LOCOMOTION CONTROL FOR MANY-MUSCLE HUMANOIDS

Yoonsang Lee[1,2] Moon Seok Park[3]

Taesoo Kwon[4] Jehee Lee[1]

[1] Seoul National University

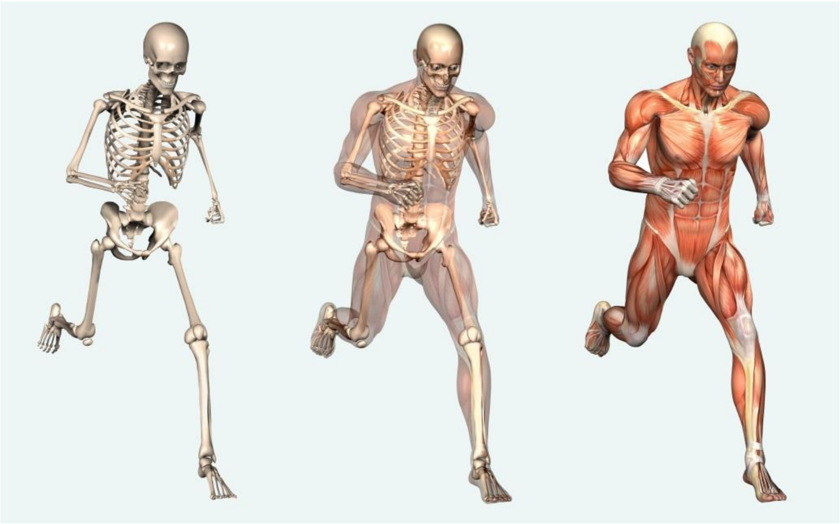
[2] Samsung Electronics Co., Ltd.

[3] Seoul National University Bundang Hospital

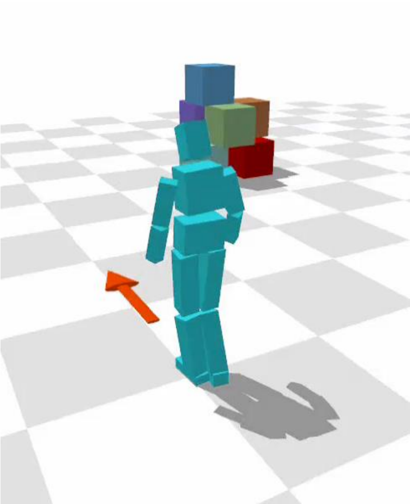
[4] Hanyang University

Human Movements

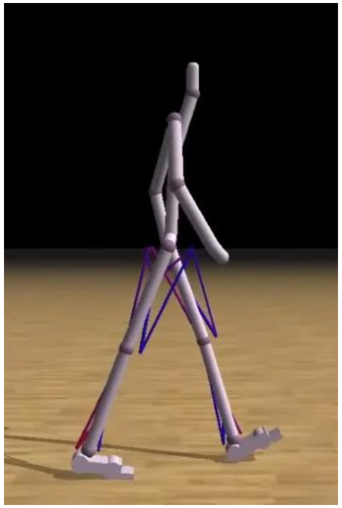
- Complex musculoskeletal system
- Coordination of muscle activation



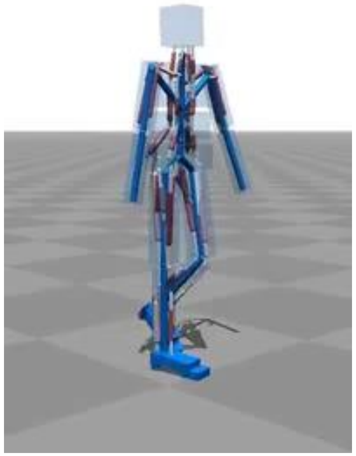
Why Many-Muscles?



Lee et al. 2010



Wang et. al. 2012

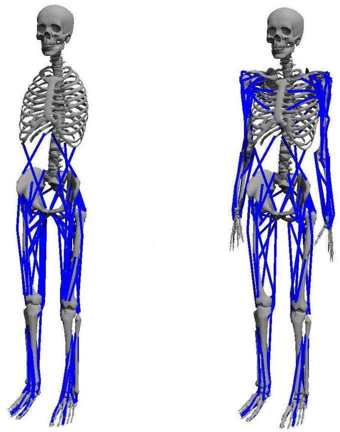


Geijtenbeek et. al. 2013

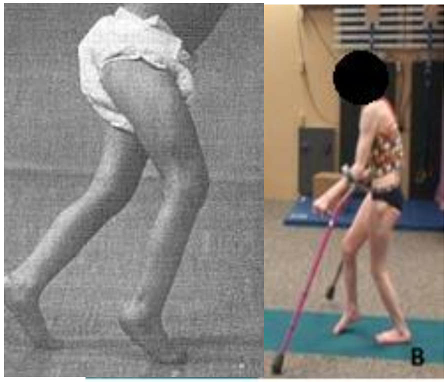
- Enough for complex movements?

Goal

- Controlling locomotion with complex musculoskeletal system
  - Arbitrarily many (100+) muscles

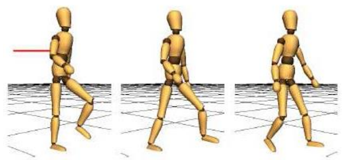


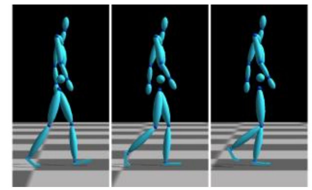
- Predicting new gait patterns under varied conditions
  - Pathologic gait patterns



Related Work - Biped Control


Kwon et al. 2010


Yin et al. 2007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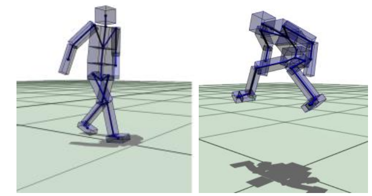
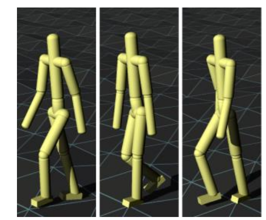
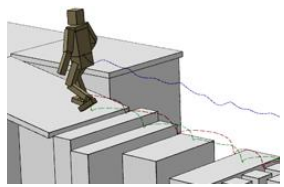
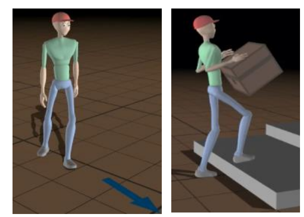

Lasa et al. 2010

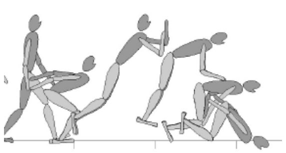

Wu et al. 2010


Lee et al. 2010


Mordatch et al. 2010


Coros et al. 2010


Brown et al. 2013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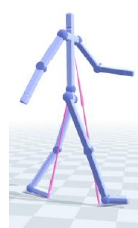
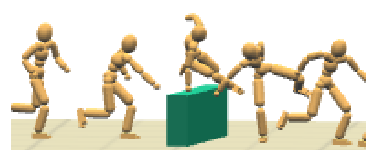
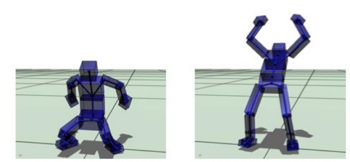

Muico et al. 2009

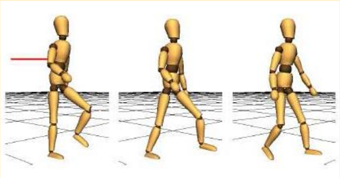

Liu et al. 2012


Al Borno et al. 2013

Related Work - Biped Control

FSM / Simple Models

Kwon et al. 2010



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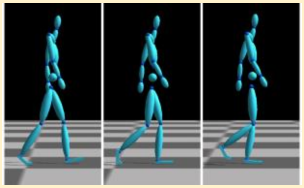

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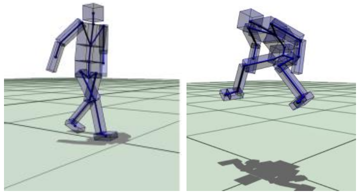

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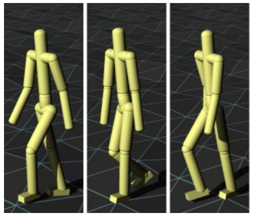

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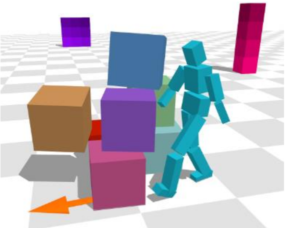

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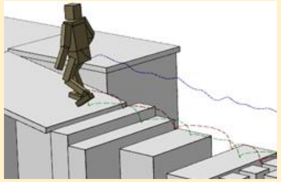
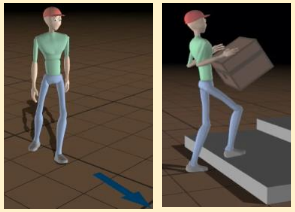
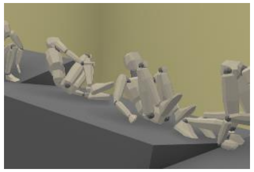


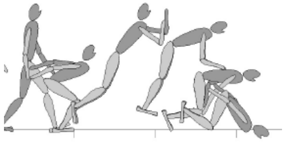
Mordatch et al. 2010



Coros et al. 2010



Brown et al. 2013



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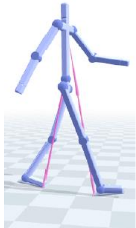
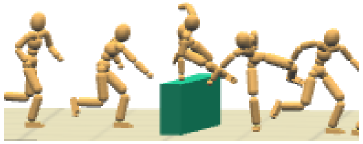
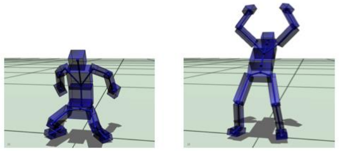


Muico et al. 2009



Liu et al. 2012



Al Borno et al. 2013

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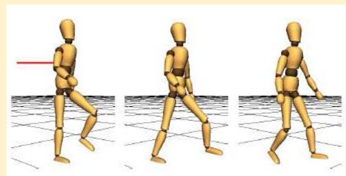
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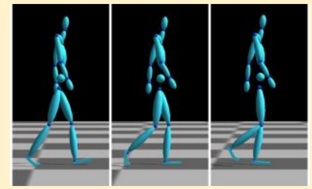
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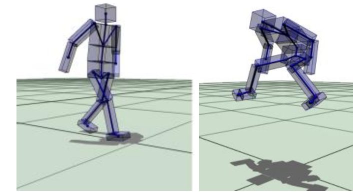
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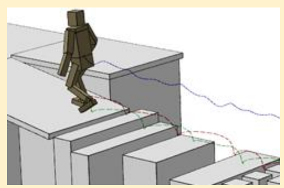
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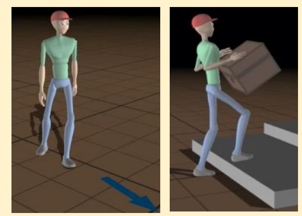
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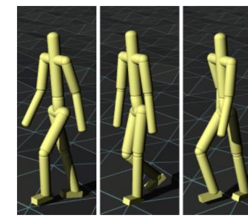
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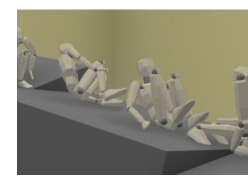
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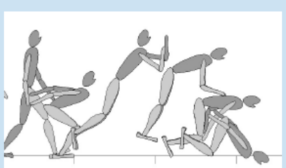
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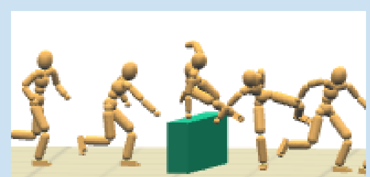
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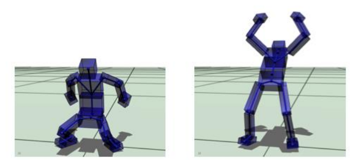
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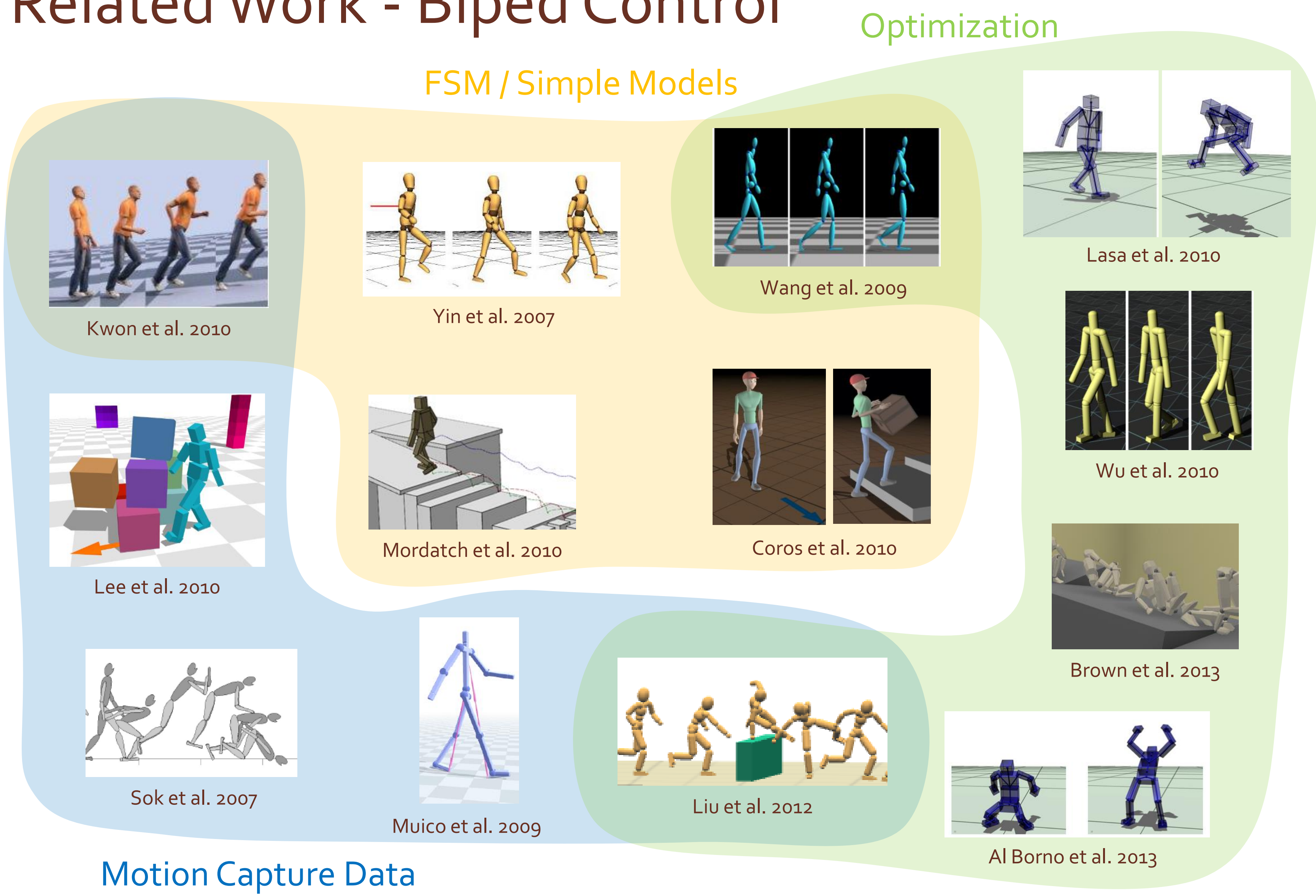
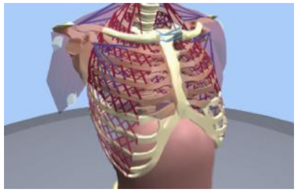
Motion Capture Data

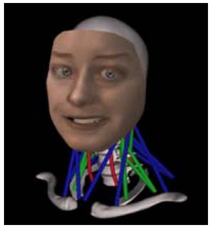
Related Work - Biped Control



Related Work – Musculoskeletal Analysis & Simulation



Zordan et. al. 2004



Lee & Terzopoulos 2006

Sueda et. al. 2008

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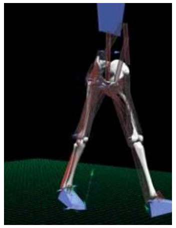
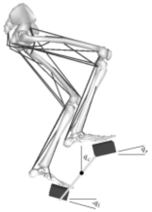
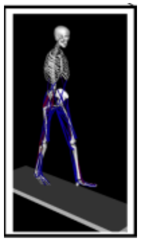


Anderson & Pandy 1999



Thelen et. al. 2003



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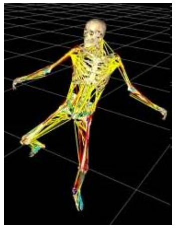
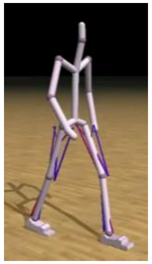


Nakamura et. al. 2004



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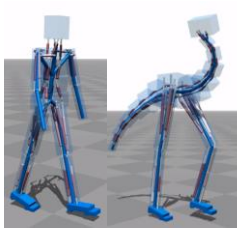

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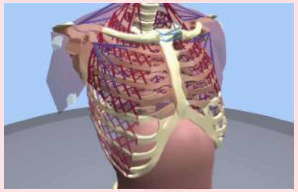
Mordatch et. al. 2013

Related Work – Musculoskeletal Analysis & Simulation

Specific Body Parts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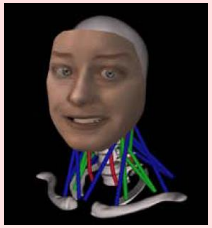
Lee & Terzopoulos 2006


Sueda et. al. 2008


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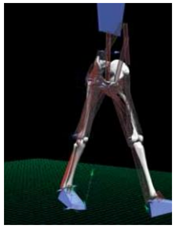
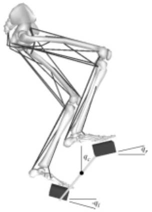

Anderson & Pandy 1999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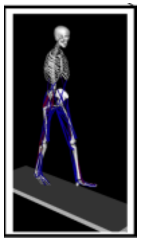
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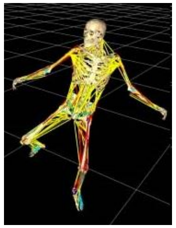
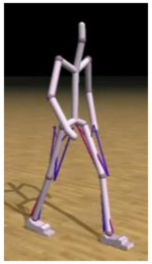
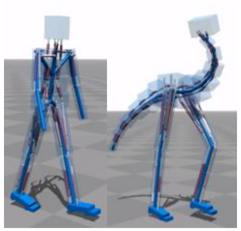

Nakamura et. al. 2004


Wang et. al. 2012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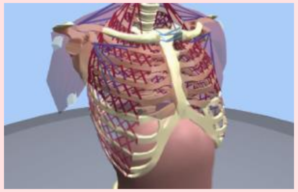
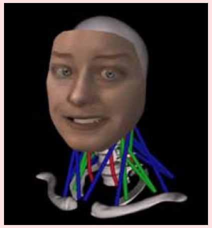
Related Work – Musculoskeletal Analysis & Simulation

Specific Body Parts



Zordan et. al. 2004



Lee & Terzopoulos 2006

Sueda et. al. 2008

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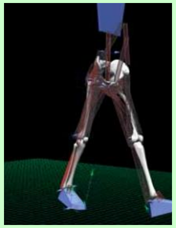
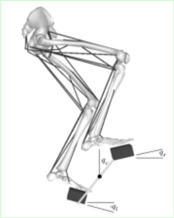
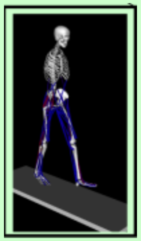
Musculoskeletal Analysis



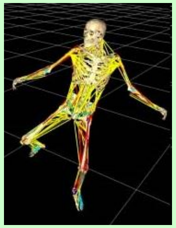
Anderson & Pandy 1999



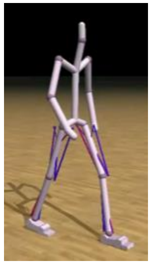
Thelen et. al. 2003



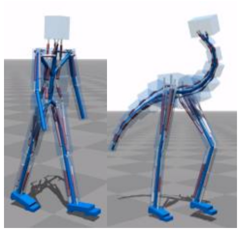
Thelen et. al. 2006



Nakamura et. al. 2004



Wang et. al. 2012



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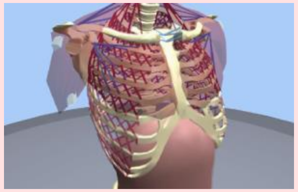
Mordatch et. al. 2013

Related Work – Musculoskeletal Analysis & Simulation

Specific Body Parts



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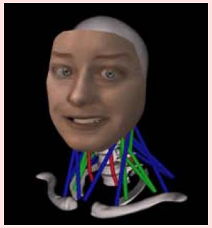

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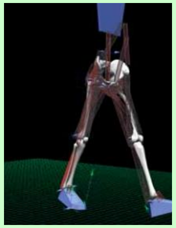

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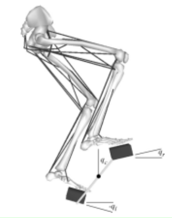

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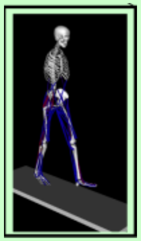

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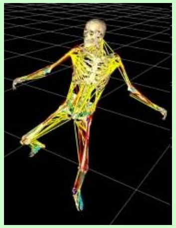
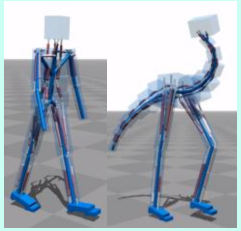


Nakamura et. al. 2004

Locomotion Control & Synthesis

Wang et. al. 2012

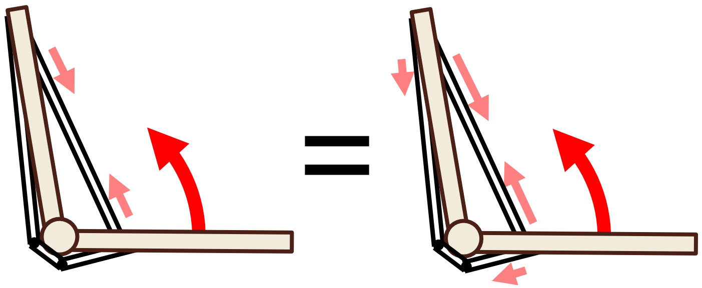


Geijtenbeek et. al. 2013

Mordatch et. al. 2013

Challenges of Many-Muscle Control

- Underdetermined system (muscle redundancy)
  - # muscles > # total DOFs
  - Multiple sets of muscle forces ➡ Same joint torque



- What is best motion for a given situation? (adaptability)
- Complexity of muscle contraction dynamics

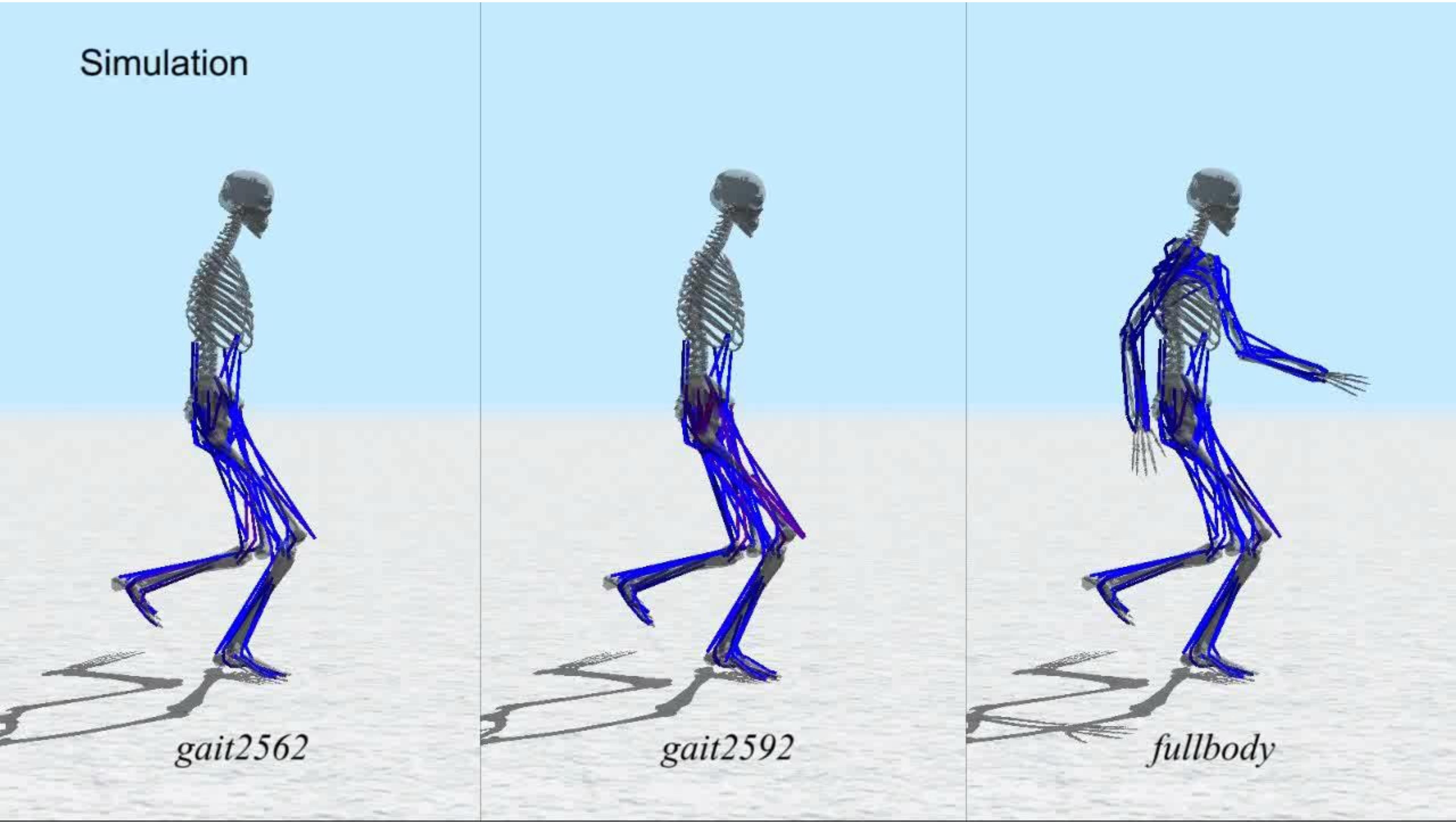
➡ **Integrated controller design**

Our Approach

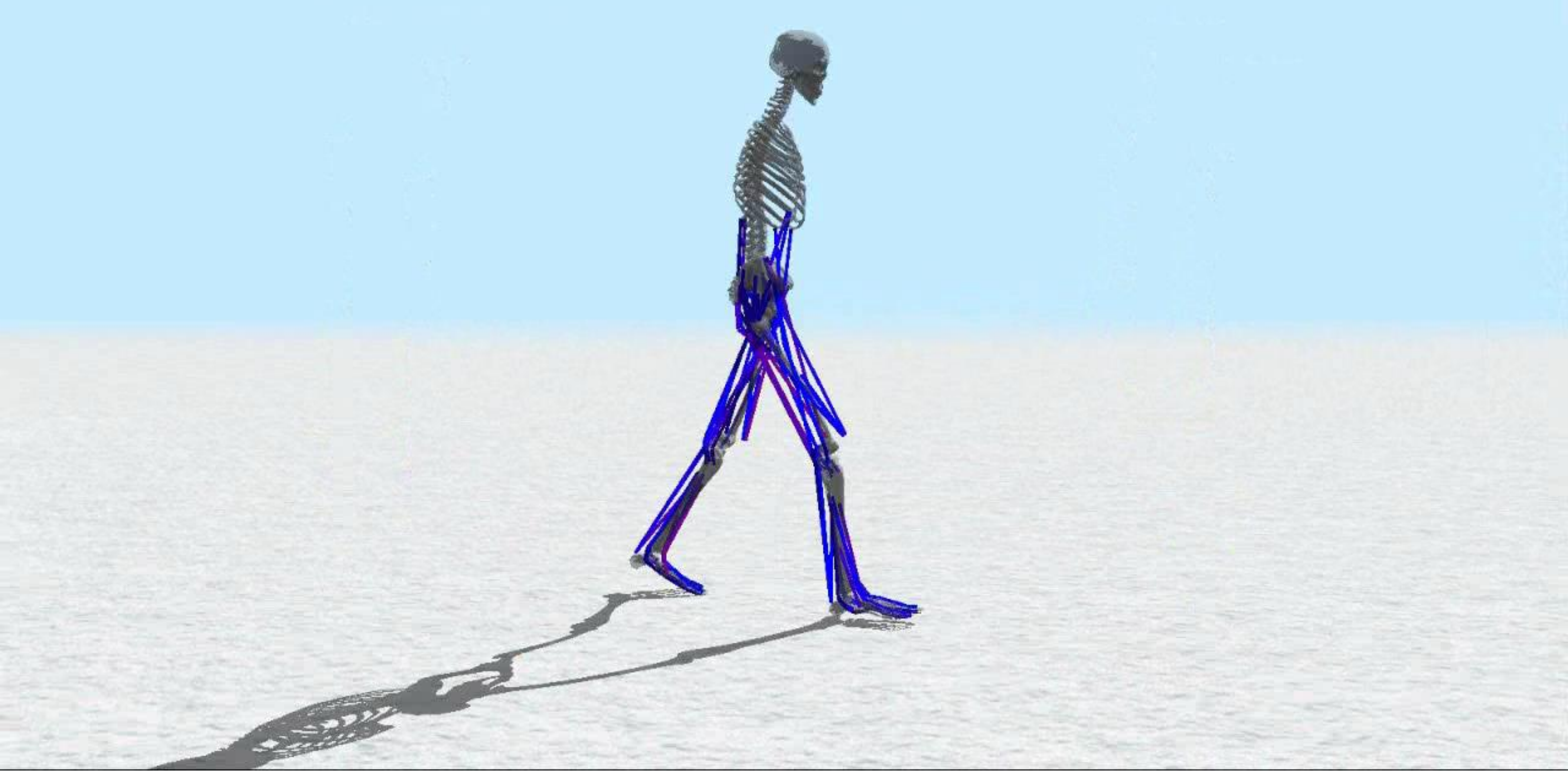
- Find optimal muscle actuation considering nonlinear muscle dynamics
  - **Seamlessly integrating muscle dynamics into QP formulation**
  - ***Muscle optimization***

Our Approach

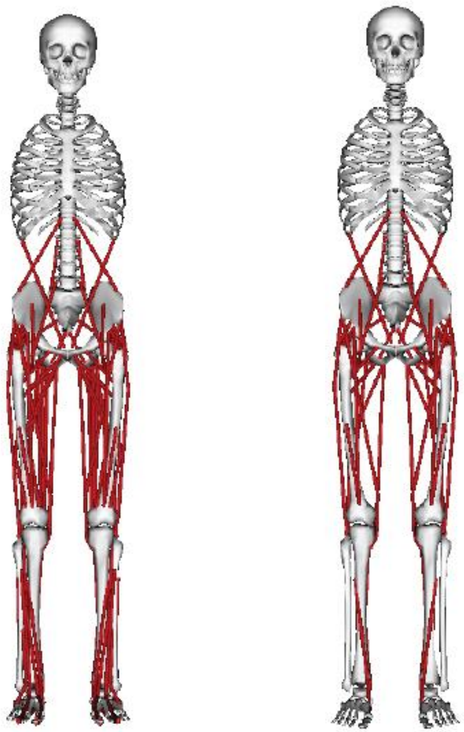
- Gait adaptation under various conditions
  - **Finding best motion for given condition by offline optimization**
  - ***Trajectory optimization***


Simulation
gait2562
gait2592
fullbody

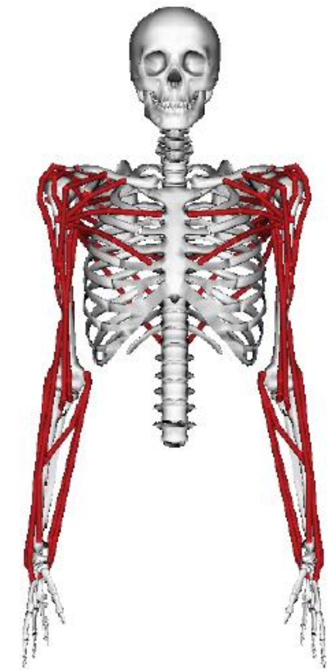
Left Ankle Plantar Flexor Weakness



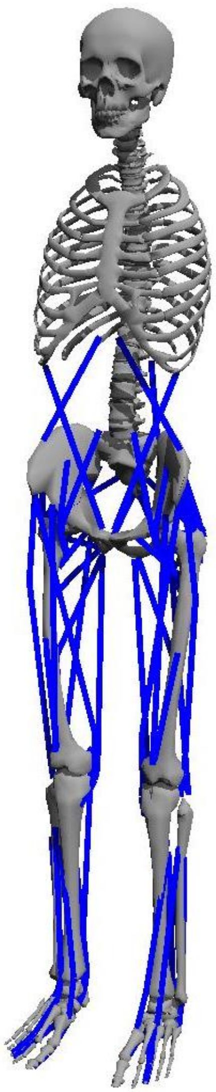
Musculoskeletal Models



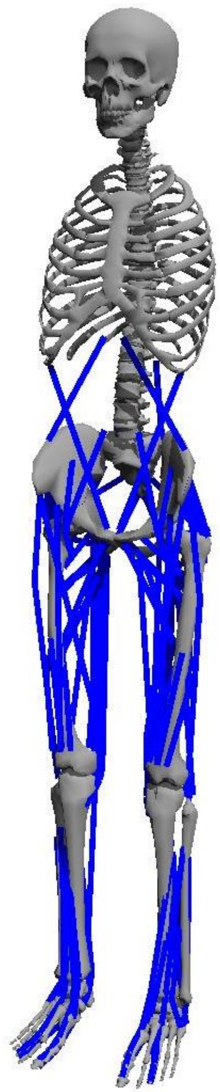
Delp et al. 1990; Anderson and Pandy 1999



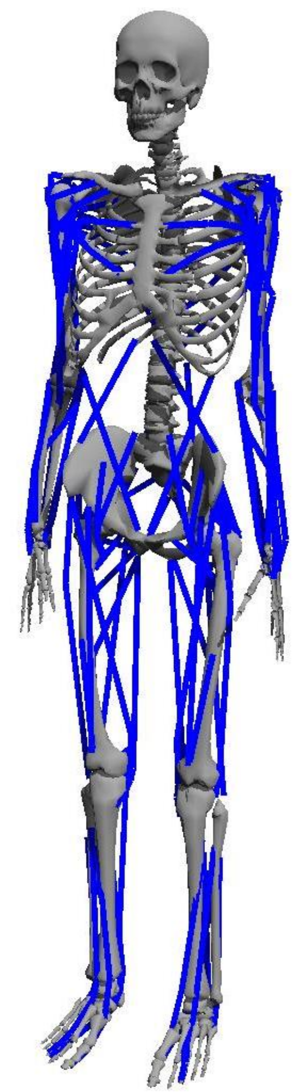
Steele and Hamner 2013



Gait2562
(25 DOFs, 62 muscles)

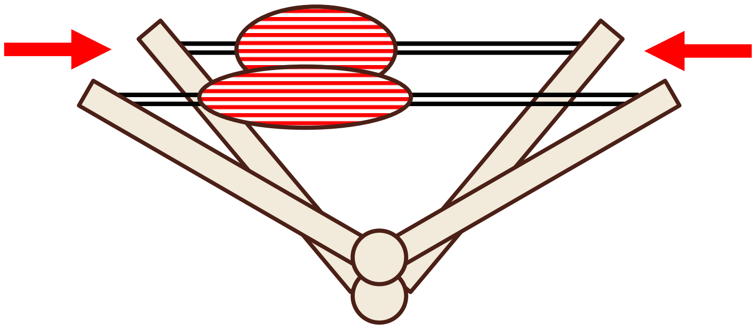


Gait2592
(25 DOFs, 92 muscles)

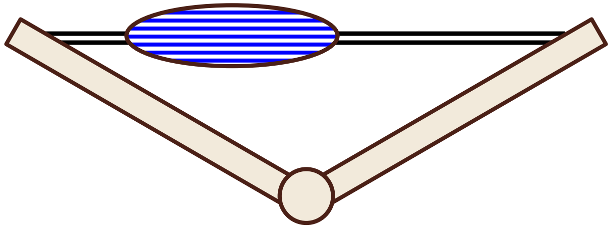


Fullbody
(39 DOFs, 120 muscles)

Muscle Activation

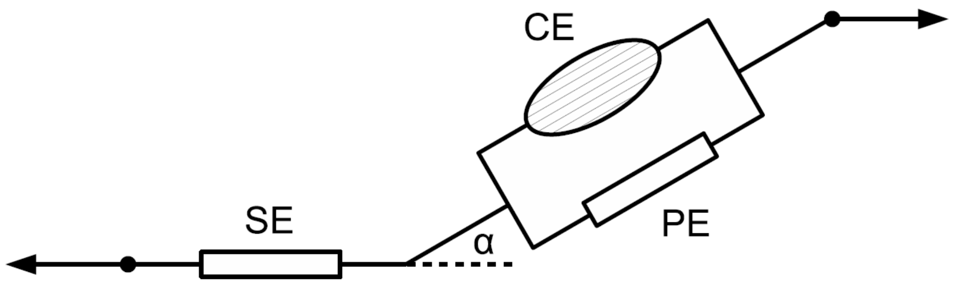


activation=1

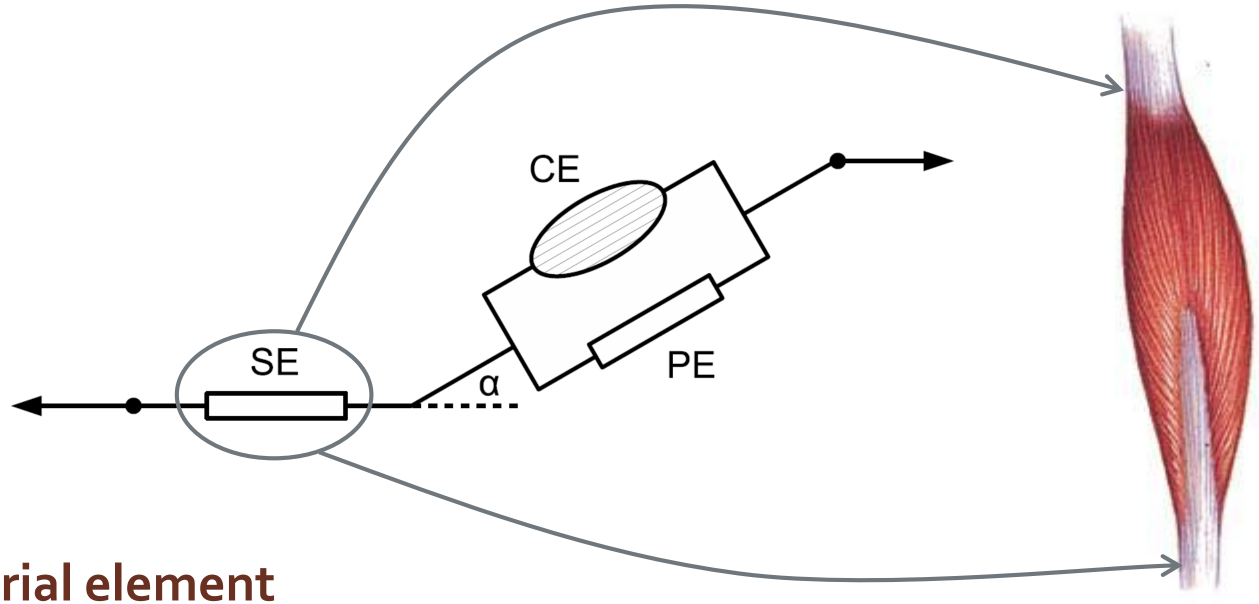


activation=0

Hill-Type Muscle Model

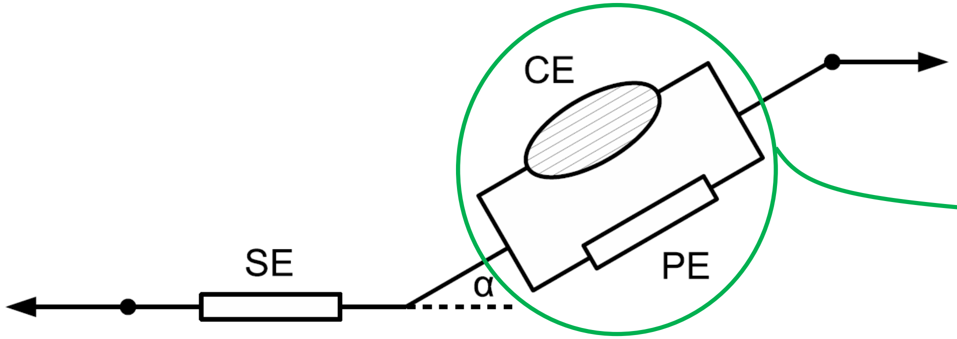


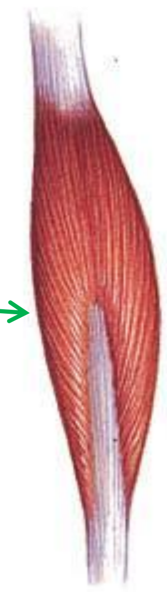
Hill-Type Muscle Model



SE : serial element
CE : contractile element
PE : passive element
α: pennation angle

Hill-Type Muscle Model





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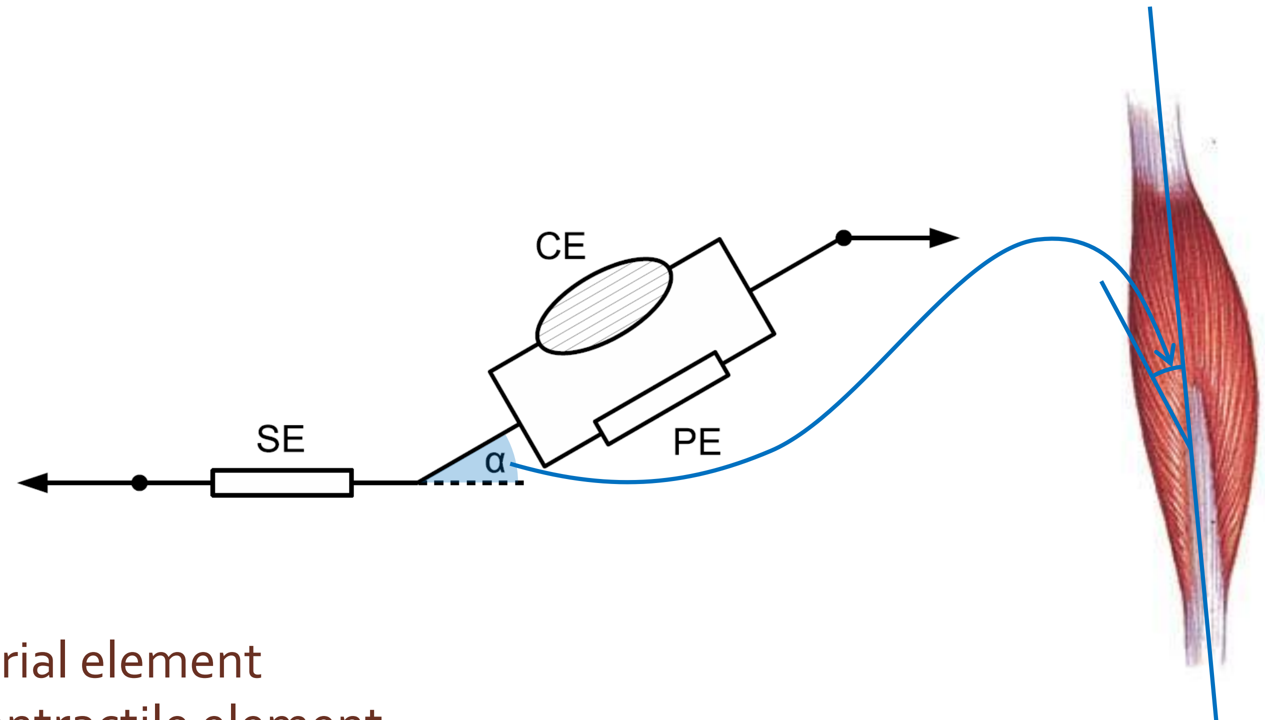
Hill-Type Muscle Model



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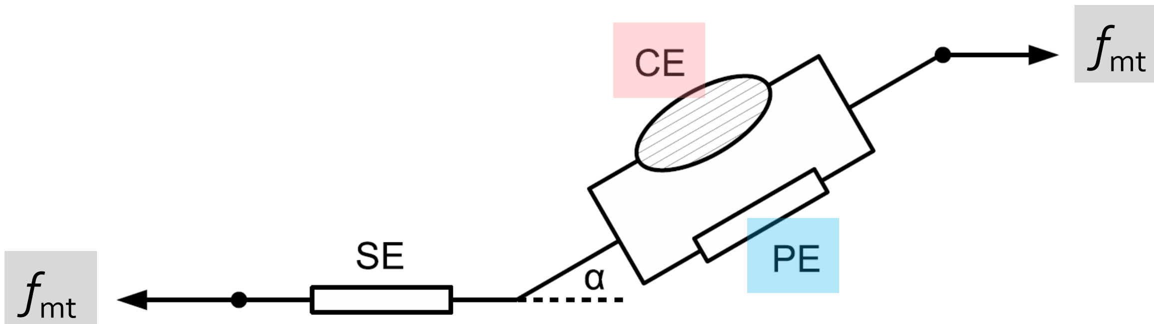
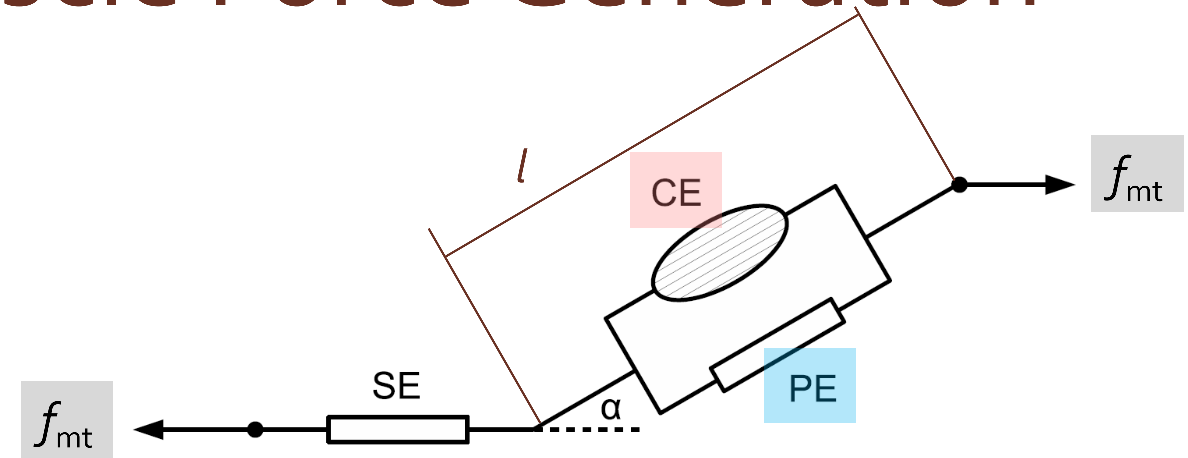
Muscle Force Generation



$$f_{mt} = (f_{ce} + f_{pe})cos(\alpha)$$

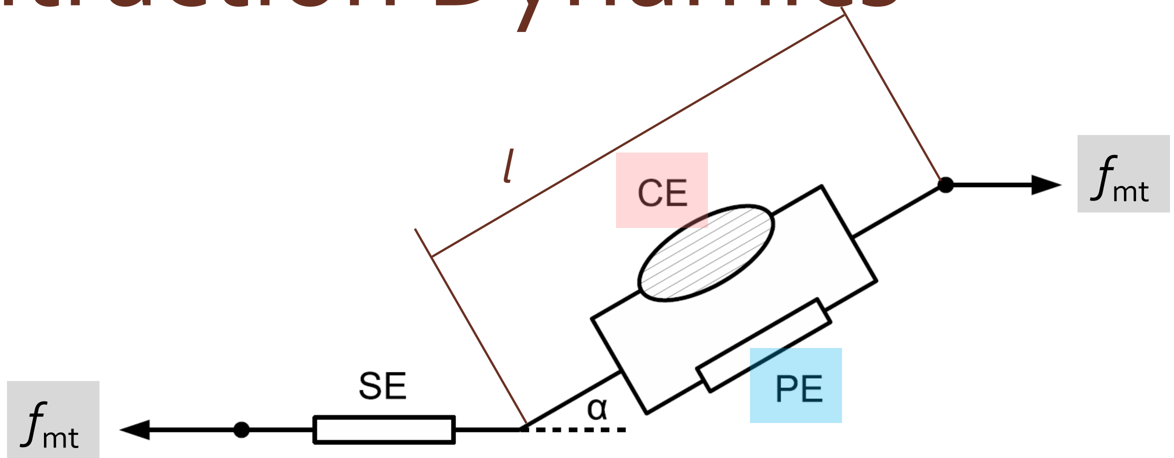
Muscle Force Generation



$$f_{mt} = (f_{ce} + f_{pe})cos(\alpha)$$

$$f_{ce} \rightarrow f(a, l, \dot{l}) \qquad f_{pe} \rightarrow f(l)$$

Contraction Dynamics



$$f_{mt} = (f_{ce} + f_{pe})cos(\alpha)$$

$$f(a, l, \dot{l}) \qquad f(l)$$

$$\dot{l} = f(a, l)$$

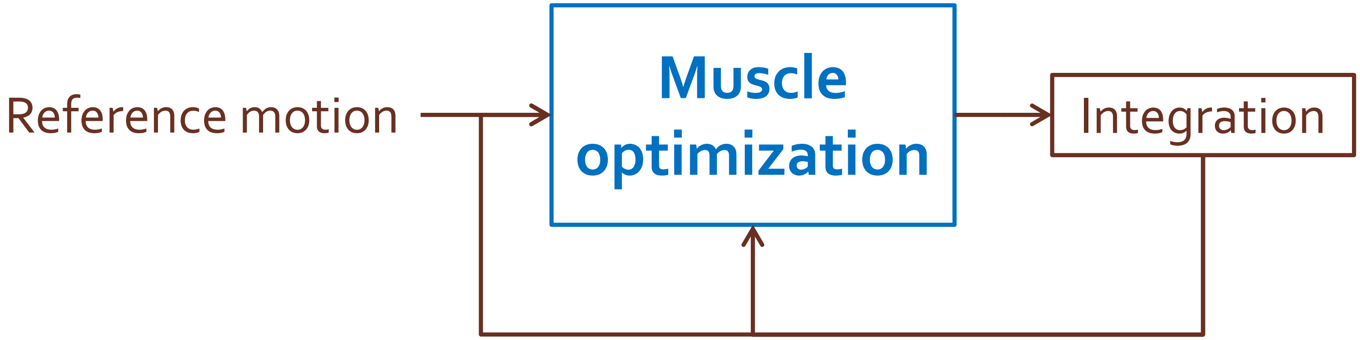
Many-Muscle Control

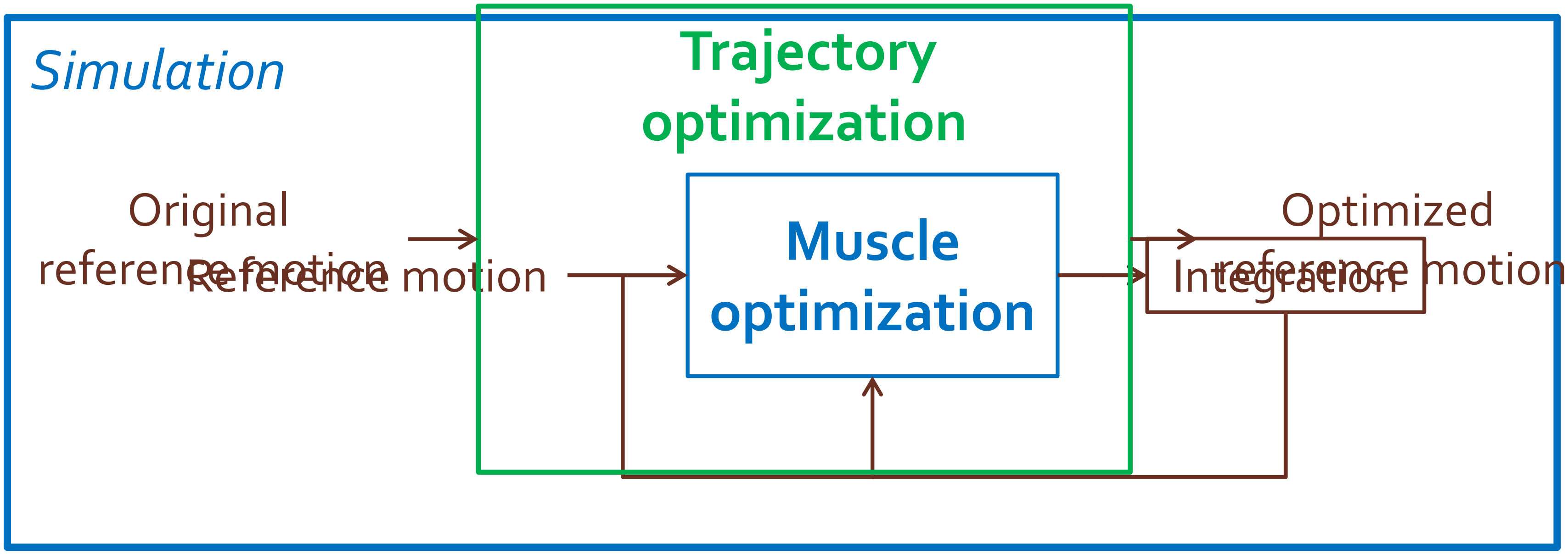
- Muscle optimization
  - Optimal muscle activation under physics laws & muscle dynamics
- Trajectory optimization
  - Modulates reference motion for robustness & adaptability

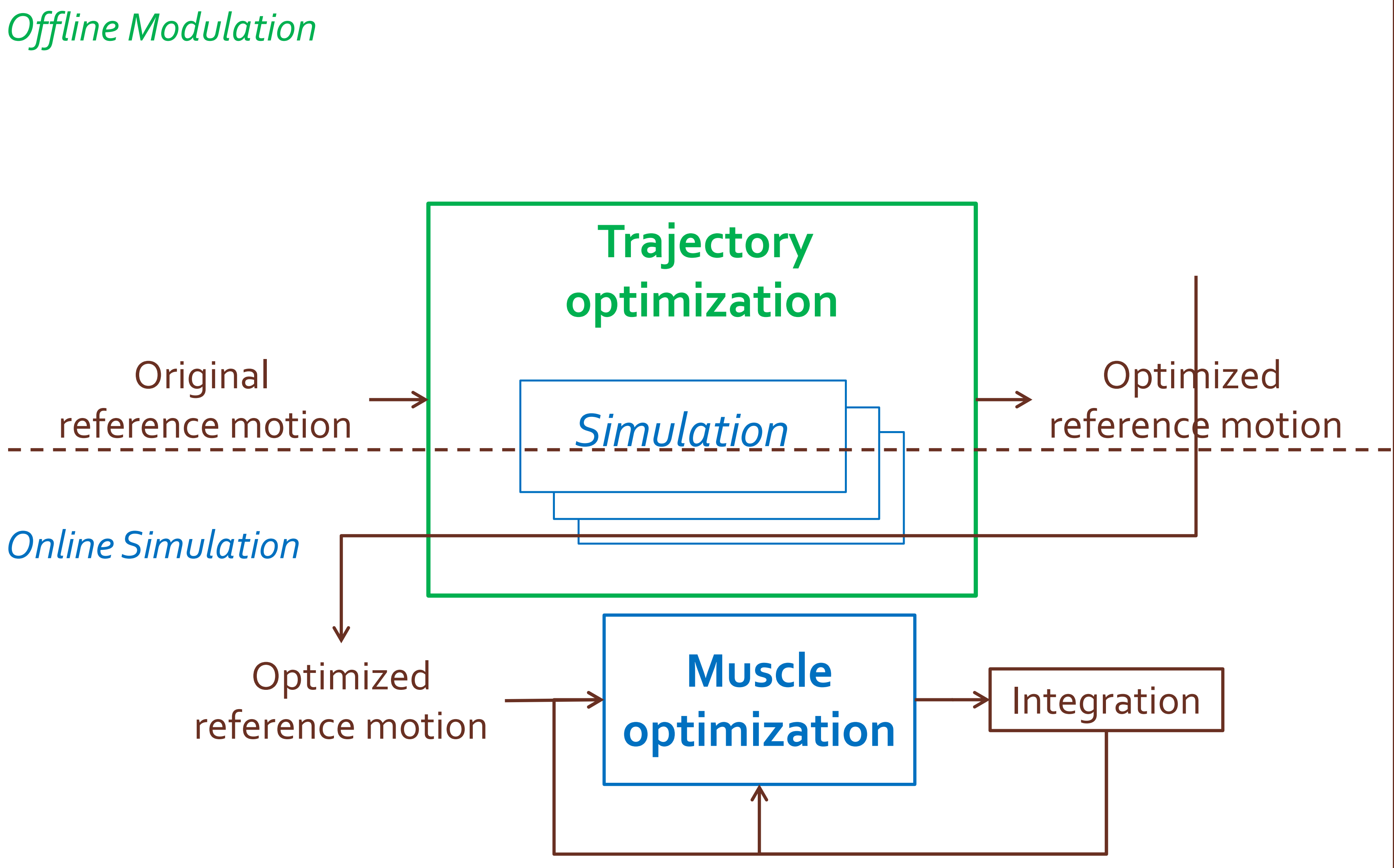
Many-Muscle Control

- Muscle optimization
  - Optimal muscle activation under physics laws & muscle dynamics
  - *Per-frame tracking simulation*
- Trajectory optimization
  - Modulates reference motion for robustness & adaptability
  - *Offline modulation*

Simulation




Simulation
Trajectory optimization
Original reference motion
Reference motion
Muscle optimization
Integration
Optimized reference motion


Offline Modulation
Trajectory optimization
Original reference motion
Simulation
Optimized reference motion
Online Simulation
Optimized reference motion
Muscle optimization
Integration

Muscle Optimization

$\mathbf{a}$ $\ddot{\mathbf{q}}$ $\boldsymbol{\lambda}$

- Finds best (muscle activation, acceleration, contact force) to follow reference motion.

- Muscle activation - resolving muscle redundancy.

- Acceleration & contact force - optimal results under physics laws.

- Reference motion is adjusted by balance strategy by [Kwon & Hodgins 2010].

- Objective

Effort	$\|\mathbf{a}\|^2$	
Contact force	$\|\boldsymbol{\lambda}\|^2$	
Tracking	$\|\ddot{\mathbf{q}}_d - \ddot{\mathbf{q}}\|^2$	
End-Effectors	$\|\ddot{\mathbf{y}}_d^i - \ddot{\mathbf{y}}^i\|^2$	$i \in \{\text{left foot, right foot, torso}\}$

- Objective

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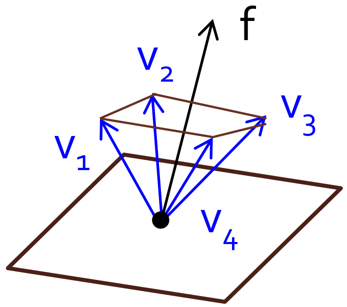
- Inequality Constraints

$$\boldsymbol{f} = \lambda_1 \boldsymbol{v_1} + \lambda_2 \boldsymbol{v_2} + \lambda_3 \boldsymbol{v_3} + \lambda_4 \boldsymbol{v_4}$$

Friction cone	$\boldsymbol{\lambda} \geq \mathbf{0}$
Non-penetration	$\mathbf{C}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{d}(\mathbf{q}, \dot{\mathbf{q}}) \geq \mathbf{0}$
Muscle activation	$\mathbf{0} \leq \mathbf{a} \leq \mathbf{1}$



Equality Constraint - Equation of Motion

$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) =$ (muscle force) + (contact force)

Equality Constraint - Equation of Motion

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) = \text{(muscle force)} + \text{(contact force)}$$

$$\vdots$$

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{G}(\mathbf{q}, \mathbf{l})(\mathbf{A}(\mathbf{l}, \dot{\mathbf{l}})\mathbf{a} + \mathbf{p}(\mathbf{l}, \dot{\mathbf{l}})) + \mathbf{H}(\mathbf{q})\boldsymbol{\lambda}$$

Quadratic Programming

$$\underset{\ddot{\mathbf{q}},\mathbf{a},\boldsymbol{\lambda}}{\text{minimize}} \quad w_1\|\mathbf{a}\|^2 + w_2\|\boldsymbol{\lambda}\|^2 + w_3\|\ddot{\mathbf{q}}_d - \ddot{\mathbf{q}}\|^2 + \sum_i w_4^i\|\ddot{\mathbf{y}}_d^i - \ddot{\mathbf{y}}^i\|^2$$

$$\text{subject to} \quad \mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{c}(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{G}(\mathbf{q},\mathbf{l})(\mathbf{A}(\mathbf{l},\dot{\mathbf{l}})\mathbf{a} + \mathbf{p}(\mathbf{l},\dot{\mathbf{l}})) + \mathbf{H}(\mathbf{q})\boldsymbol{\lambda}$$

$$\boldsymbol{\lambda} \geq \mathbf{0}$$

$$\mathbf{C}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{d}(\mathbf{q},\dot{\mathbf{q}}) \geq \mathbf{0}$$

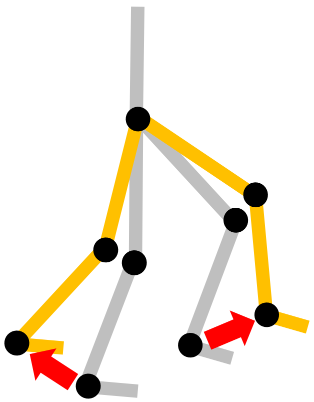
$$\mathbf{0} \leq \mathbf{a} \leq \mathbf{1}$$

Trajectory Optimization

- Modulates reference motion to
  - Reproduce original reference motion more accurately and robustly
  - Adapt to new conditions and requirements

Trajectory Optimization

- Optimize foot trajectories only
  - Most essential components of fullbody gaits
  - Step locations is a key factor for balance
  - Represented by



× 3 key frames

Trajectory Optimization

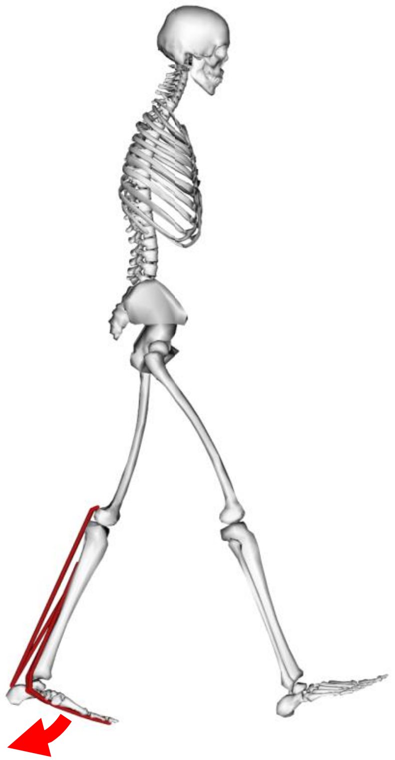
- Objective
  - Pose difference
  - Falling down
  - Efficiency (consumed energy / move distance)
  - Contact force
  - Muscle force

- Covariance Matrix Adaptation

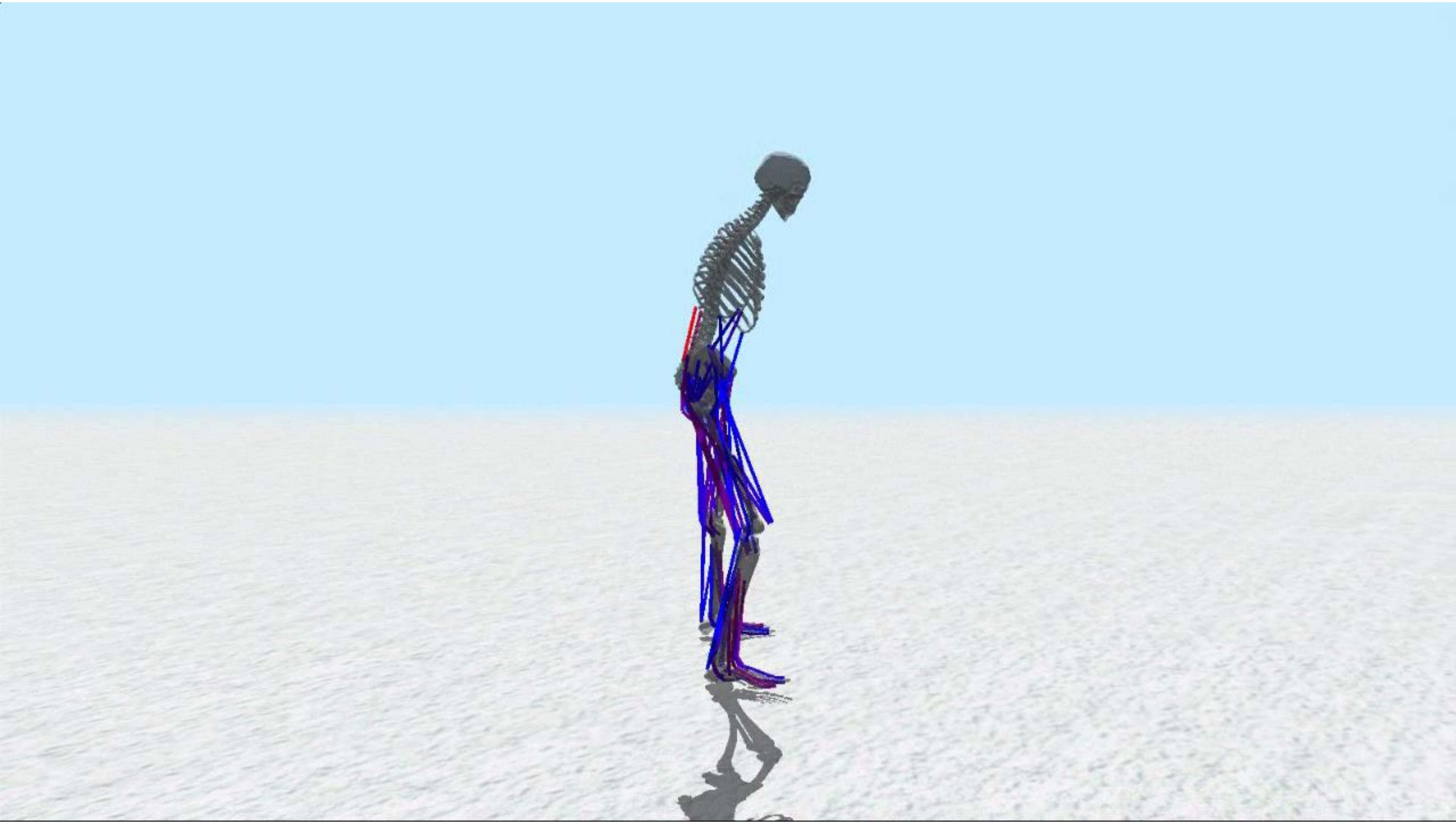
Motion Capture Reference

in-place slow run

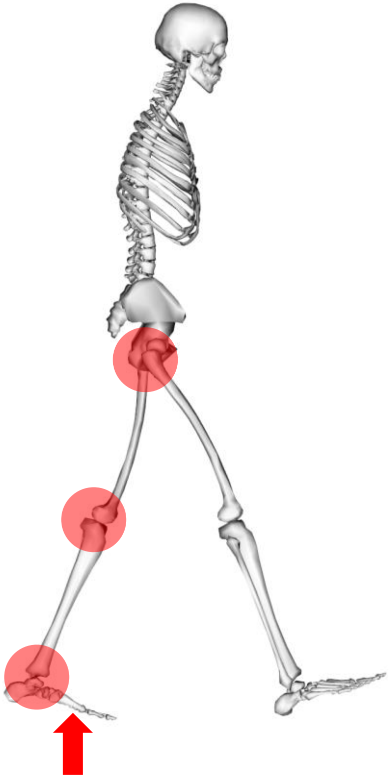
Unilateral Painful Ankle Plantar Flexor



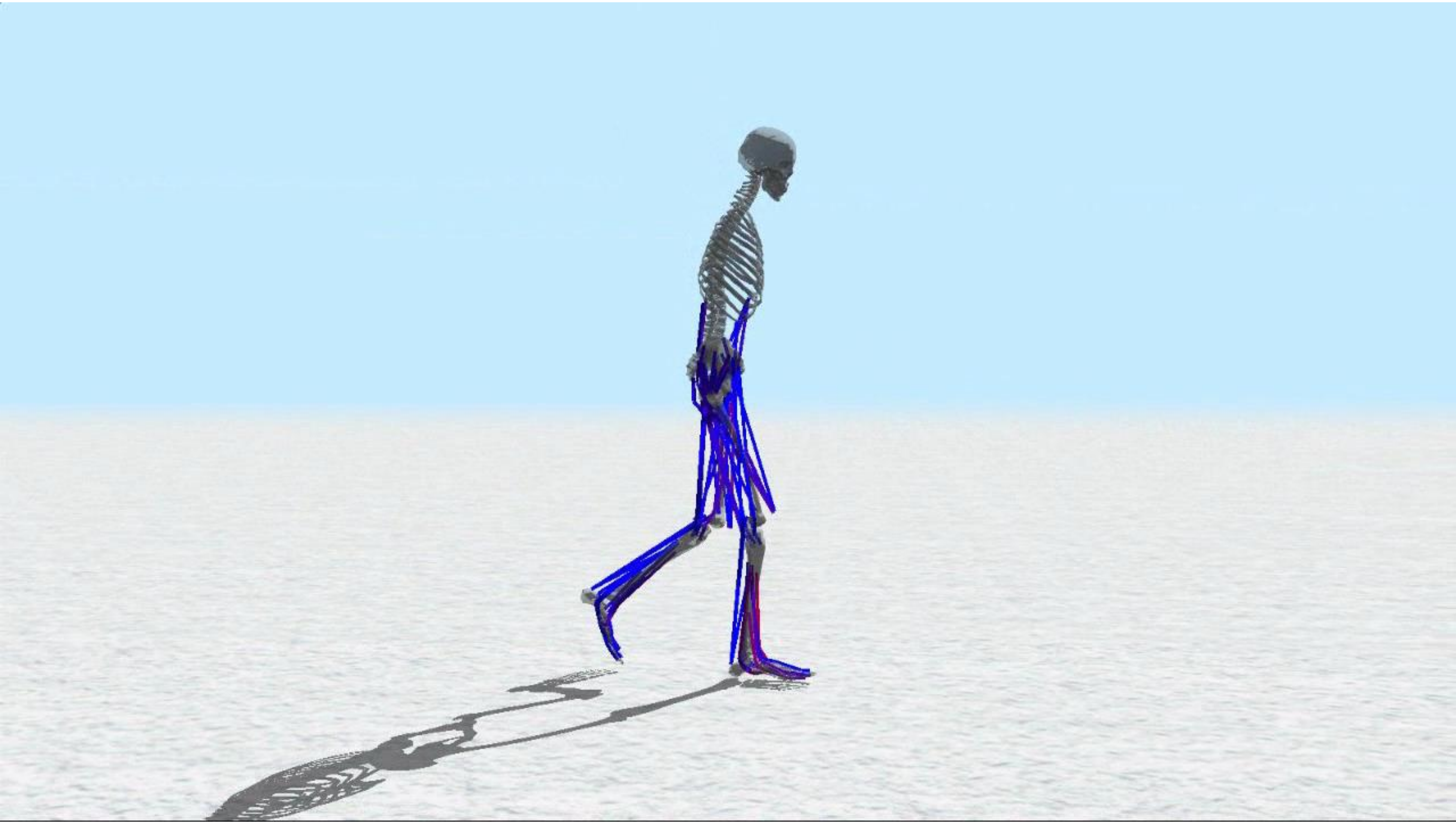
- People tend to reduce the use of the ankle plantar flexor.
- Minimizing muscle force of left ankle plantar flexor



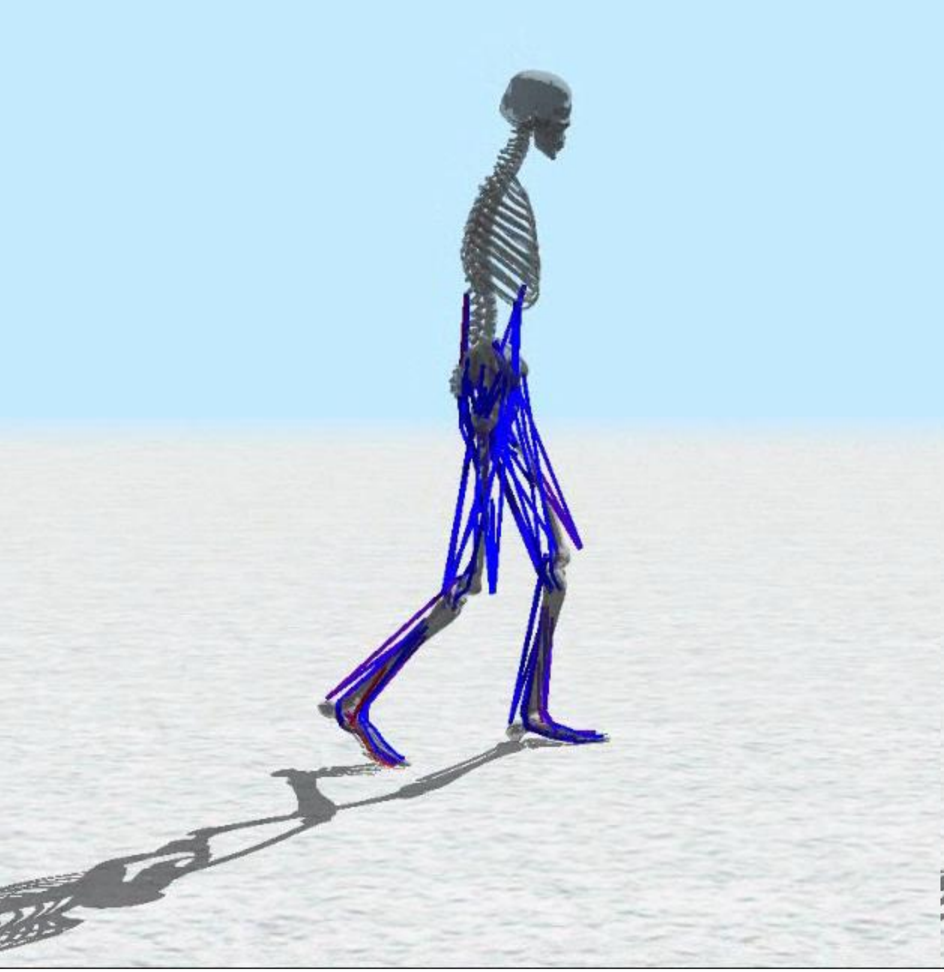
Painful Joints on Unilateral Limb



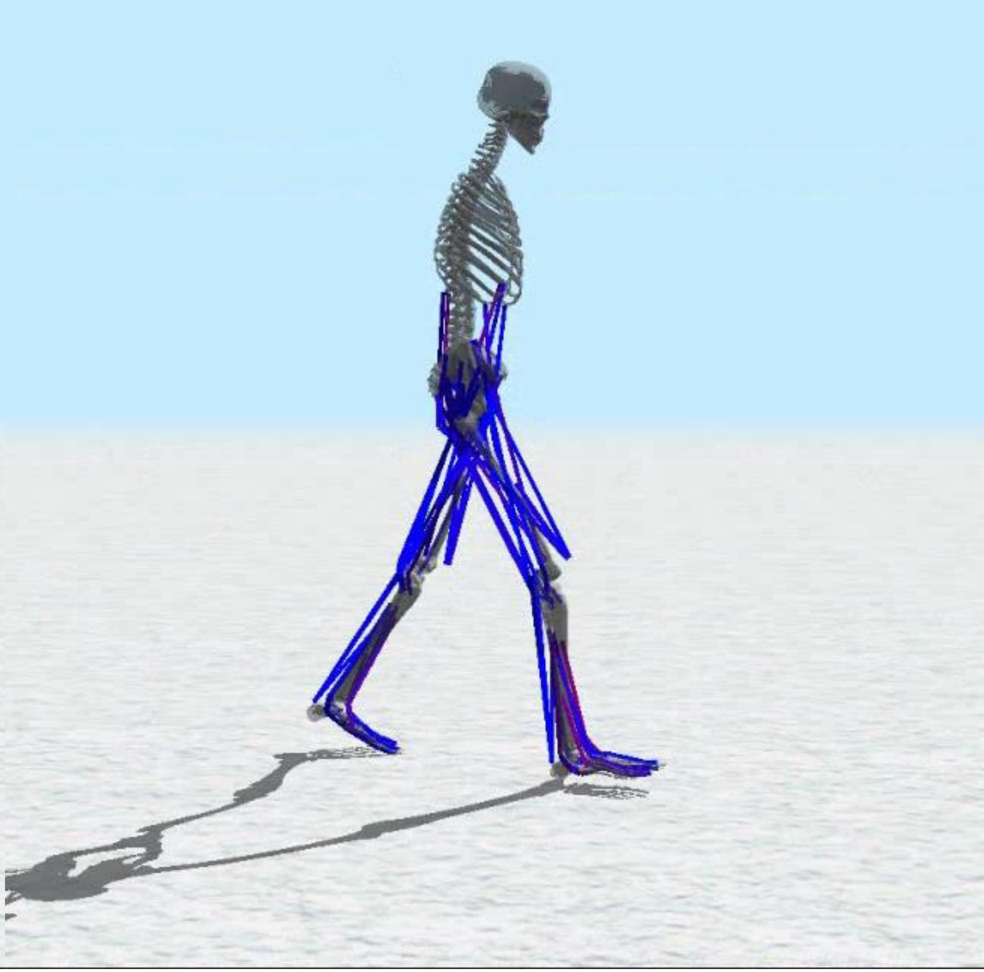
- People tend to reduce contact force of the limb.
- Minimizing contact force of left limb



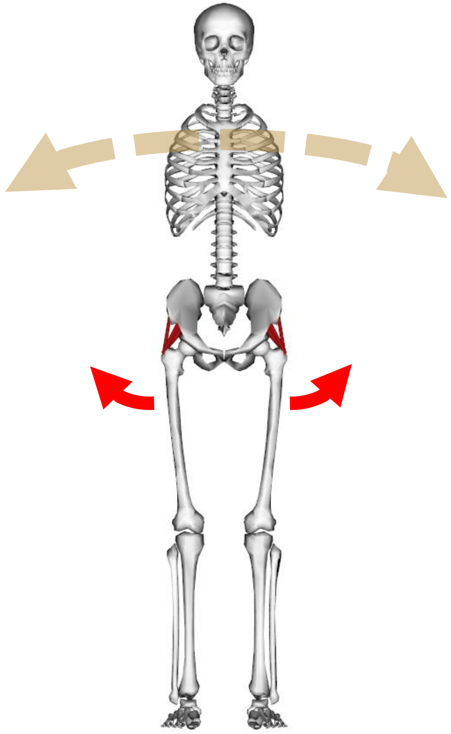
Painful Left Ankle Plantar Flexor



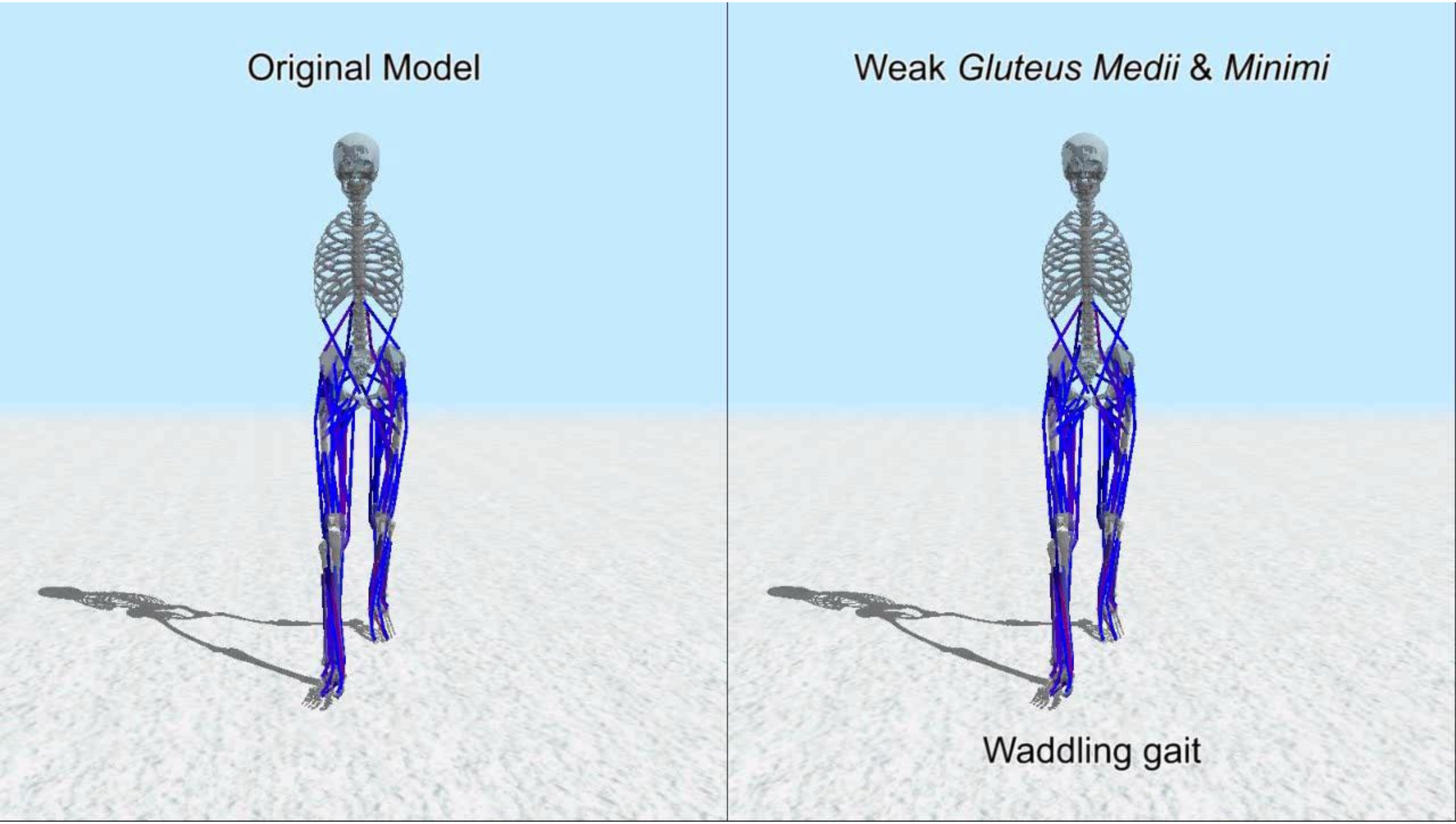
Painful Joints on Left Leg



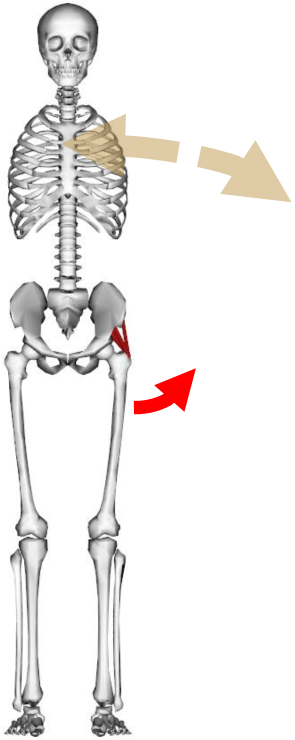
Bilateral *Gluteus Medius* & *Minimus* Weakness



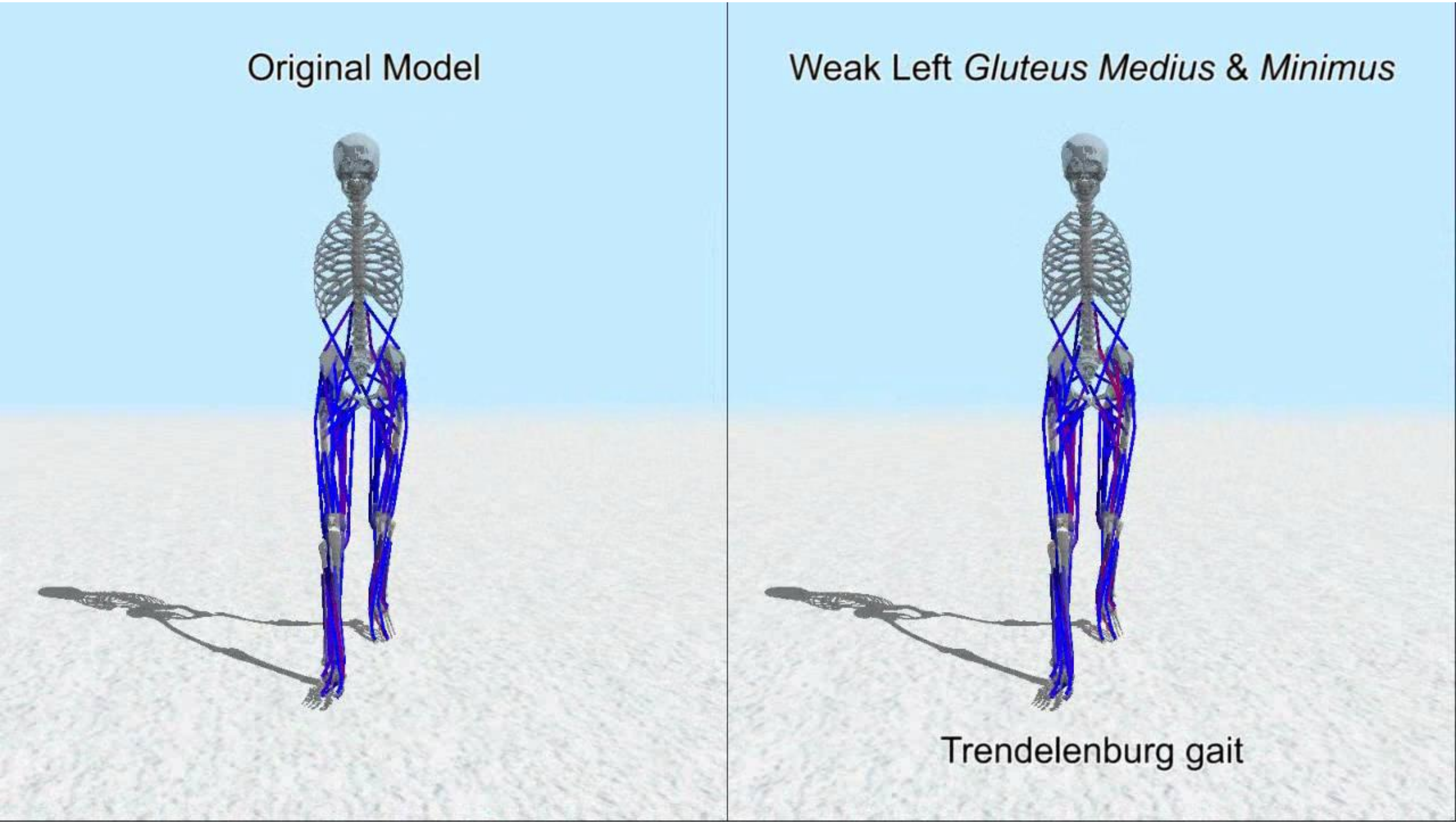
- *Waddling gait* is observed for these people.
- Scaling maximum isometric force by 0.4


Original Model
Weak Gluteus Medii & Minimi
Waddling gait

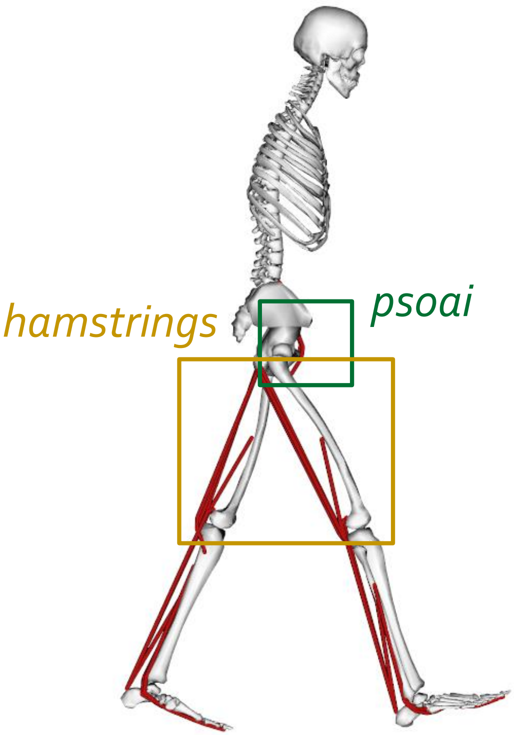
Unilateral *Gluteus Medius* & *Minimus* Weakness



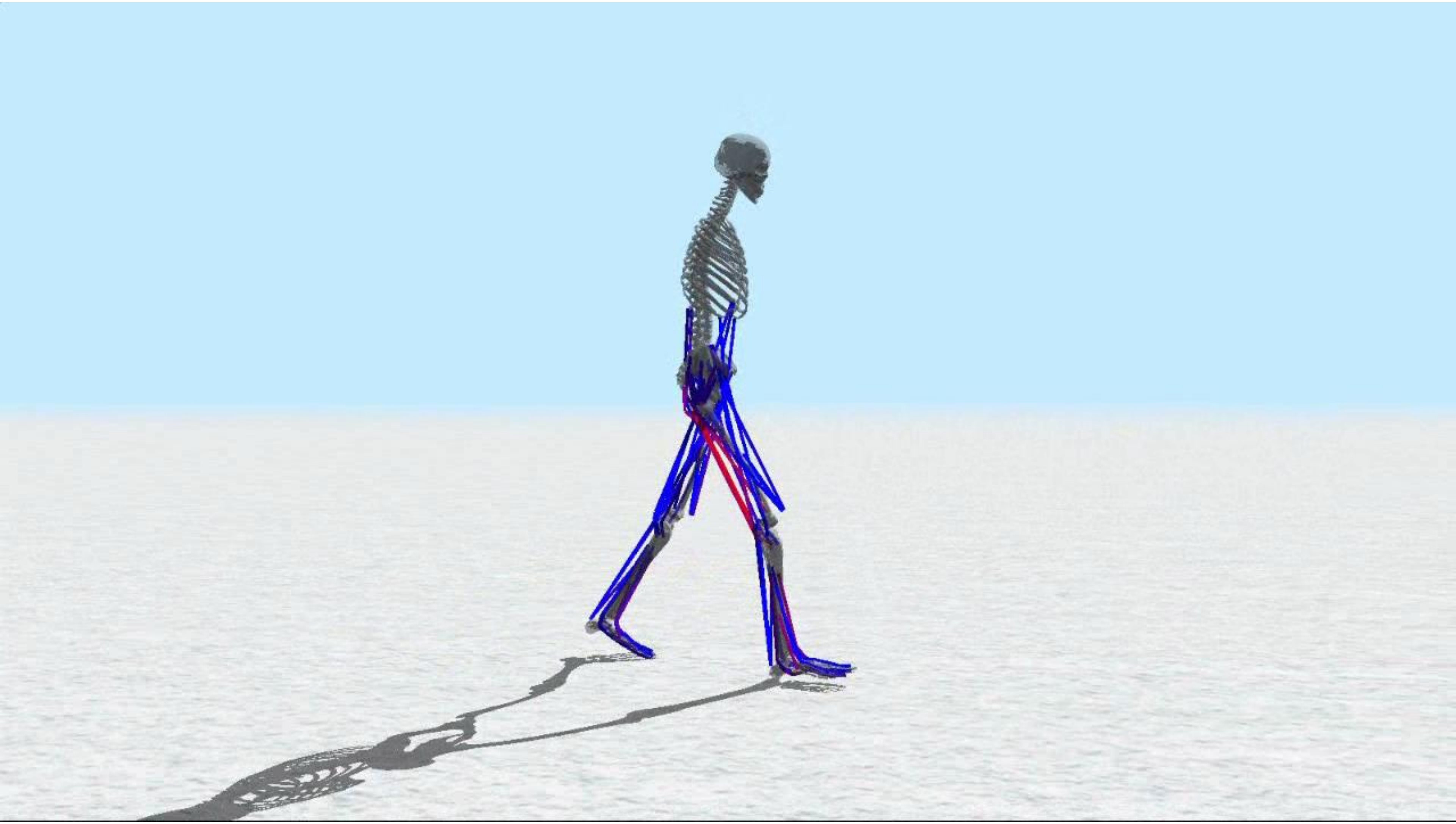
- *Trendelenburg gait* is observed for these people.
- Scaling maximum isometric force by 0.2


Original Model
Weak Left *Gluteus Medius* & *Minimus*
Trendelenburg gait

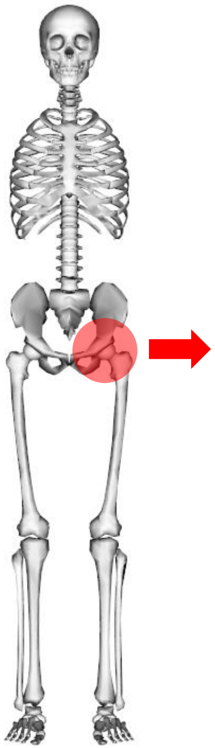
Hamstrings, *Psoai* Tightness & Ankle Plantar Flexors Weakness



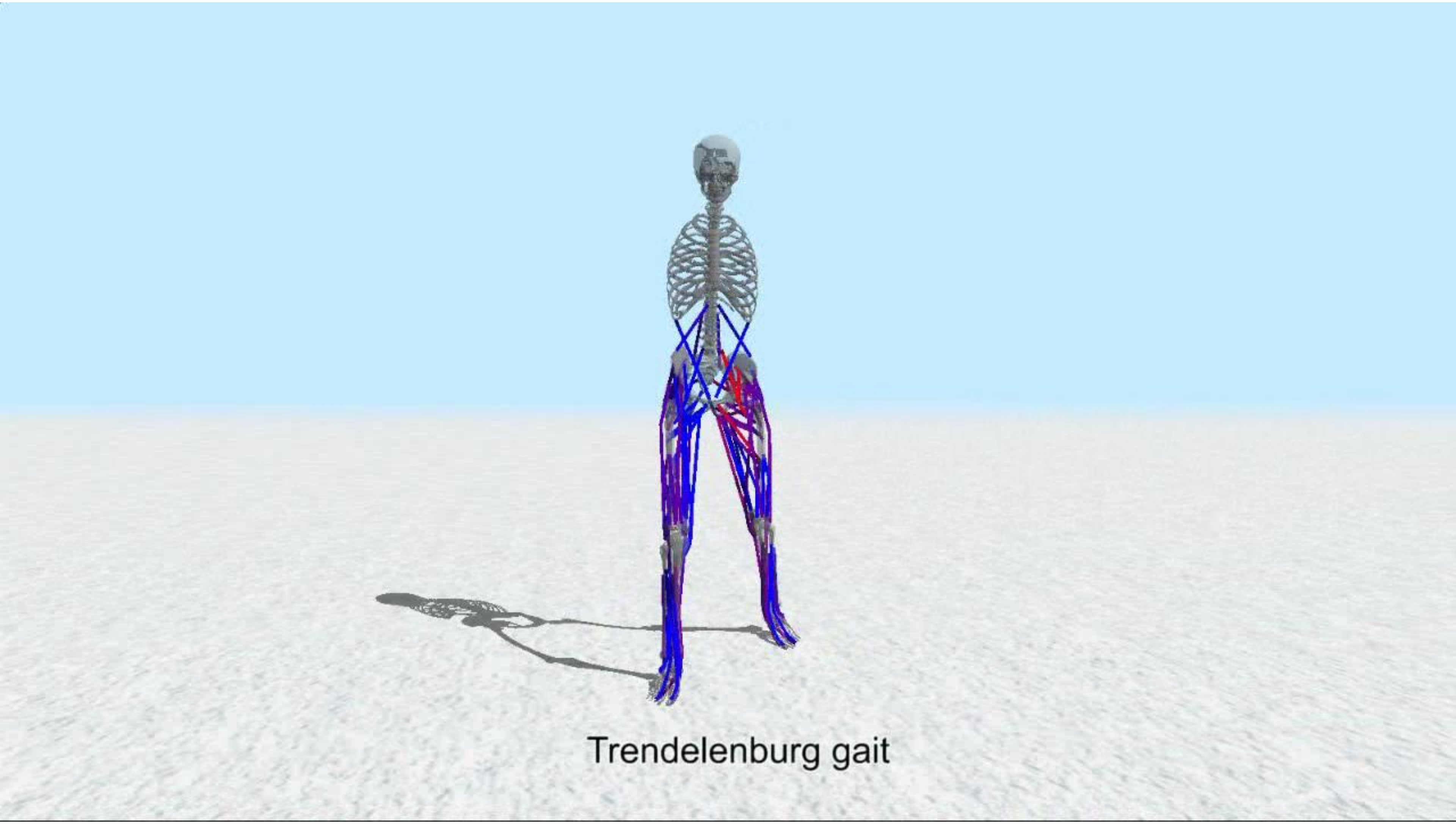
- Most common reason for *Crouch gait*
- Scaling tendon slack length & maximum isometric force
  - by 0.8 (tightness) & by 0.2 (weakness), respectively

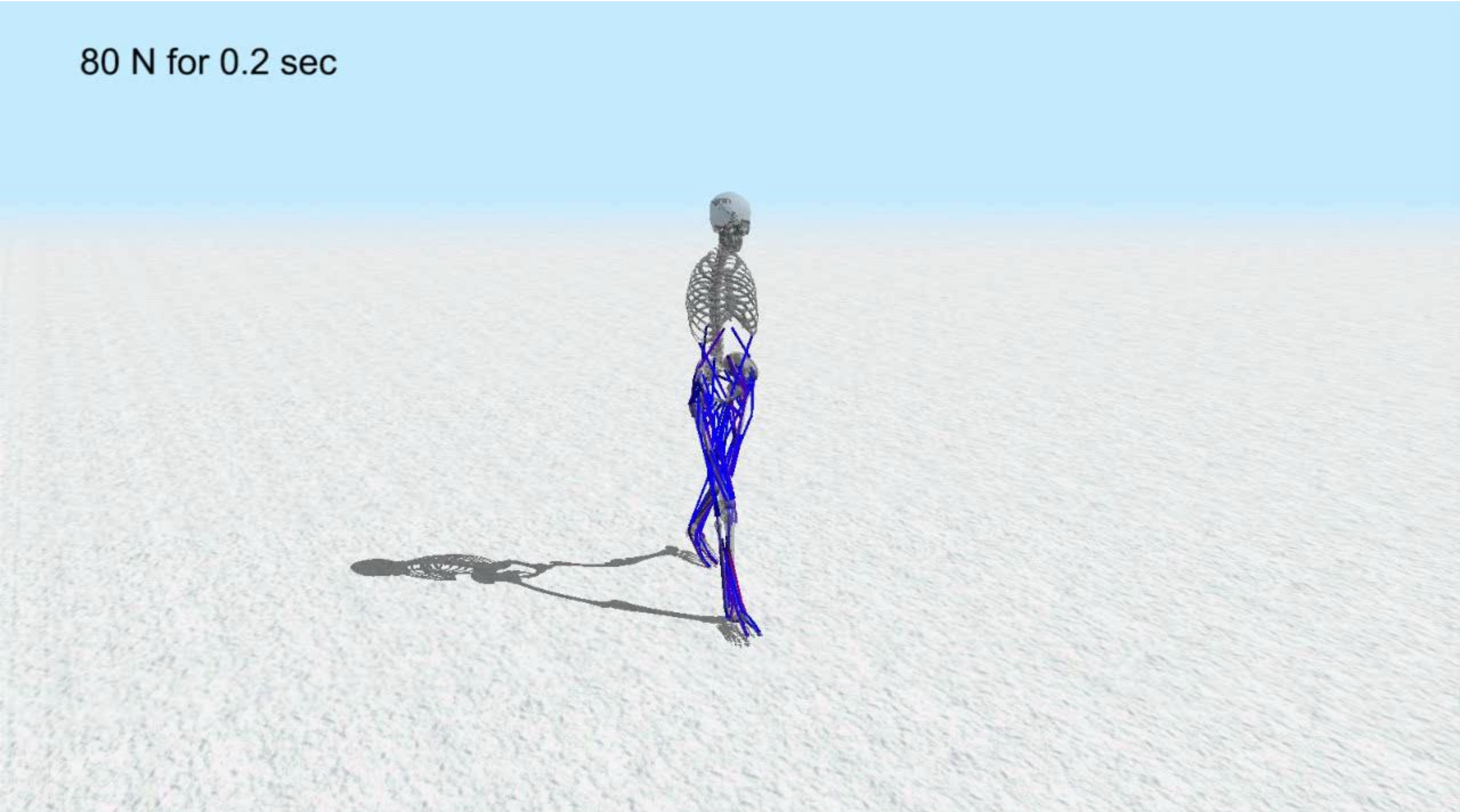


Unilateral Dislocation of Hip

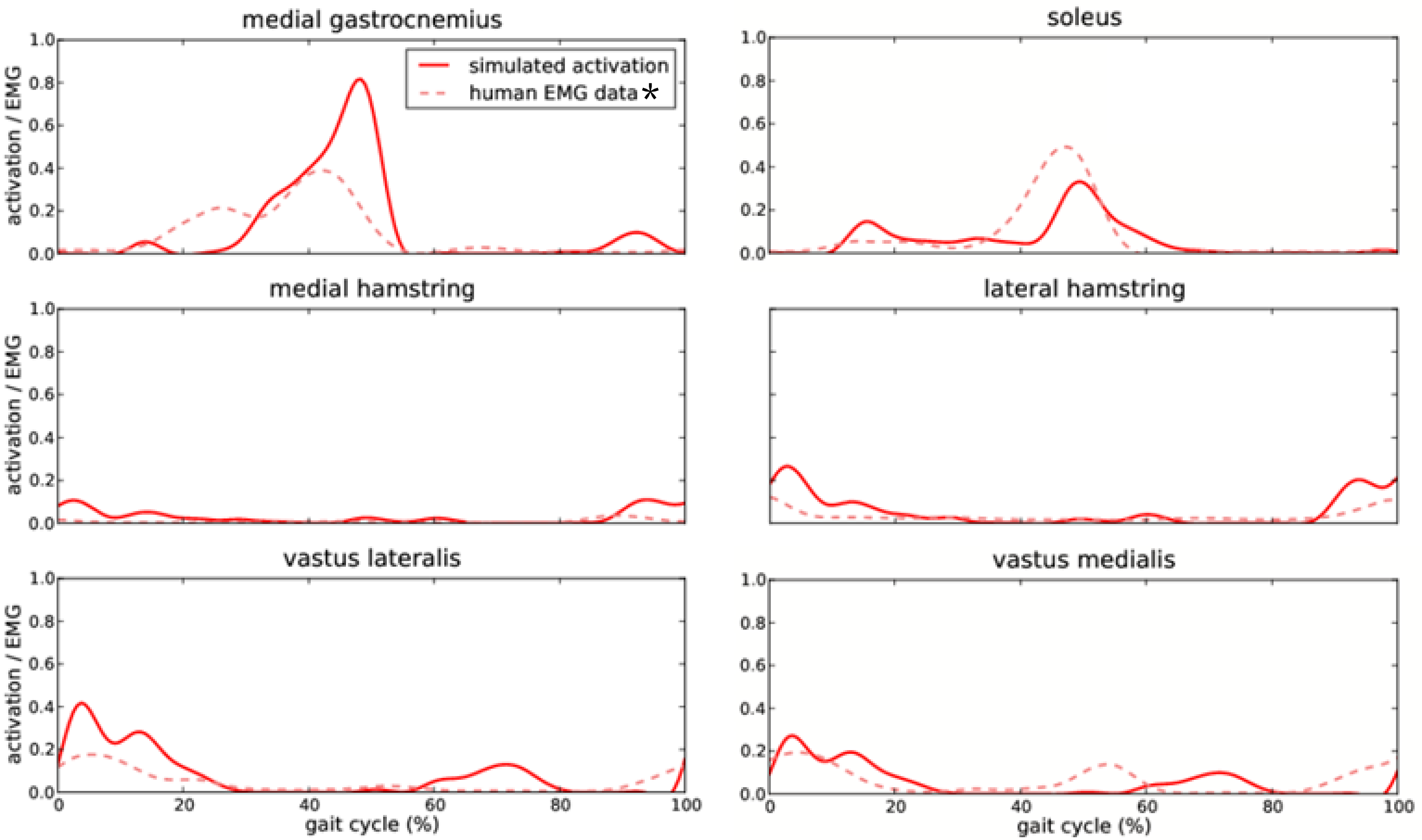


- *Trendelenburg gait* is observed for these people.
- Moving left hip joint 3 cm in the lateral direction


Trendelenburg gait


80 N for 0.2 sec

Comparison with EMG data



*Reported by Demircan et al. [2009]

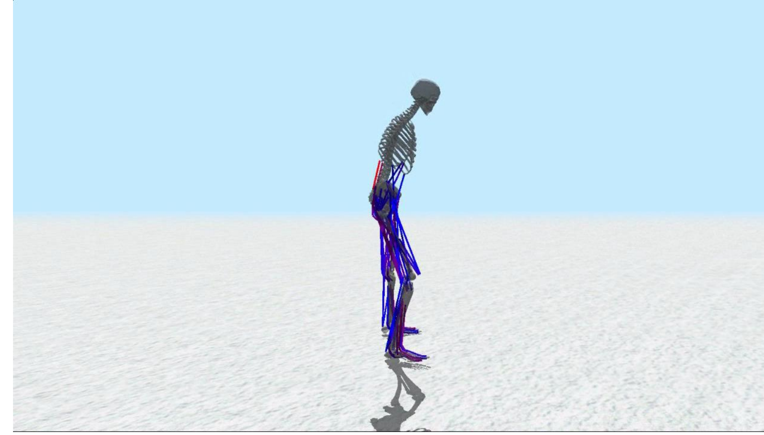
Discussion

- First locomotion controller for “many-muscle” humanoids developed for clinical purpose.
- Shows details of humanoids to reproduce various pathologic gait patterns
- Virtual surgical planning

Acknowledgements

- Thanks to anonymous reviewers

- Funding
  - National Research Foundation of Korea (NRF) No.2011-0018340 , No. 2007-0056094.



Locomotion Control for Many-Muscle Humanoids

Yoonsang Lee Moon Seok Park Taesoo Kwon Jehee Lee