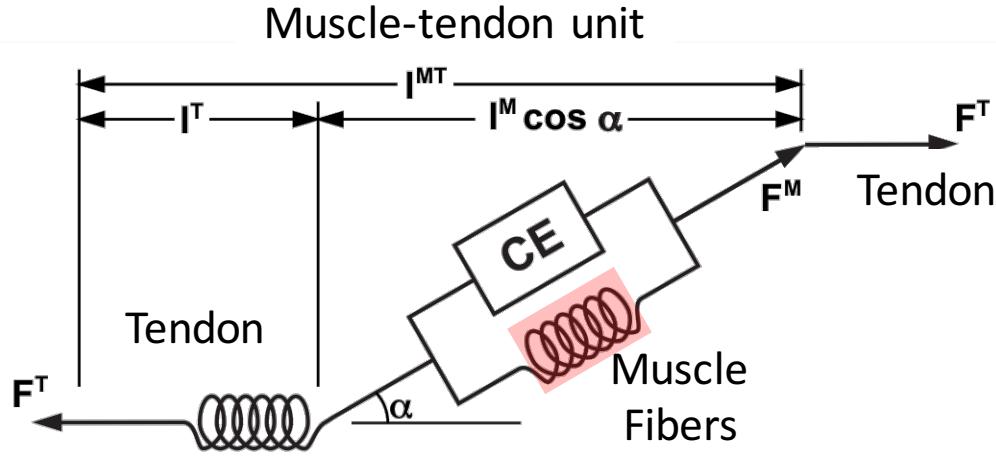


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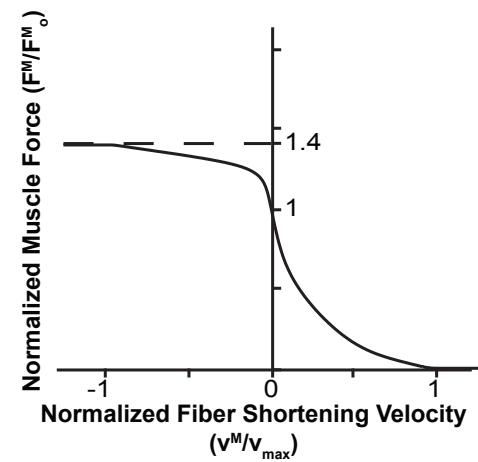


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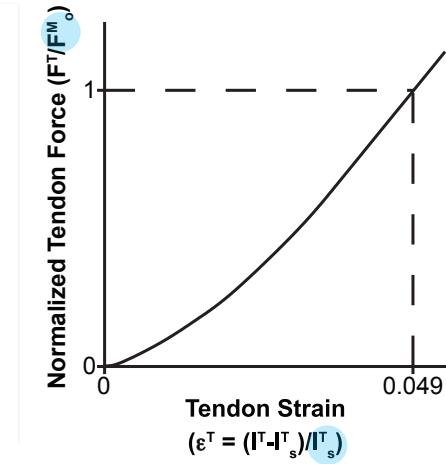
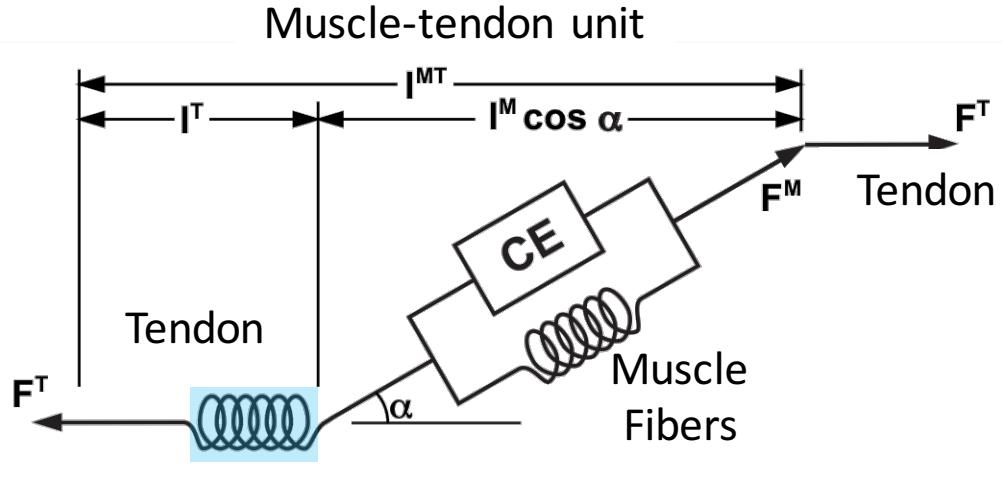


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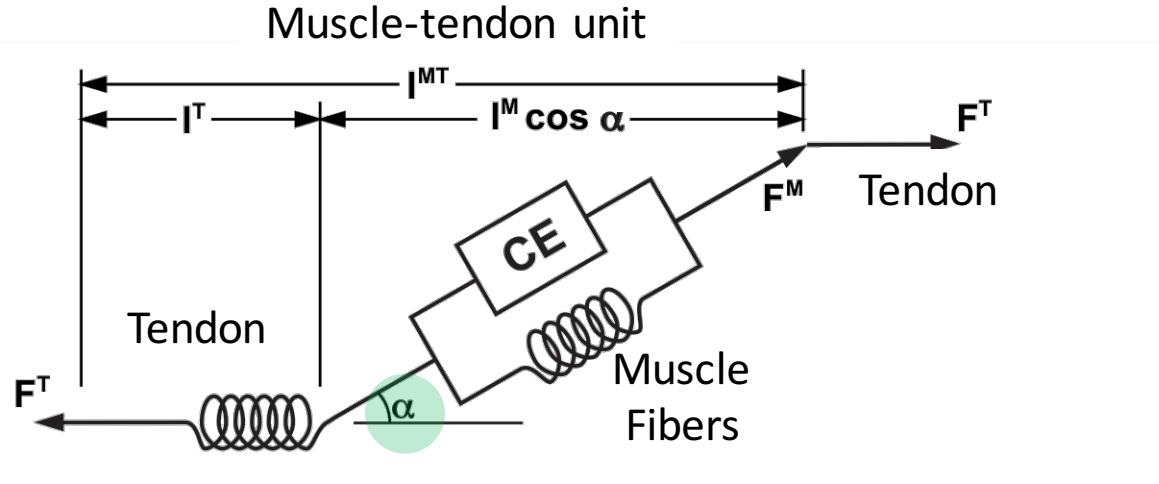
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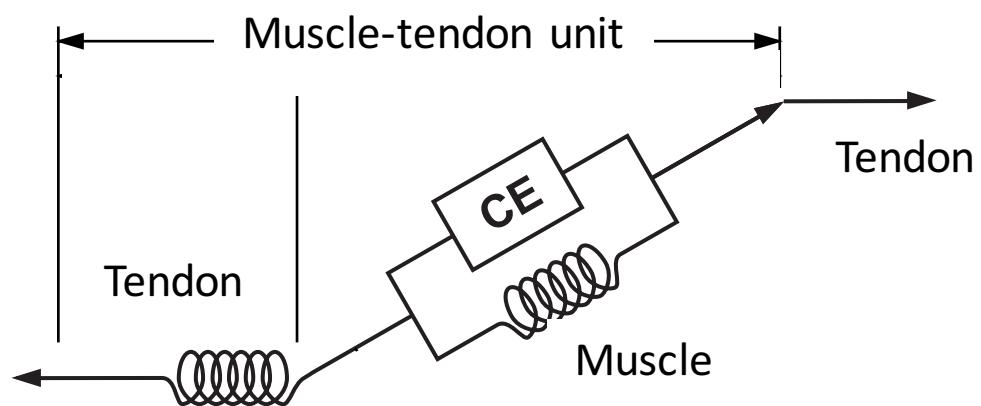
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# Muscle Model Components

Muscle Path



Force Generating Capacity



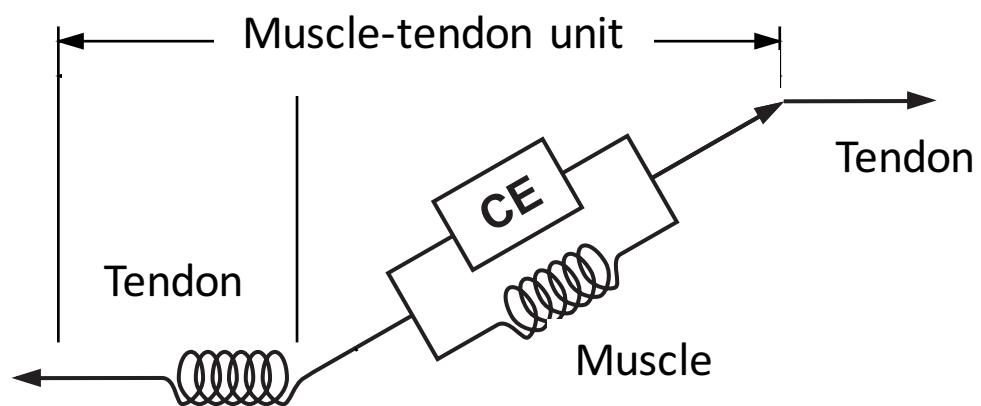
1. Model and inherent assumptions
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3. Consequences of modeling assumptions in simulation

# Muscle Model Components

Muscle Path

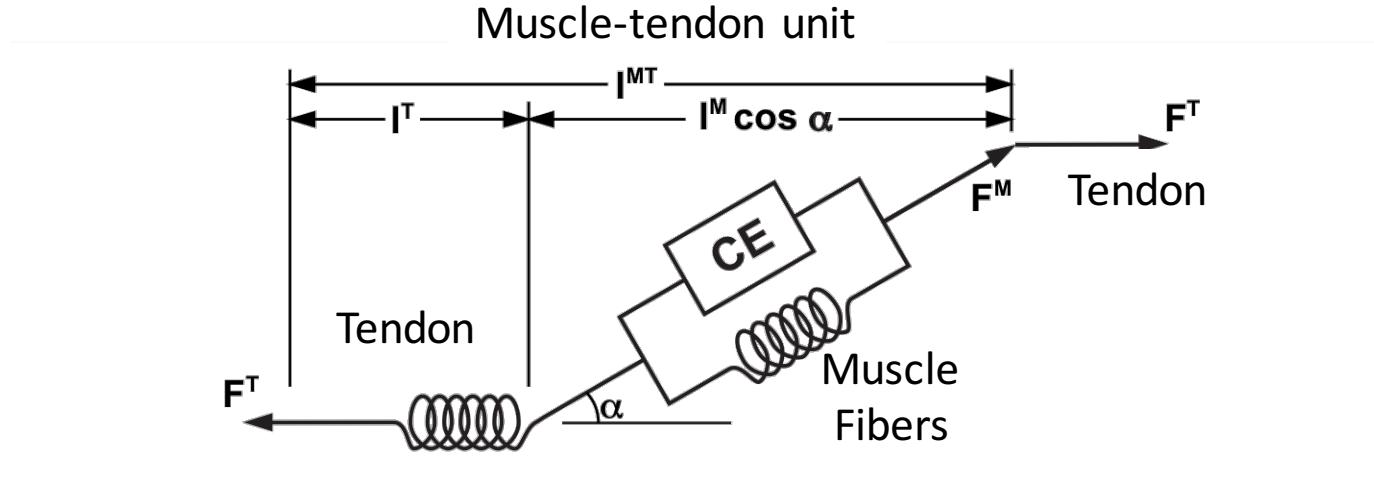


Force Generating Capacity



1. Model and inherent assumptions
2. **Choosing and validating parameters**
3. Consequences of modeling assumptions in simulation

# Muscles: Choosing parameters



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# Muscles: Choosing parameters

- Cadaver measurements
  - Raw data<sup>7</sup>:
    - $l^M$ : muscle fiber length
    - $l^S$ : sarcomere length
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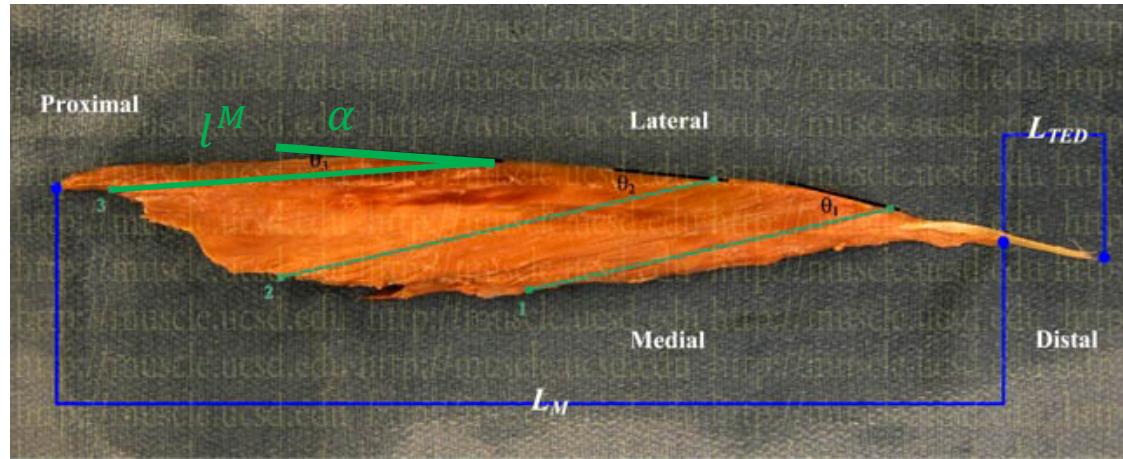


Image: <http://muscle.ucsd.edu/projects/architecture/LE/psoas.shtml>

<sup>7</sup>S. R. Ward et al., "Are current measurements of lower extremity muscle architecture accurate?" Clin Orthop Relat Res, vol. 467, no. 4, pp. 1074–1082, 2009.

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    - $\alpha$ : pennation angle of muscle

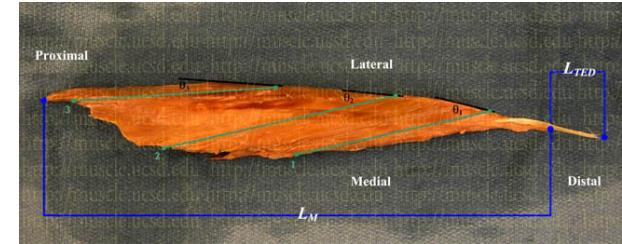


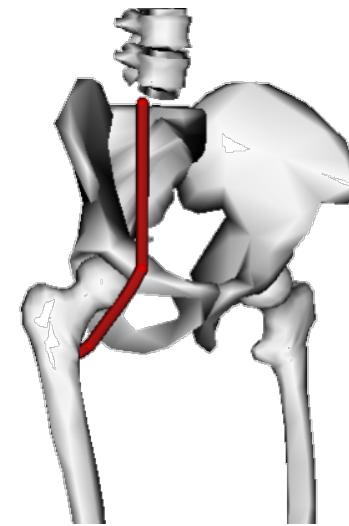
Image: <http://muscle.ucsd.edu/>

- Model parameters:
  - $l_o^M$ : optimal muscle fiber length
$$l_o^M = \frac{l_o^S}{l^S} \cdot l^M$$
  - $\alpha_o$ : pennation angle of muscle at optimal fiber length
$$\alpha_o = \sin^{-1} \left( \frac{l^S}{l_o^S} \sin \alpha \right)$$

<sup>7</sup>S. R. Ward et al., "Are current measurements of lower extremity muscle architecture accurate?" Clin Orthop Relat Res, vol. 467, no. 4, pp. 1074–1082, 2009.

# Muscles: Choosing parameters

- Cadaver measurements
  - Model parameters:
    - $l_s^T$ : tendon slack length
      - Pose Model



hip flexion: 7°  
hip abduction: 2°  
hip rotation: 0°

# Muscles: Choosing parameters

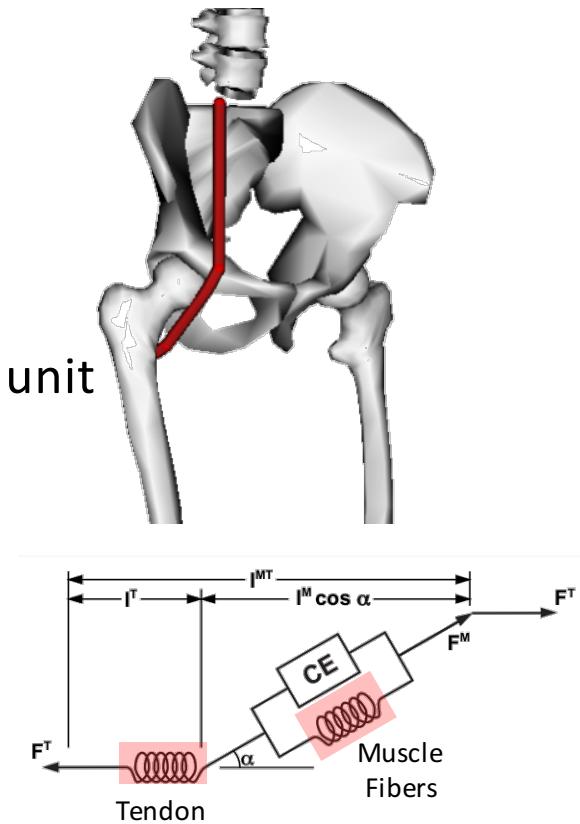
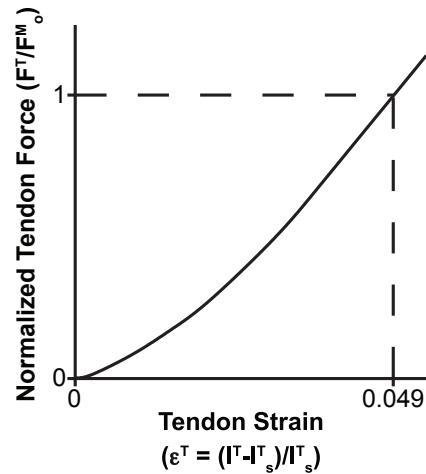
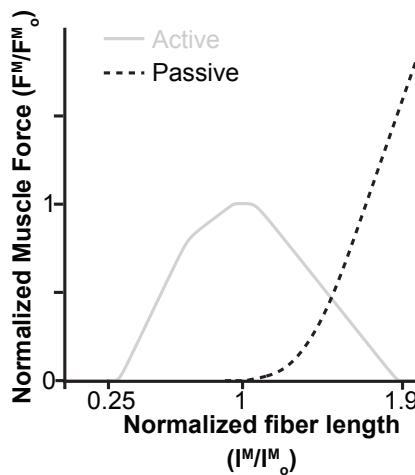
- Cadaver measurements

- Model parameters:

- $l_s^T$ : tendon slack length

- Pose Model

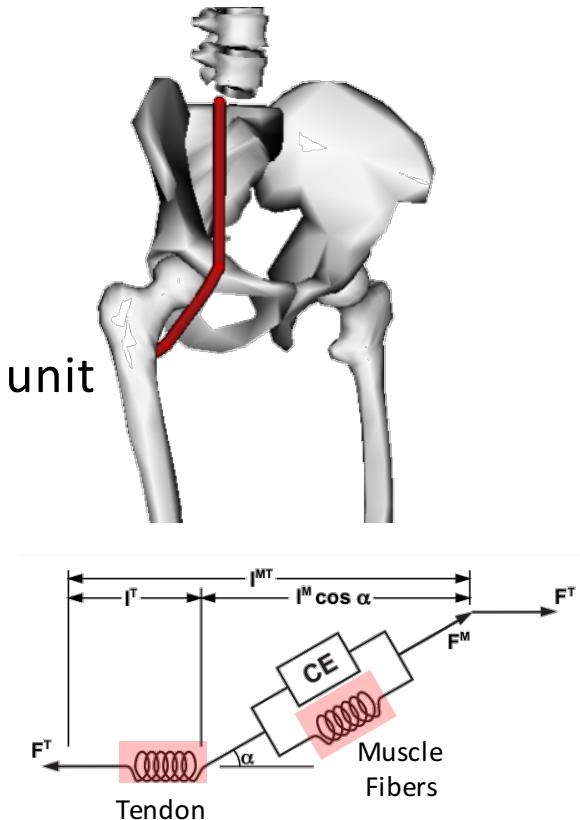
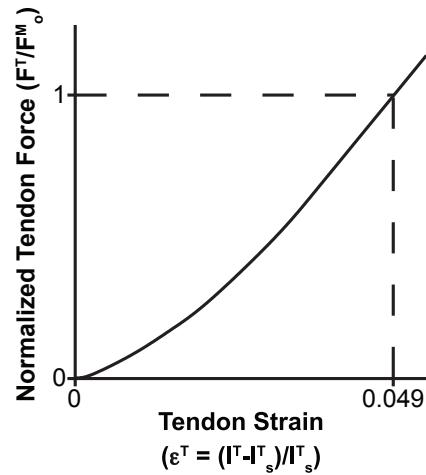
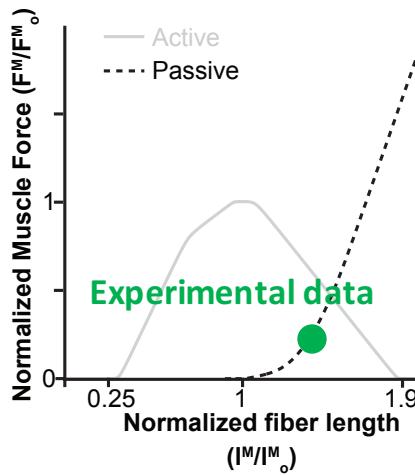
- Equilibrate passive muscle-tendon unit



# Muscles: Choosing parameters

- Cadaver measurements

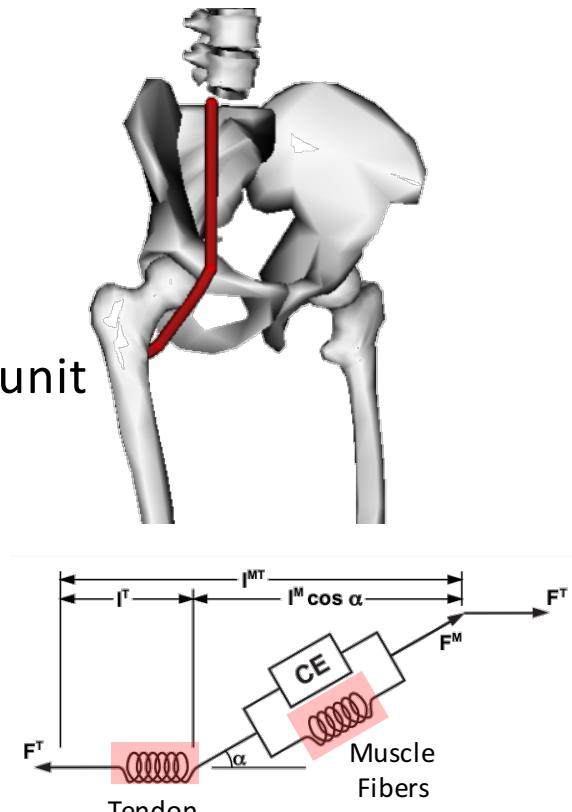
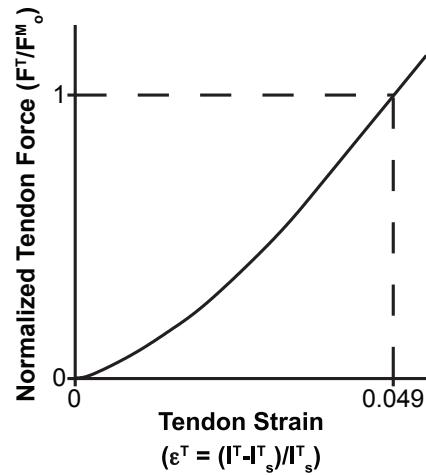
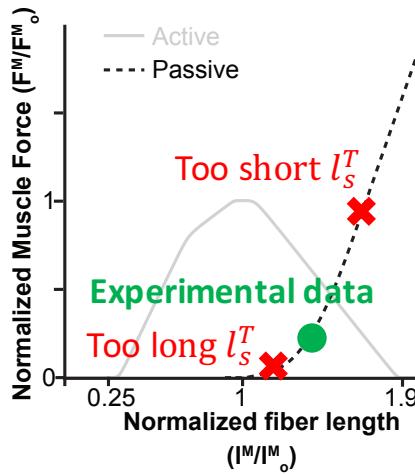
- Model parameters:
  - $l_s^T$ : tendon slack length
  - Pose Model
  - Equilibrate passive muscle-tendon unit



# Muscles: Choosing parameters

- Cadaver measurements

- Model parameters:
  - $l_s^T$ : tendon slack length
    - Pose Model
    - Equilibrate passive muscle-tendon unit  
(Iteratively solve for  $l_s^T$ )



# Muscles: Choosing parameters

- Imaging data
  - Raw data:
    - $V_{total}$ : total muscle volume
    - $\phi^M$ : muscle volume fraction
  - Model parameters:
    - $F_o^M = \sigma_o^M \cdot \frac{\phi^M V_{total}}{l_o^M}$   

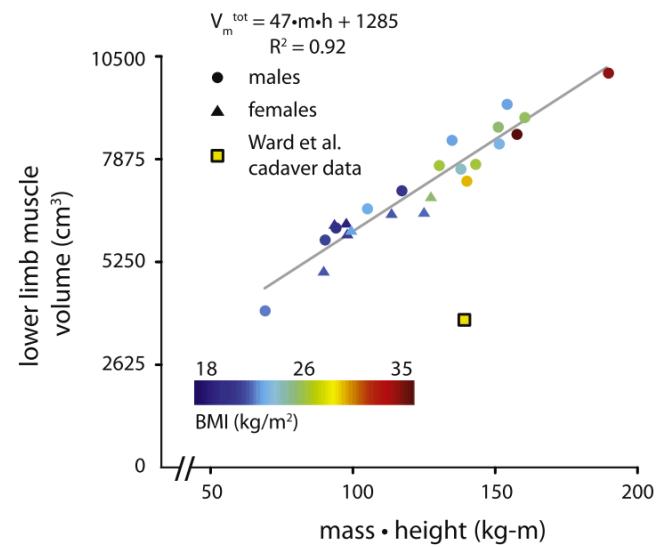



Figure: <sup>8</sup>Handsfield *et al.* 2014

<sup>8</sup>G. G. Handsfield et al., "Relationships of 35 lower limb muscles to height and body mass quantified using MRI.", J. Biomech., vol. 47, no. 3, pp. 631–8, Feb. 2014.

# Muscles: Choosing parameters

## Variability in parameters:

SUPPLEMENTAL TABLE I  
MUSCULOTENDON PARAMETERS WITH EXPECTED VARIATION

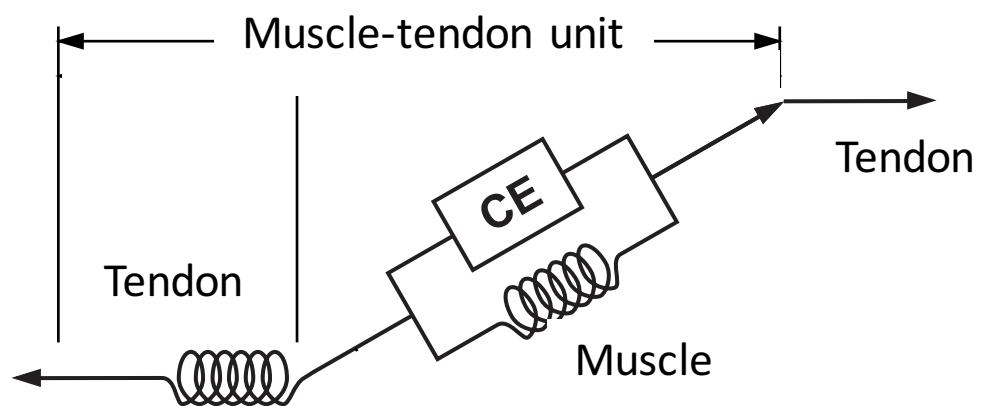
Muscle	Abbreviation	Optimal force (N) ( $\pm$ S.D.)	Optimal fiber length (cm) ( $\pm$ S.D.)	Tendon slack length (cm) <sup>a</sup> ( $\pm$ S.D.)	Pennation angle (°) ( $\pm$ S.D.)
Adductor brevis	addbrevis	626 (130)	10.3 (1.4)	3.5* (1.7)	6.6 (3.4)
Adductor longus	addlong	917 (220)	10.8 (2.0)	13.2 (2.6)	7.9 (3.9)
Adductor magnus <sup>bc</sup>					
Adductor magnus (distal)	addmagDist	597 (131)	17.7 (3.4)	8.7* (3.5)	11.2 (5.5)
Adductor magnus (ischial)	addmagIsch	597 (131)	15.6 (3.0)	21.6 (3.2)	9.6 (4.7)
Adductor magnus (middle)	addmagMid	597 (131)	13.8 (2.6)	4.7* (2.6)	11.9 (5.8)
Adductor magnus (proximal)	addmagProx	597 (131)	10.6 (2.0)	4.0* (2.2)	17.8 (8.7)
Biceps femoris long head	bflh	1313 (402)	9.8 (2.6)	32.5 (2.8)	10.1 (4.9)
Biceps femoris short head	bfsh	557 (158)	11.0 (2.1)	10.6* (2.6)	15.1 (4.5)
Extensor digitorum longus <sup>cc</sup>	edl	603 (115)	6.9 (1.1)	36.9 (1.5)	12.5 (3.4)
Extensor hallucis longus <sup>cc</sup>	ehl	286 (51)	7.5 (1.1)	32.7 (1.4)	11.3 (2.7)
Flexor digitorum longus	fdl	423 (148)	4.5 (1.1)	37.9 (1.1)	12.9 (4.6)
Flexor hallucis longus	fhl	908 (273)	5.3 (1.3)	35.4 (1.3)	14.8 (4.3)
Gastrocnemius lateral head	gaslat	1575 (404)	5.9 (1.0)	37.6 (1.1)	12.0 (3.3)
Gastrocnemius medial head	gasmed	3116 (727)	5.1 (1.0)	39.9 (1.1)	9.5 (4.3)
Gluteus maximus <sup>be</sup>					
Gluteus maximus (superior)	glmax1	984 (181)	14.7 (2.4)	4.9* (4.0)	20.3 (24.3)
Gluteus maximus (middle)	glmax2	1406 (260)	15.7 (2.6)	6.8* (4.4)	21.0 (25.3)
Gluteus maximus (inferior)	...1...2	948 (175)	16.7 (2.7)	7.0* (4.9)	21.9 (26.3)

# Muscle Model Components

Muscle Path



Force Generating Capacity



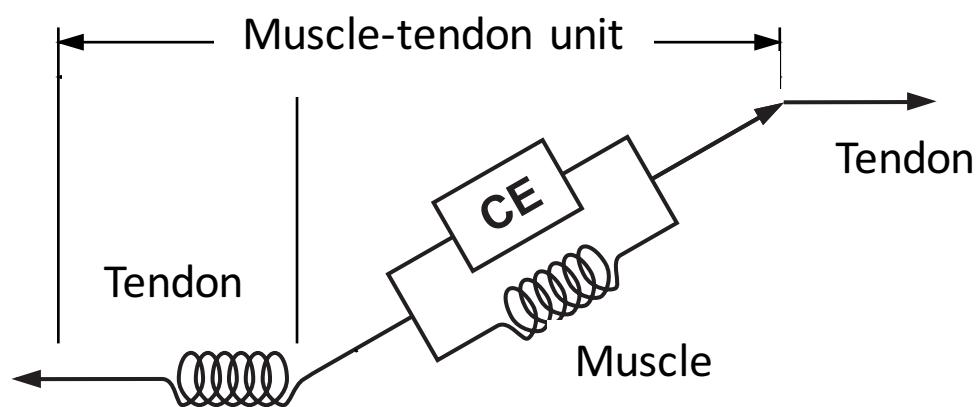
1. Model and inherent assumptions
2. **Choosing and validating parameters**
3. Consequences of modeling assumptions in simulation

# Muscle Model Components

Muscle Path



Force Generating Capacity



1. Model and inherent assumptions
2. Choosing and validating parameters
3. **Consequences of modeling assumptions in simulation**

# Muscles: Modeling Assumptions

- 1-D Hill-Type Model
  - All muscle fibers change length uniformly
  - Exaggerate force-length and force-velocity effects on force generation

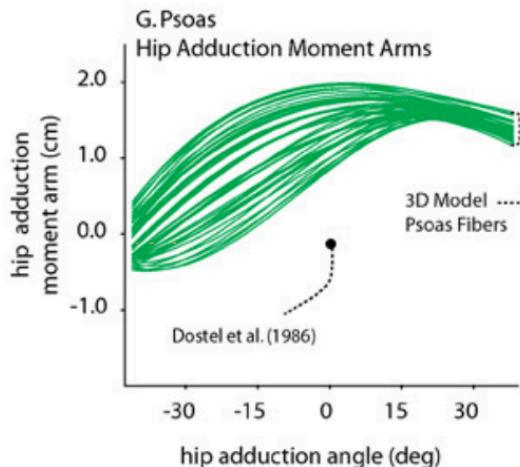


Figure: <sup>9</sup>Blemker *et al.* 2005

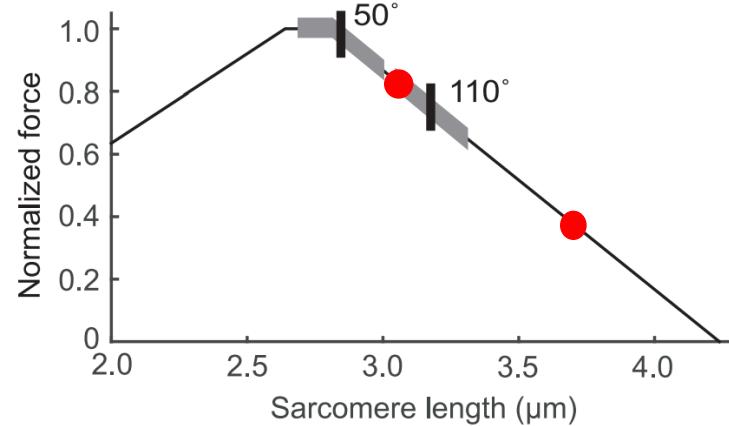


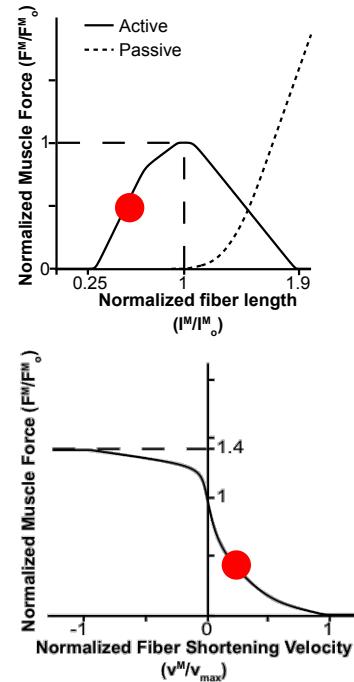
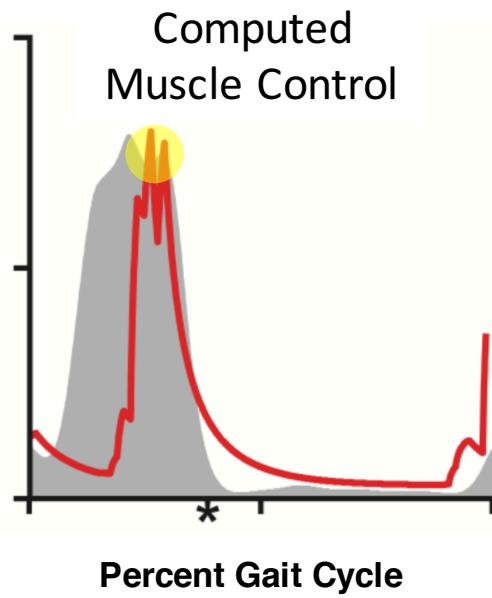
Figure: <sup>10</sup>Chen *et al.* 2016

<sup>9</sup>Blemker, Silvia S., and Scott L. Delp. "Three-dimensional representation of complex muscle architectures and geometries." *Annals of biomedical engineering* 33.5 (2005): 661-673.

<sup>10</sup>Chen, Xuefeng, et al. "Changes in sarcomere lengths of the human vastus lateralis muscle with knee flexion measured using in vivo microendoscopy." *Journal of Biomechanics* 49.13 (2016): 2989-2994.

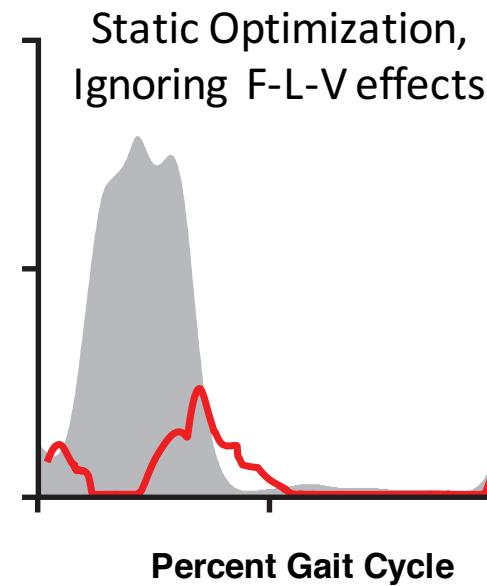
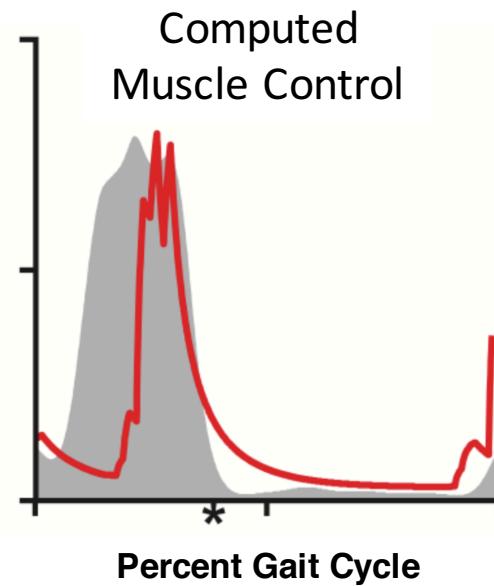
# Muscles: Consequences of Modeling Assumptions in Simulation

- Exaggerated force-length and force-velocity effects on active force generation necessitate high specific tension
  - e.g. gastrocnemius in running



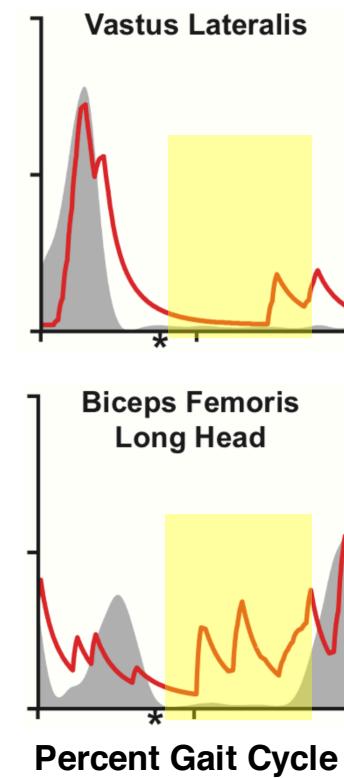
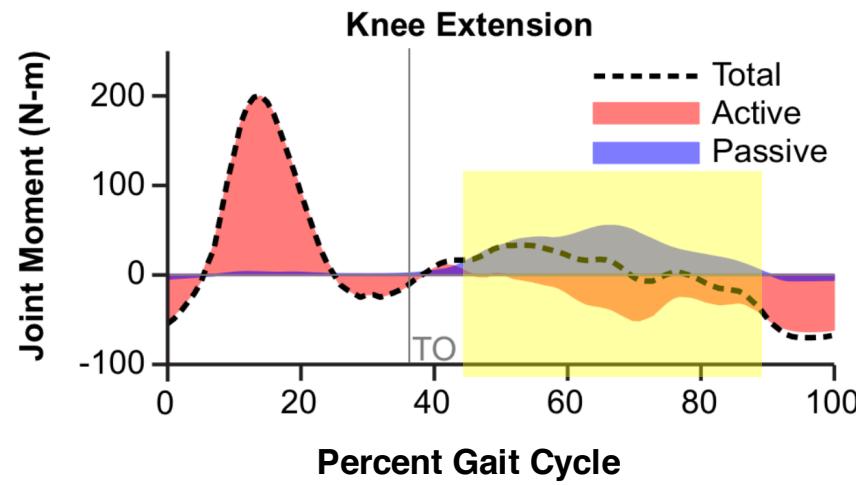
# Muscles: Consequences of Modeling Assumptions in Simulation

- Exaggerated force-length and force-velocity effects on active force generation necessitate high specific tension
  - e.g. gastrocnemius in running



# Muscles: Consequences of Modeling Assumptions in Simulation

- Excessive passive force generation, and compensatory muscle activity
  - e.g. vasti and hamstrings in running

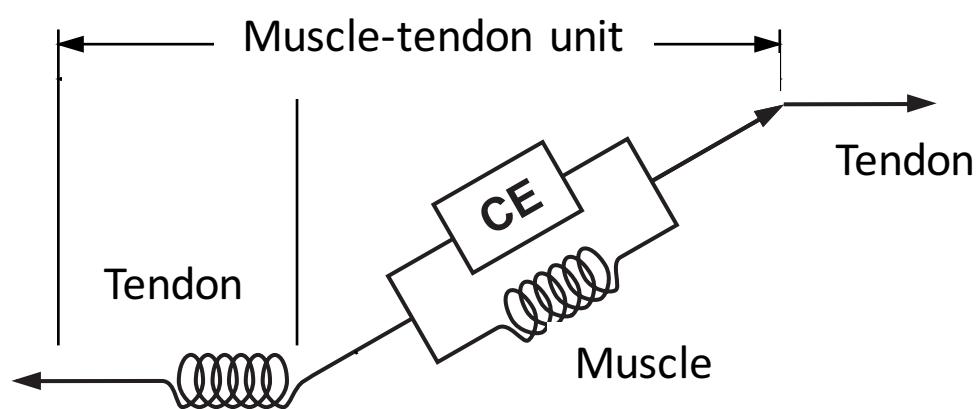


# Muscle Model Components

Muscle Path



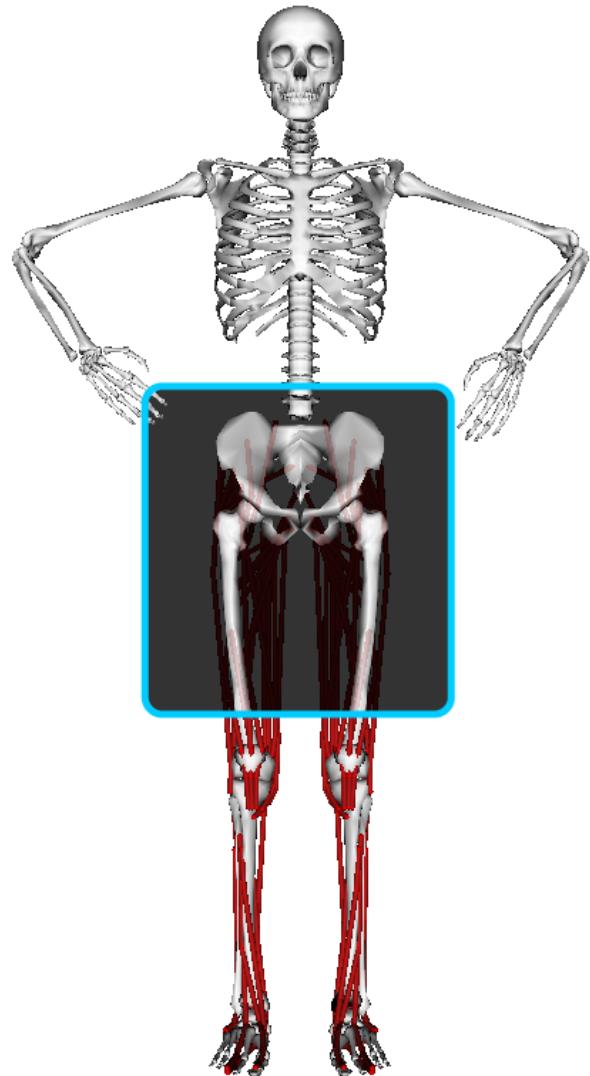
Force Generating Capacity



1. Model and inherent assumptions
2. Choosing and validating parameters
3. **Consequences of modeling assumptions in simulation**

# Outline

- Components of a model
  - Rigid Bodies  
(e.g., pelvis)
  - Joints  
(e.g., hip)
  - Force-generating elements  
(e.g., muscles)
- **Validating a model in context of its intended use**

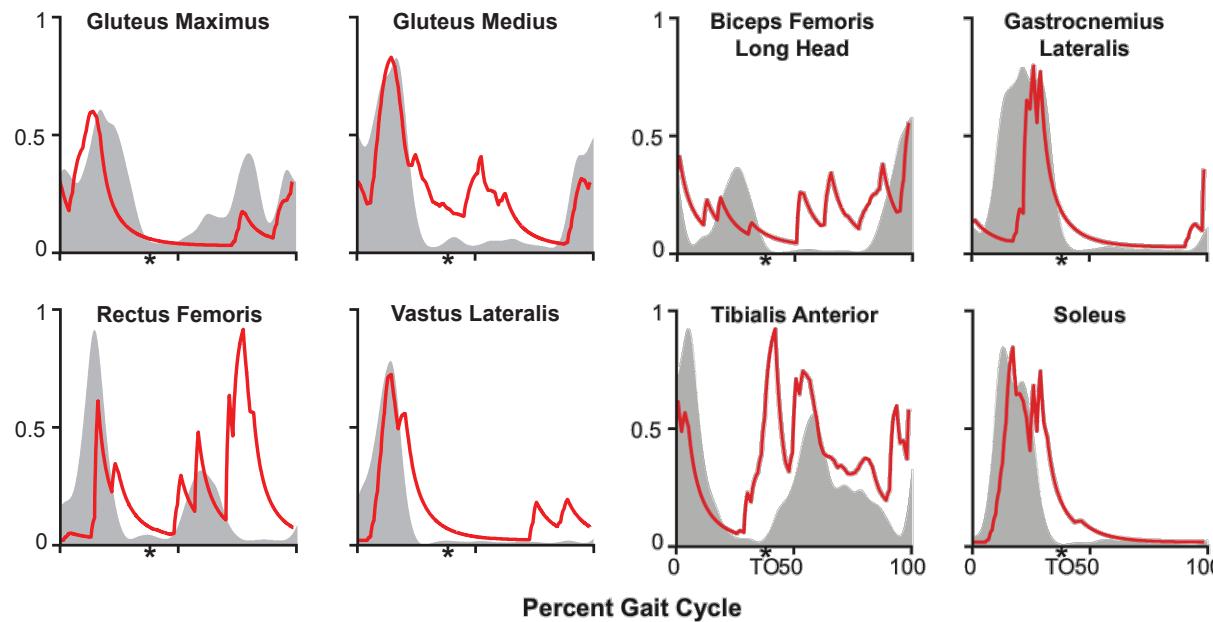


# Validating a Model in Context of Simulation

1. Are the musculotendon parameters reflective and/or scalable to an individual subject?

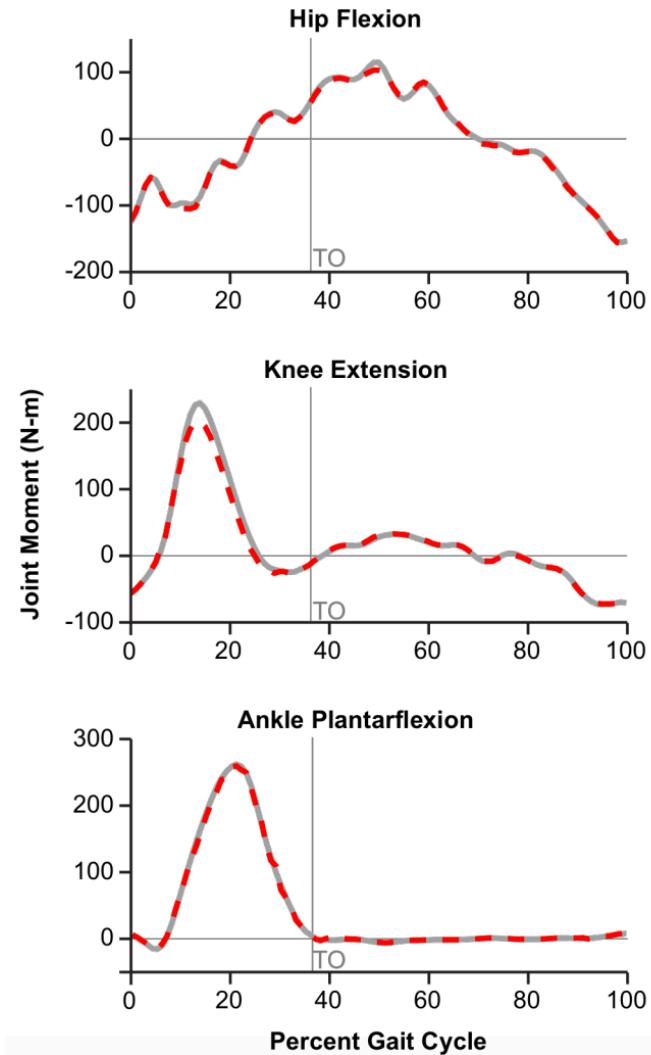
# Validating a Model in Context of Simulation

1. Are the musculotendon parameters reflective and/or scalable to an individual subject?
2. Do simulated muscle activity agree well with experimental measures?

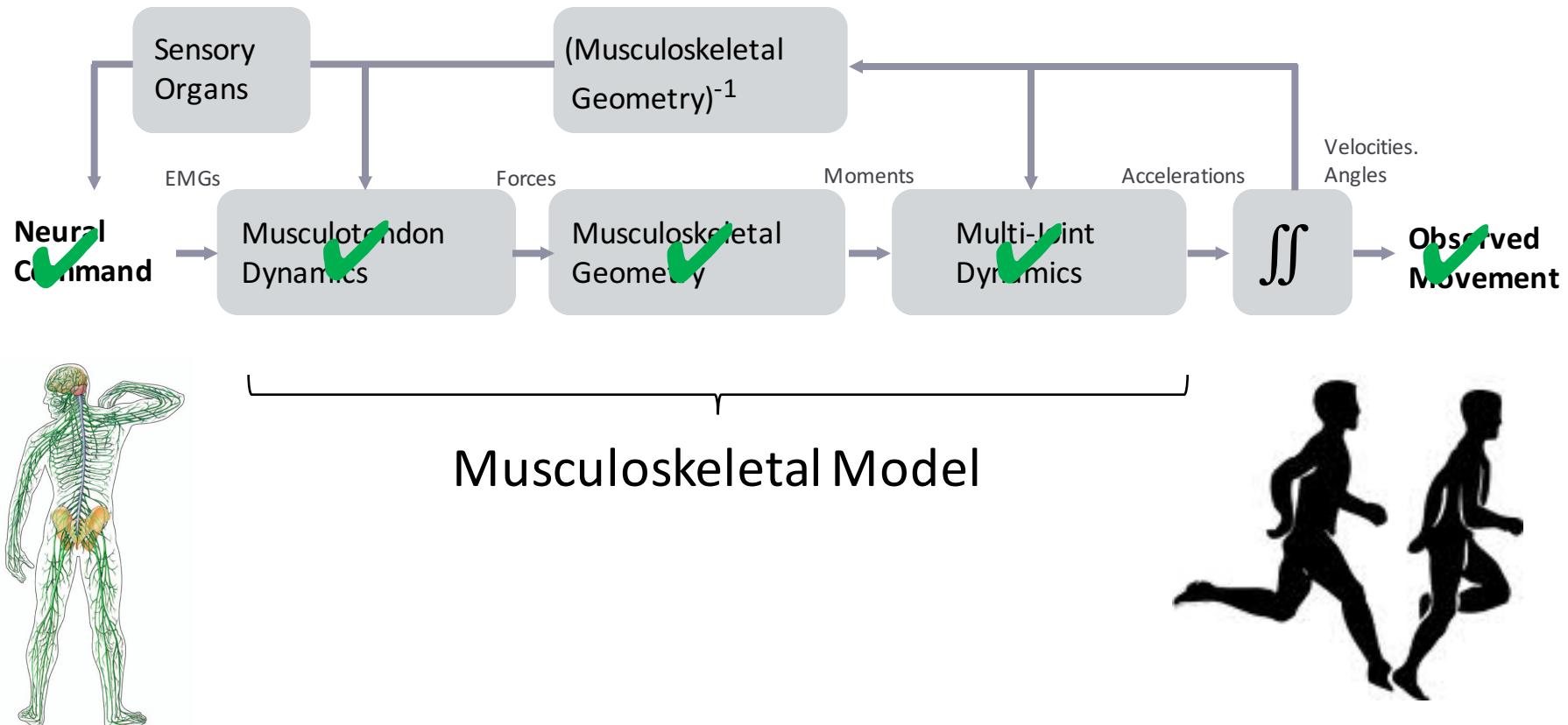


# Validating a Model in Context of Simulation

1. Are the musculotendon parameters reflective and/or scalable to an individual subject?
2. Do simulated muscle activity agree well with experimental measures?
3. Are the muscles truly driving the motion?

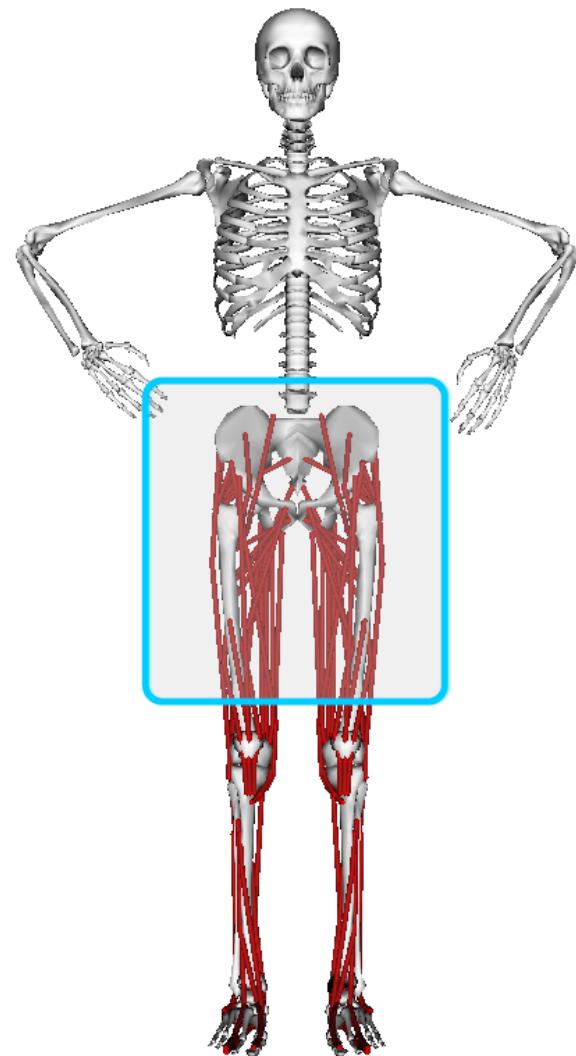


# Validating a Model in Context of Simulation



# Conclusion

- Components of a model
  - Rigid Bodies  
(e.g., pelvis)
  - Joints  
(e.g., hip)
  - Force-generating elements  
(e.g., muscles)
- Validating a model in context of its intended use



# Downloading Model and Data

[https://simtk.org/projects/full\\_body/](https://simtk.org/projects/full_body/)

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## Full Body Model for use in Dynamic Simulations of Human Gait

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*Rajagopal, Apoorva, et al. "Full-Body Musculoskeletal Model for Muscle-Driven Simulation of Human Gait." IEEE Transactions on Biomedical Engineering 63.10 (2016): 2068-2079. (2016)*

[Abstract](#) [View](#)

Full body musculoskeletal model with muscle-actuated lower extremity and torque-actuated torso/upper extremity for use in dynamic simulations of human movement.

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Our paper describes a full body OpenSim model with musculotendon parameters derived from experimental measurements of 21 cadaver lower limbs and magnetic resonance images of 24 young adult subjects. Our model is derived from the lower body model published by Arnold et al. (2010) and the tracking upper body by Hamner et al. (2013), but updates the muscle force distribution to reflect those of a young, healthy population, includes a new knee model to

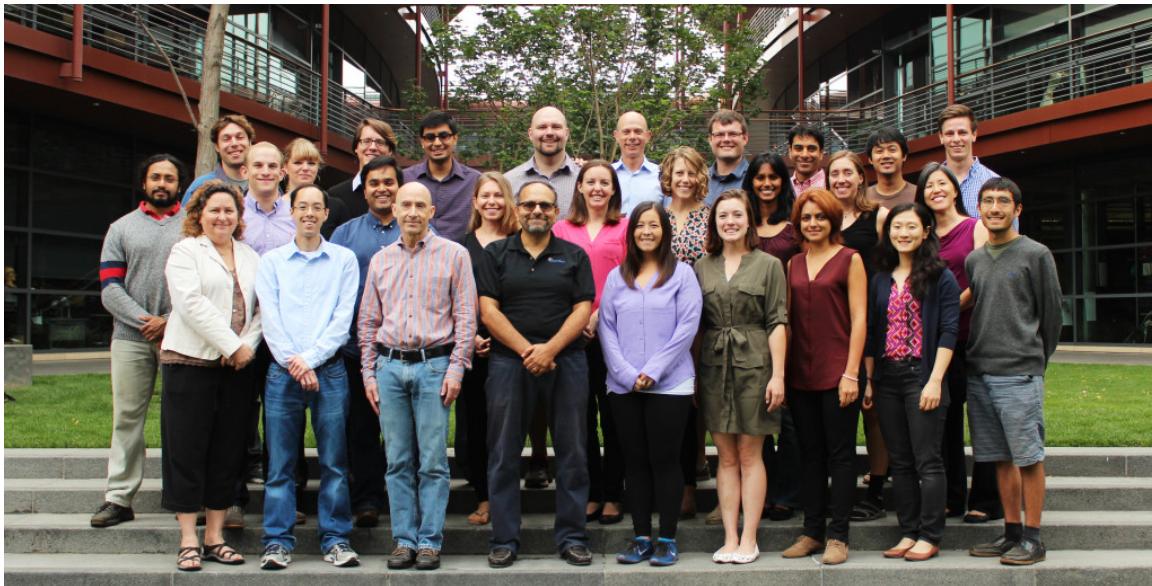
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# Thank you!

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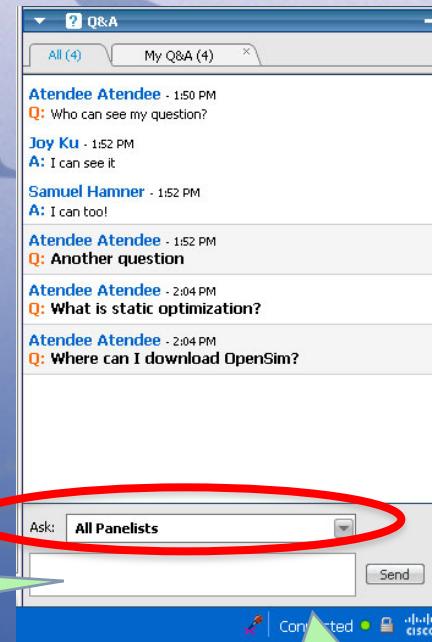
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1. Click on the Q&A button to open the Q&A panel.

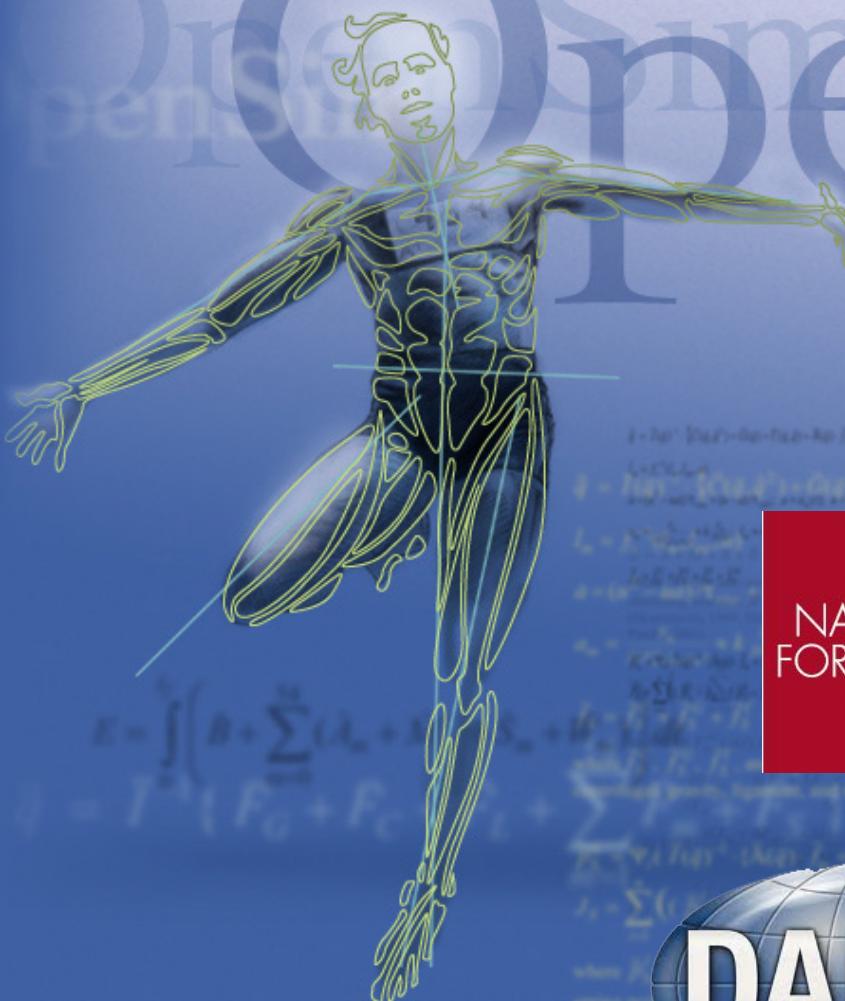


2. Type your question in the box at the bottom of the Q&A Panel.

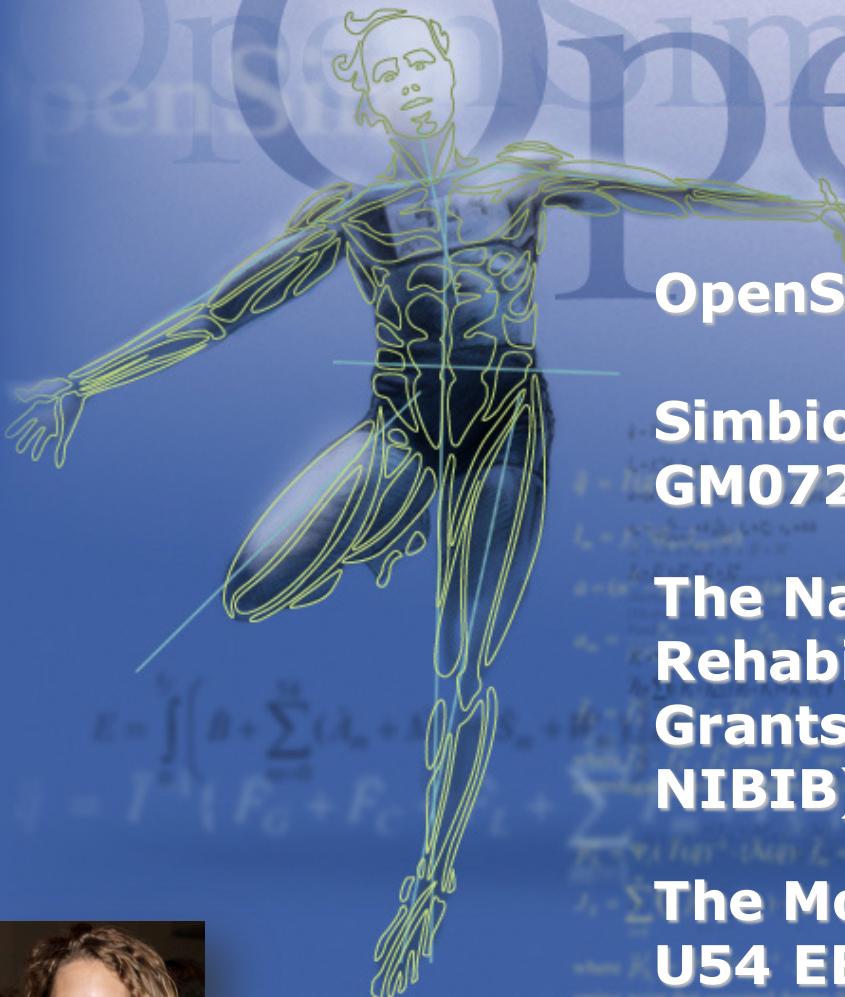
**Questions must be asked of “All Panelists”**

# OpenSim

ANY QUESTIONS?



# OpenSim



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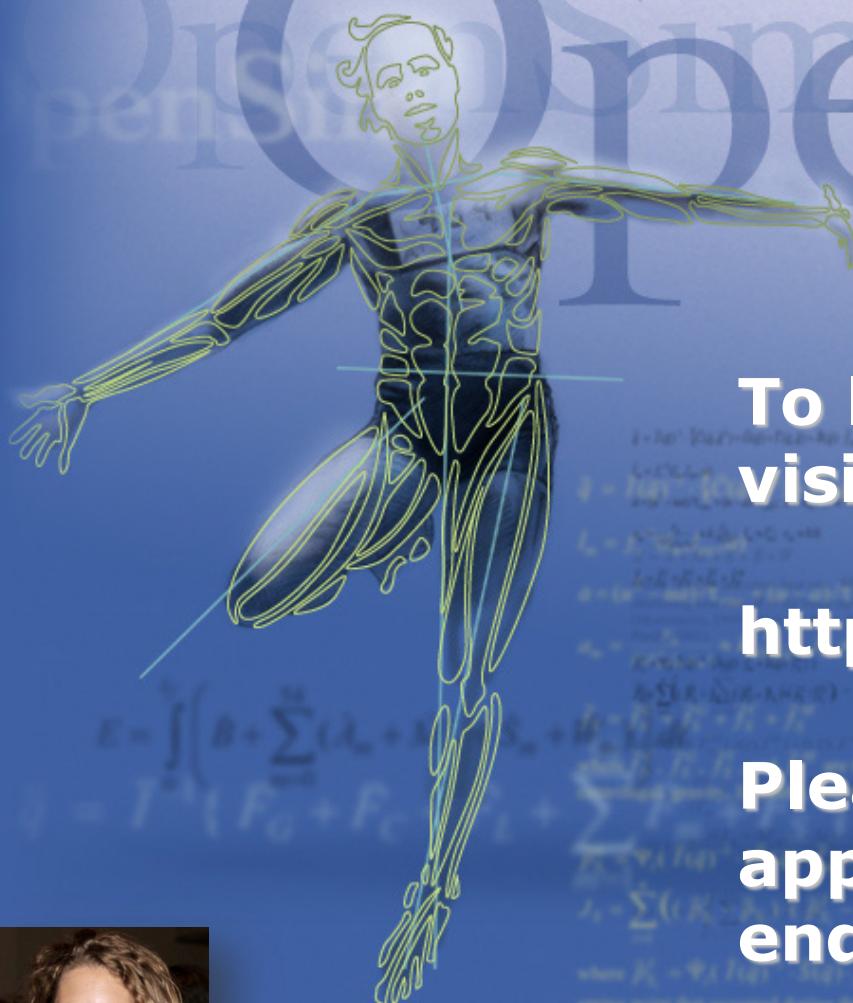
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# OpenSim

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