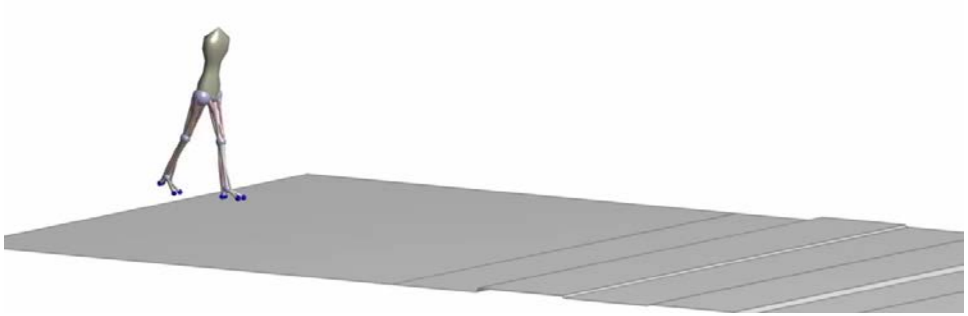
A Neuromuscular Model of Human Locomotion and its Applications to Robotic Devices

The 10th Workshop on Humanoid Soccer Robots
at 15th IEEE-RAS International Conference on Humanoid Robots
Nov 3, 2015



Seungmoon Song
Robotics Institute
Carnegie Mellon University
smsong@cs.cmu.edu
http://www.cs.cmu.edu/~smsong

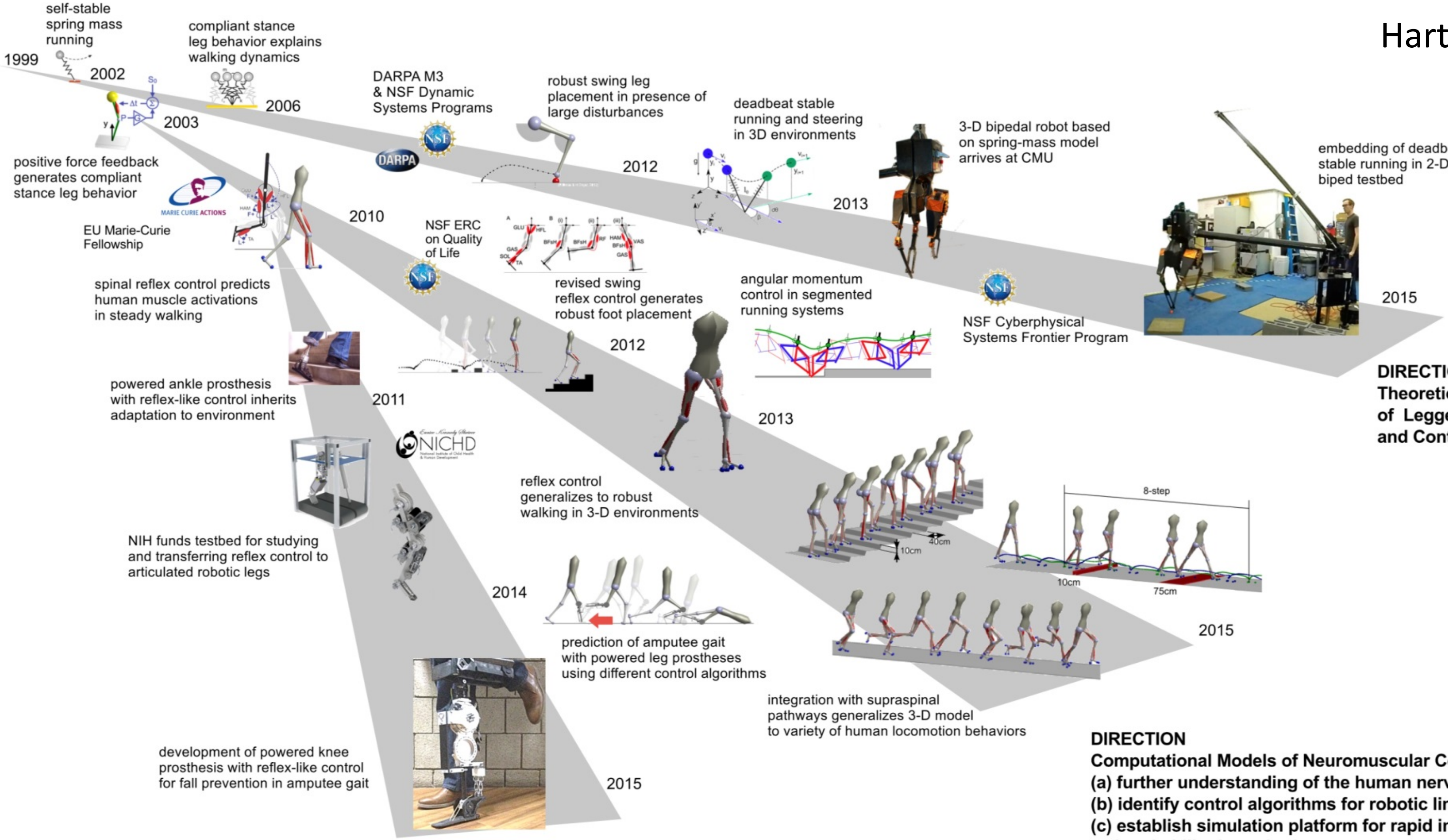
W911NR-11-1-0098 **EEC 0540865** **1R01HD075492**

How does human walk?

S Song, Y Ryoo, and D Hong, Development of an omnidirectional walking engine for full-sized lightweight humanoid robots, *ASME IDETC*, 2011.

Geyer Group

Hartmut Geyer



1999

self-stable spring mass running

2002

positive force feedback generates compliant stance leg behavior

2003

compliant stance leg behavior explains walking dynamics

2006

DARPA M3 & NSF Dynamic Systems Programs

robust swing leg placement in presence of large disturbances

2012

deadbeat stable running and steering in 3D environments

2013

3-D bipedal robot based on spring-mass model arrives at CMU

NSF Cyberphysical Systems Frontier Program

embedding of deadbeat stable running in 2-D biped testbed

2015

DIRECTION
Theoretical Foundation of Legged Dynamics and Control

EU Marie-Curie Fellowship

spinal reflex control predicts human muscle activations in steady walking

2010

NSF ERC on Quality of Life

revised swing reflex control generates robust foot placement

2012

angular momentum control in segmented running systems

2013

reflex control generalizes to robust walking in 3-D environments

integration with supraspinal pathways generalizes 3-D model to variety of human locomotion behaviors

2015

DIRECTION
Computational Models of Neuromuscular Control to
(a) further understanding of the human nervous system
(b) identify control algorithms for robotic limbs
(c) establish simulation platform for rapid innovation in rehabilitation robotics

powered ankle prosthesis with reflex-like control inherits adaptation to environment

2011

NIH funds testbed for studying and transferring reflex control to articulated robotic legs

2014

prediction of amputee gait with powered leg prostheses using different control algorithms

development of powered knee prosthesis with reflex-like control for fall prevention in amputee gait

2015

DIRECTION
Robotic Limbs with human-like Behavior and Dexterity

Content

Background

Neuromuscular model of human locomotion

Using the model to control bipedal robots

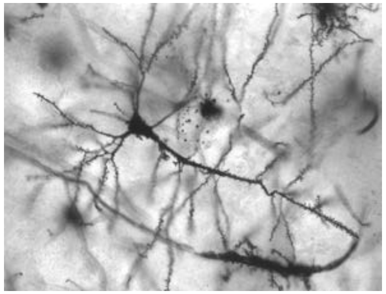
Current understanding of human locomotion control

Human locomotion is well described at the behavioral level

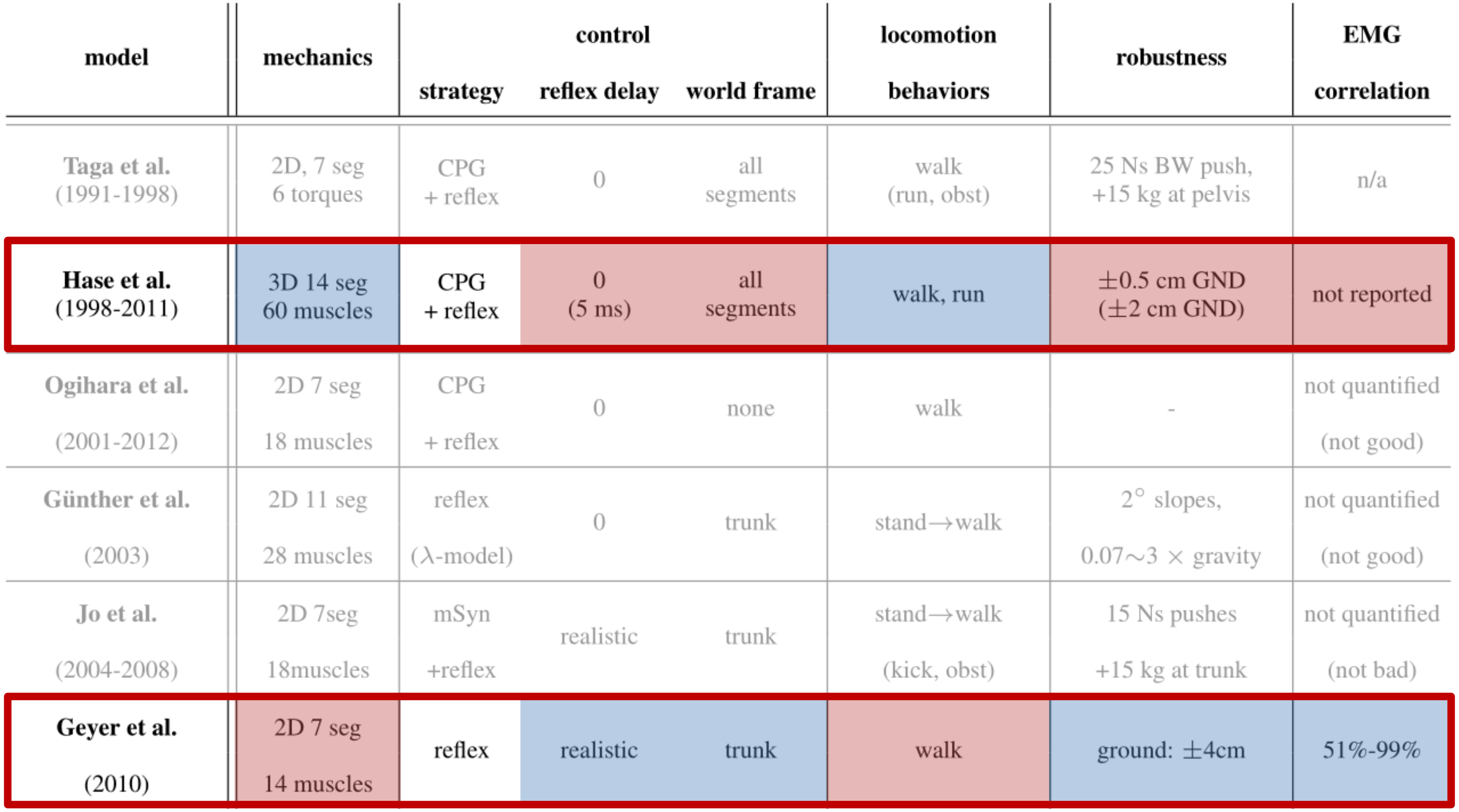
Kinematics, dynamics, muscle activations, …

Not much is understood at the neural circuit level

Spinal and supraspinal control layers
Central pattern generators (CPGs), reflexes, …



Simulation studies may provide better understanding



model	mechanics	control			locomotion	robustness	EMG
		strategy	reflex delay	world frame	behaviors		correlation
Taga et al. (1991-1998)	2D, 7 seg 6 torques	CPG + reflex	0	all segments	walk (run, obst)	25 Ns BW push, +15 kg at pelvis	n/a
Hase et al. (1998-2011)	3D 14 seg 60 muscles	CPG + reflex	0 (5 ms)	all segments	walk, run	±0.5 cm GND (±2 cm GND)	not reported
Ogihara et al. (2001-2012)	2D 7 seg 18 muscles	CPG + reflex	0	none	walk	-	not quantified (not good)
Günther et al. (2003)	2D 11 seg 28 muscles	reflex (λ-model)	0	trunk	stand→walk	2° slopes, 0.07∼3 × gravity	not quantified (not good)
Jo et al. (2004-2008)	2D 7seg 18muscles	mSyn +reflex	realistic	trunk	stand→walk (kick, obst)	15 Ns pushes +15 kg at trunk	not quantified (not bad)
Geyer et al. (2010)	2D 7 seg 14 muscles	reflex	realistic	trunk	walk	ground: ±4cm	51%-99%

- + robust 3D locomotion
- + diverse locomotion behaviors
- + predictive model

pros

cons

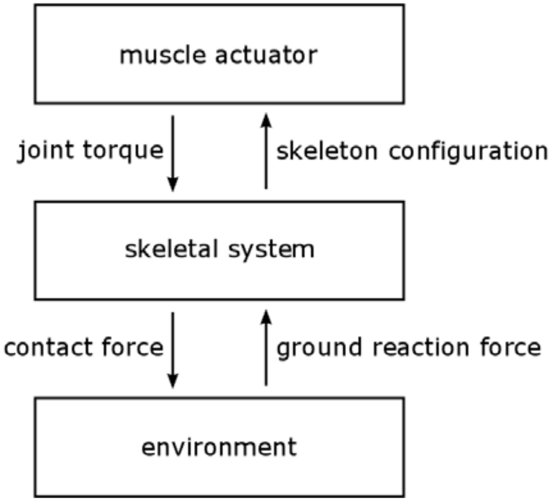
Background

Neuromuscular model of human locomotion

S Song and H Geyer, A neural circuitry that emphasizes spinal feedback generates diverse behaviors of human locomotion, *The Journal of Physiology*, 2015.

Using the model to control bipedal robots

Musculoskeletal system



muscle actuator

joint torque

skeleton configuration

skeletal system

contact force

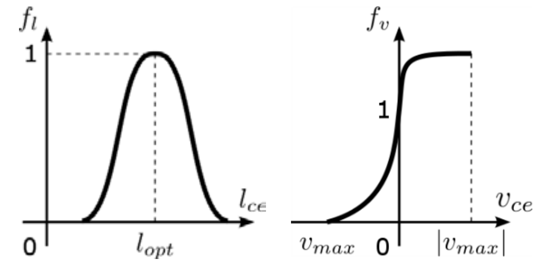
ground reaction force

environment

7 segments

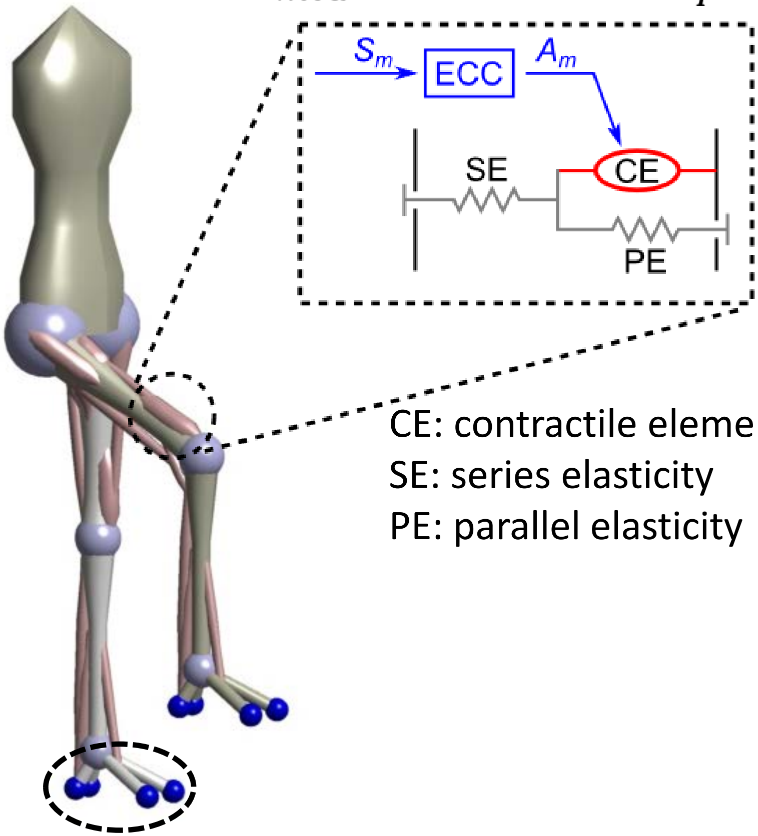
8 DOFs

22 MTUs



$$F_{ce} = A\, F_{max}\, f_l(l_{ce})\, f_v(v_{ce})$$

$$F_{mtu} = F_{se} = F_{ce} + F_{pe}$$



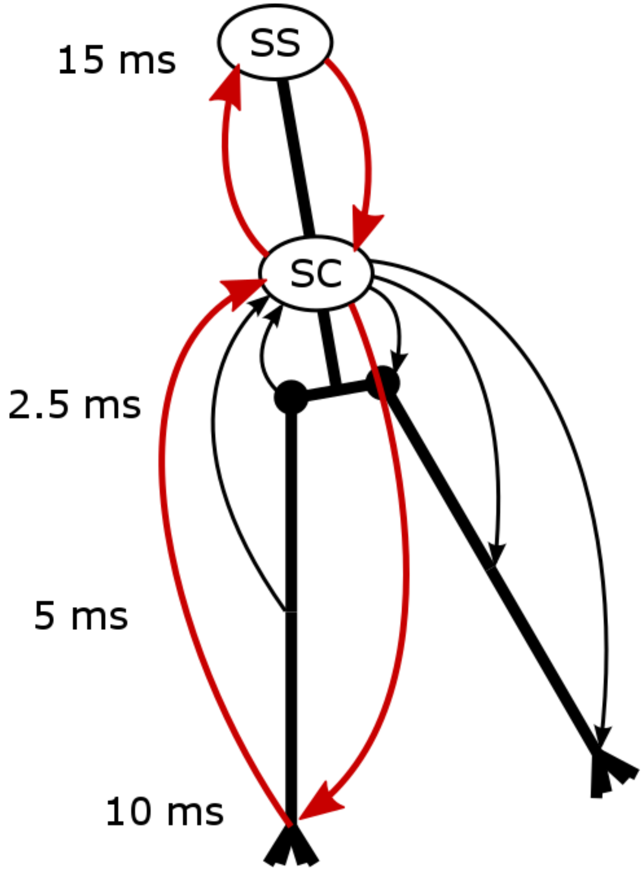
CE: contractile element

SE: series elasticity

PE: parallel elasticity

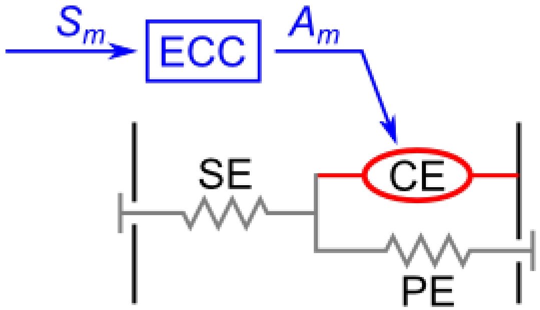
Neurophysiological transmission delays are modeled

Neural transmission delay



10 + 15 + 15 + 10 = 50 ms

Other sources of system delay



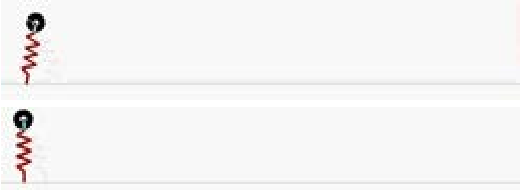
muscle dynamics

excitation-contraction coupling (ECC): ~35 ms

Spinal control consists of reflex modules that embed key functions essential for legged locomotion

Stance

Compliant leg behavior realizes walking and running

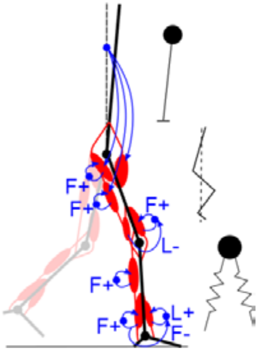


[Geyer EA, 2003]

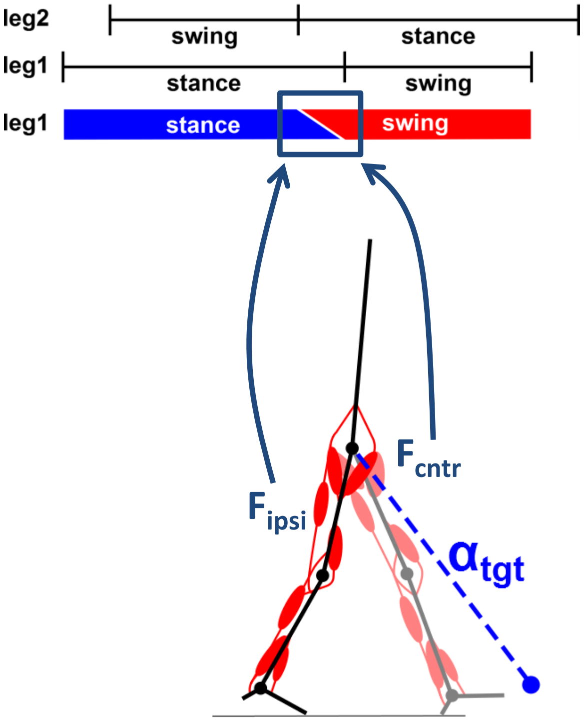
Positive force feedback generates compliant leg behavior

$$S_m = S_0 + G F_m\,(t - \Delta t)$$

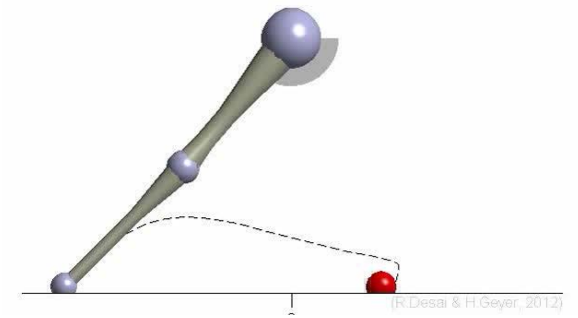
[Geyer EA, 2006]



Stance → Swing

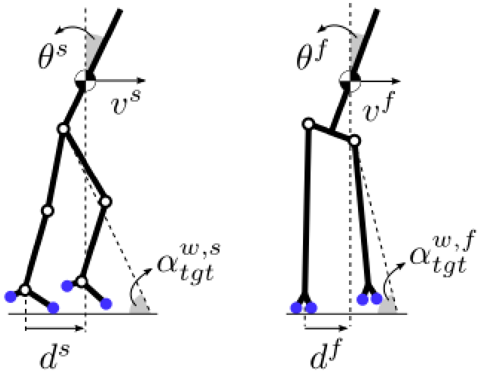


Swing



[Desai EA, 2012&2013; Song EA 2013]

$$\alpha_{tgt} = \alpha_0 - c_d d - c_v v$$

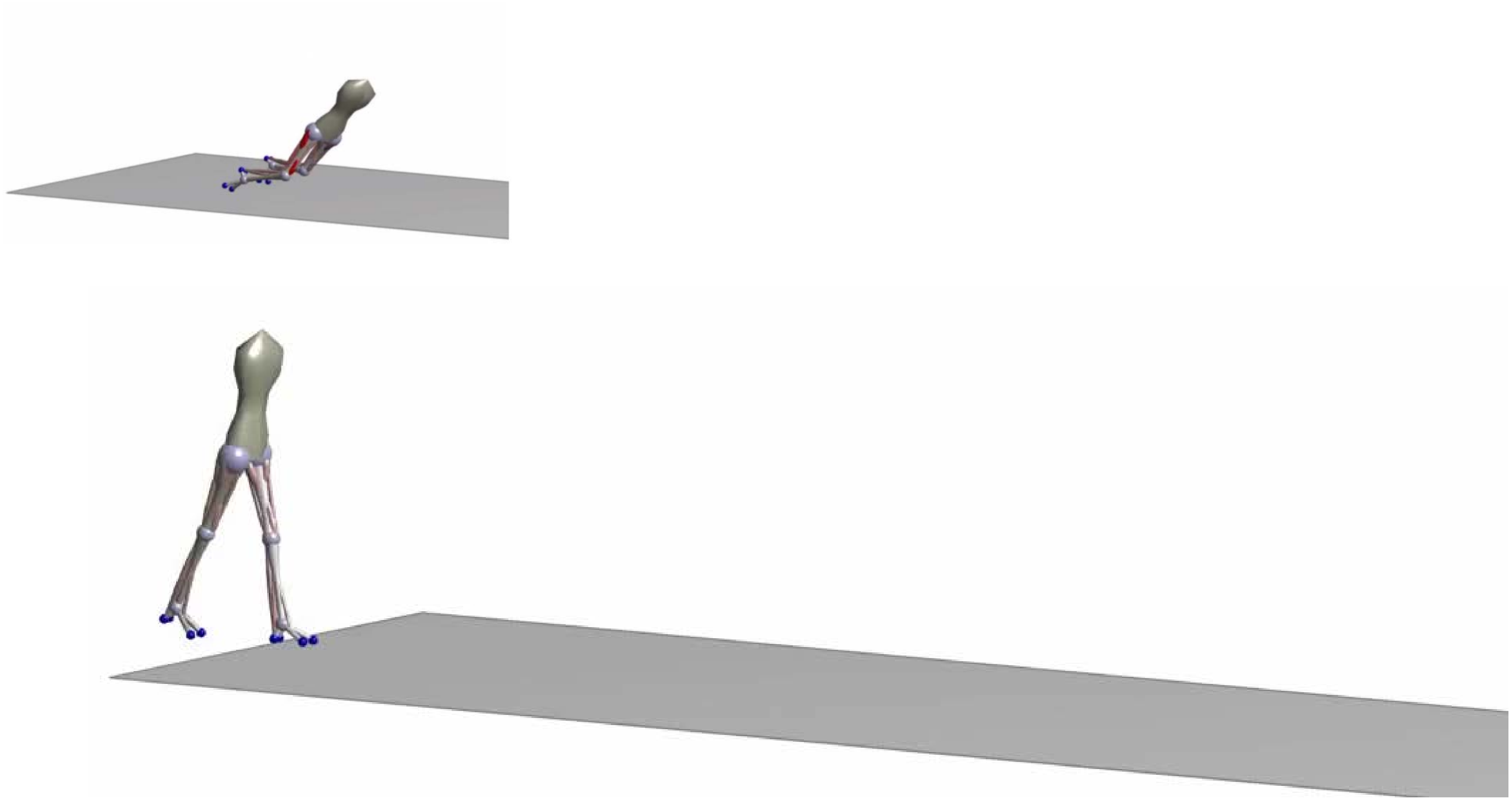


sagittal plane   frontal plane

LIPM [Kajita EA, 2001]

SIMBICON [Yin EA, 2007]

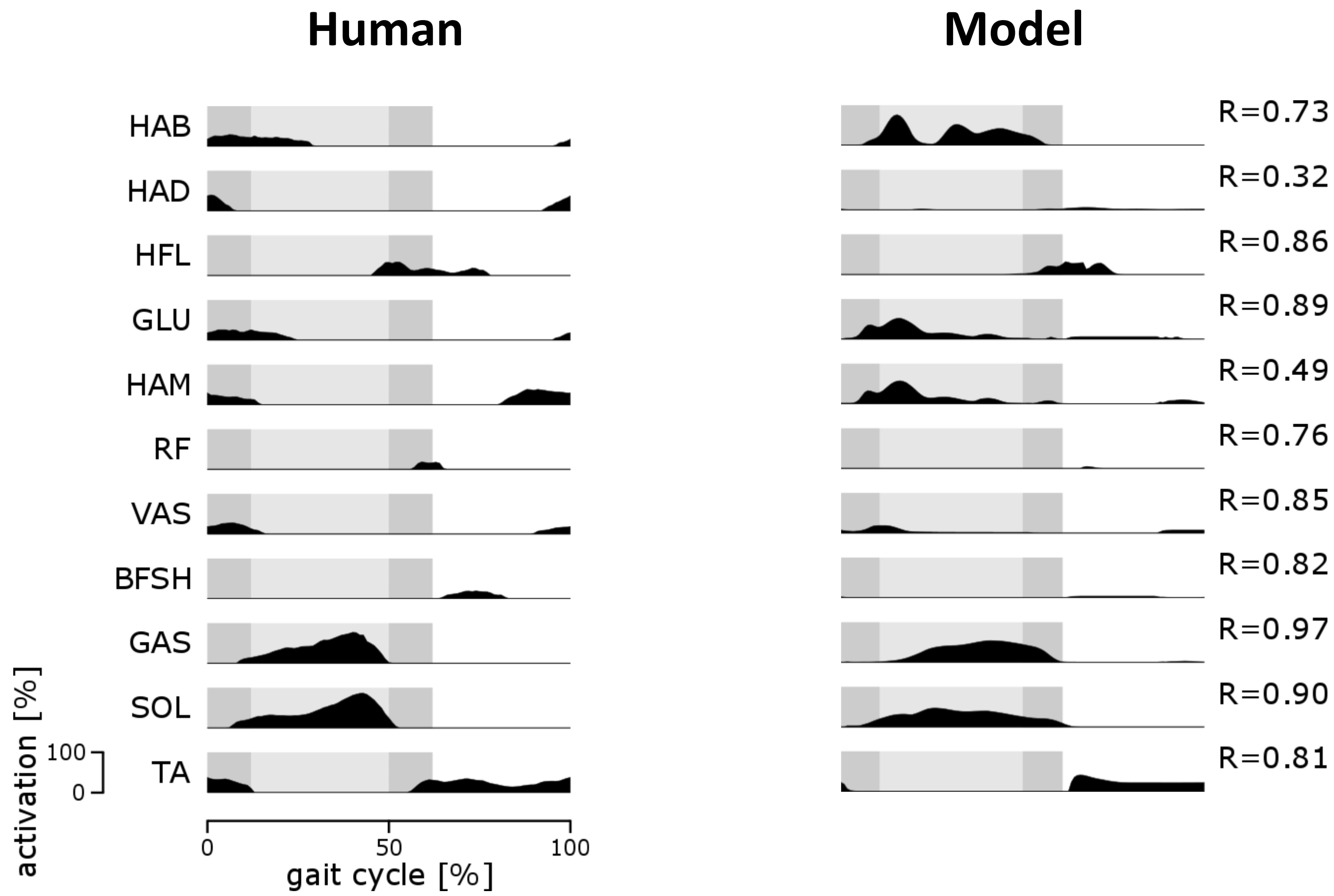
Energy optimal control parameters generates human-like walking



The neural control is plausible

The neural control *predicts* normal human locomotion

Energy optimal walking shows human-like muscle activation

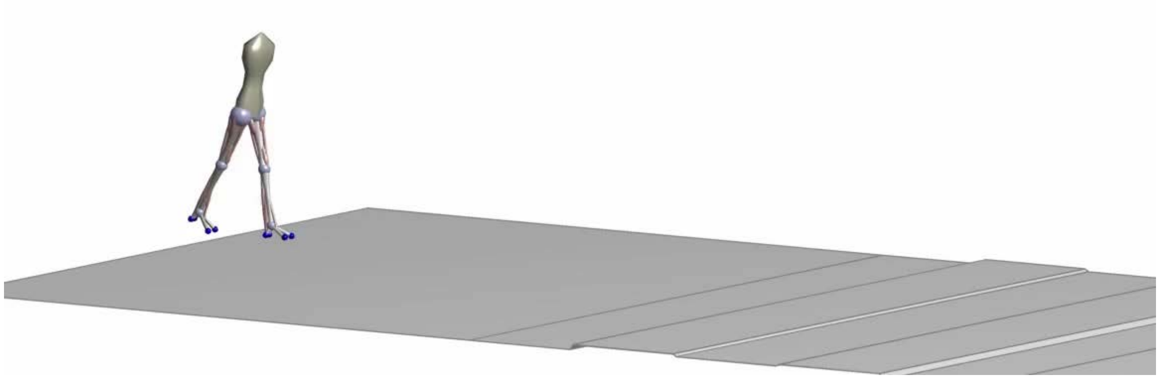


The differences come from …

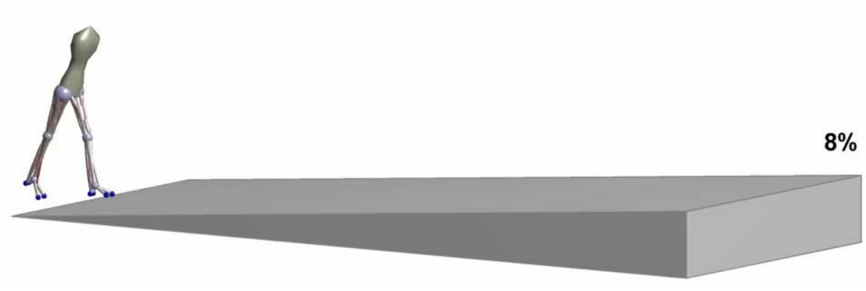
- **simplified musculoskeletal model**
- **energy optimal control parameters**

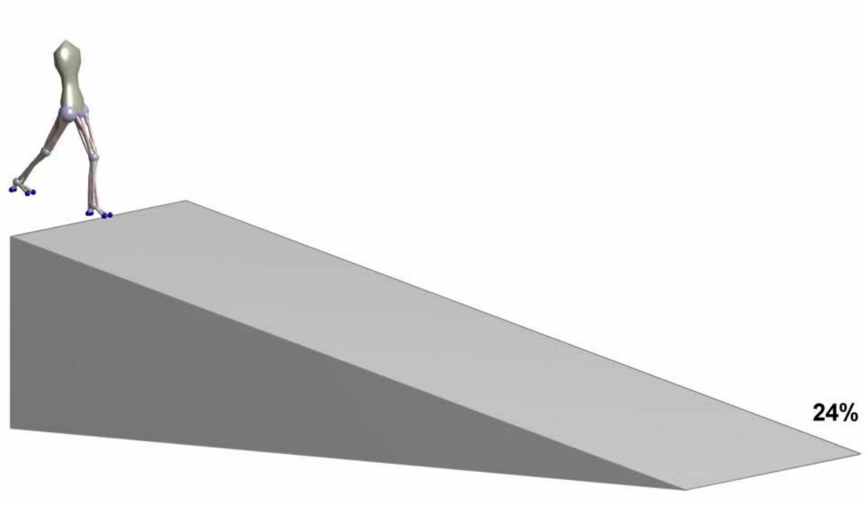
The model can generate diverse locomotion behaviors

Robust walking (±10 cm)



Slope ascend and descend

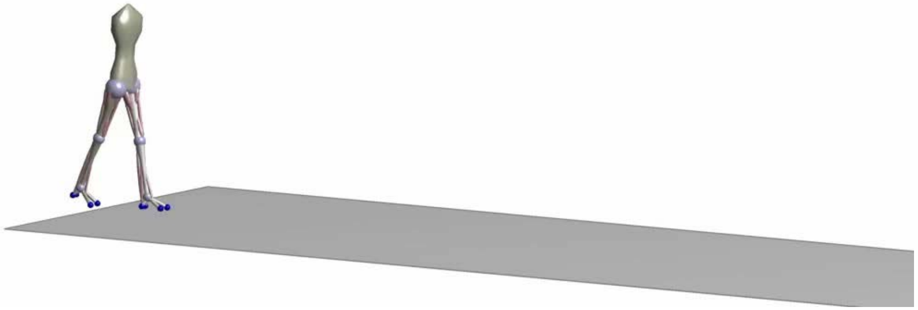




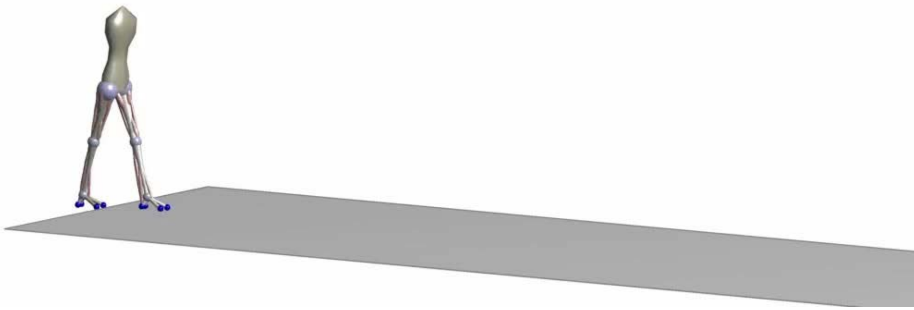
The model can generate diverse locomotion behaviors

Speed change

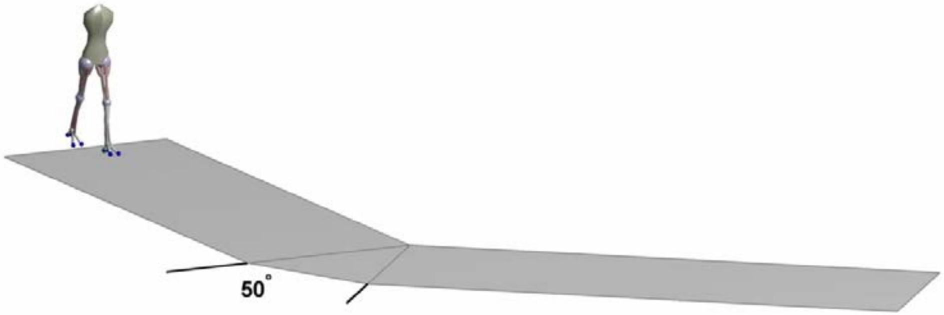
0.8 ms^{-1} ➡ 1.8 ms^{-1}



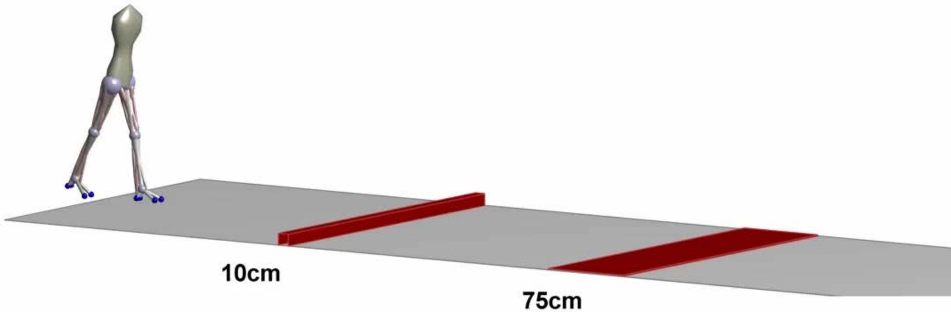
1.8 ms^{-1} ➡ 0.8 ms^{-1}



Direction change



Obstacle avoidance



S Song and H Geyer, A neural circuitry that emphasizes spinal feedback generates diverse behaviors of human locomotion, *The Journal of Physiology*, 2015.

The proposed model can generate human-like robust walking and diverse locomotion behaviors

The motor patterns of many human locomotion behaviors can be generated by chains of reflexes in the lower layer controller

The model is implemented in MATLAB Simulink

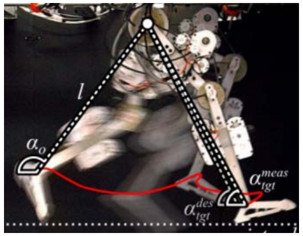
The model can be downloaded from:
http://www.cs.cmu.edu/~smsong/nmsModel/nmsModel.html

Our neuromuscular model has been used in different studies

Controllers for prosthetic legs and bipedal robots

BionX (BiOM)
[Eilenberg EA, 2010]

EPFL (COMAN)
[van der Noot EA, 2015]



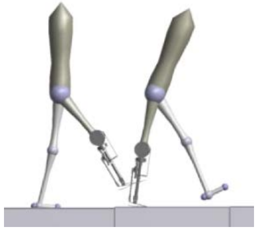
GeyerGroup
[Schepelmann EA, 2015]

GeyerGroup
[Thatte EA, 2015]

Simulation testbeds for assistive devices

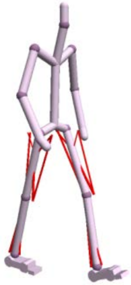
Delft Univ.
[van Dijk EA, 2013]

Samsung
[Seo EA, 2015]

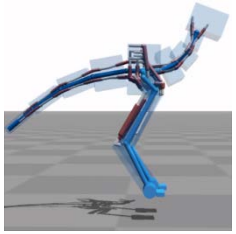


GeyerGroup
[Thatte EA, 2015]

Controllers for graphical characters



Stanford Univ.
[Wang EA, 2012]



Utrecht Univ.
[Geijtenbeek EA, 2013]

Background

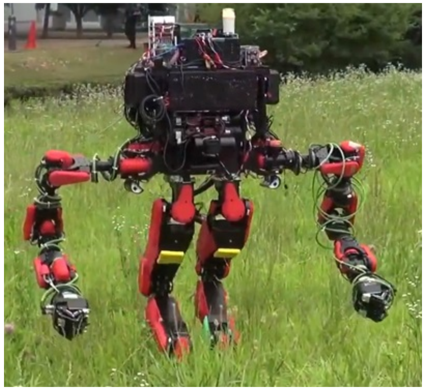
Neuromuscular model of human locomotion

Using the model to control bipedal robots

Z Batts, S Song, and H Geyer, Toward a virtual neuromuscular control for robust walking in bipedal robots, *IEEE IROS*, 2015.

Current robot walking controllers have not yet reached the robustness of human locomotion control

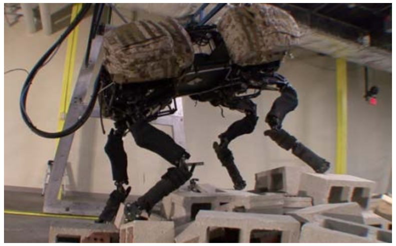
Centralized controllers



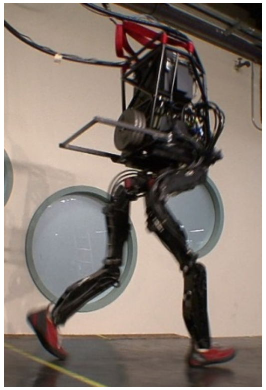
[Urata EA, 2012]

[Feng EA, 2014]

Heuristic policy-based controllers



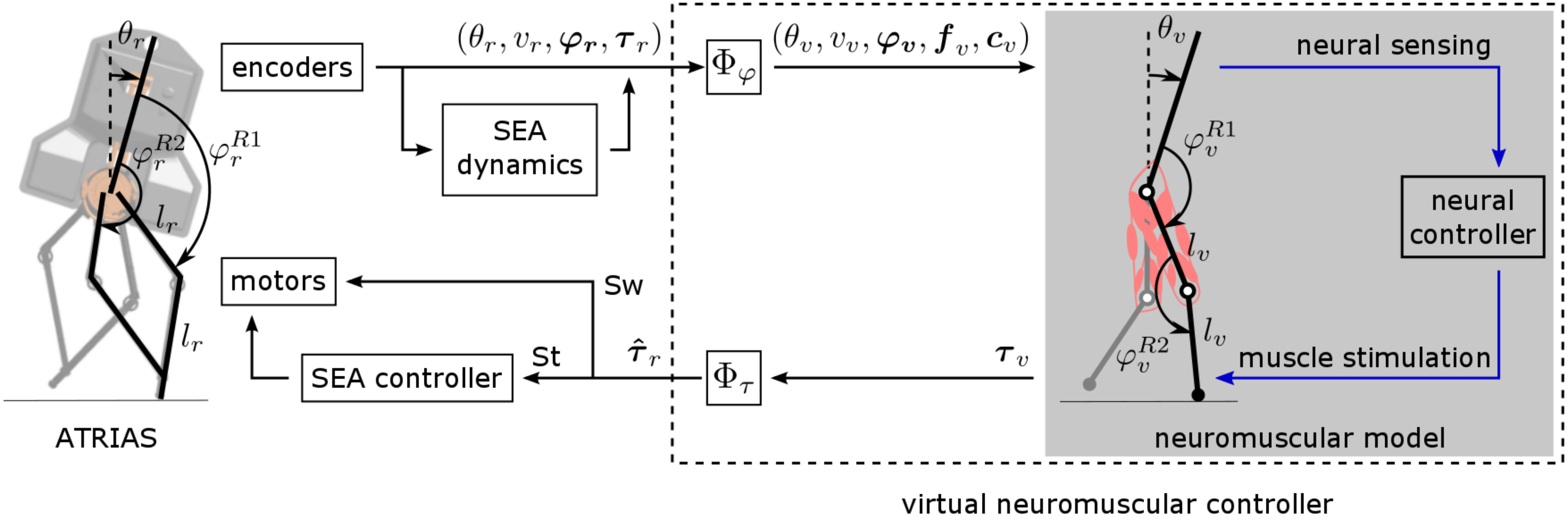
[Raibert EA, 2008]



[Nelson EA, 2012]

The reflex-based neuromuscular control may provide an alternative controller

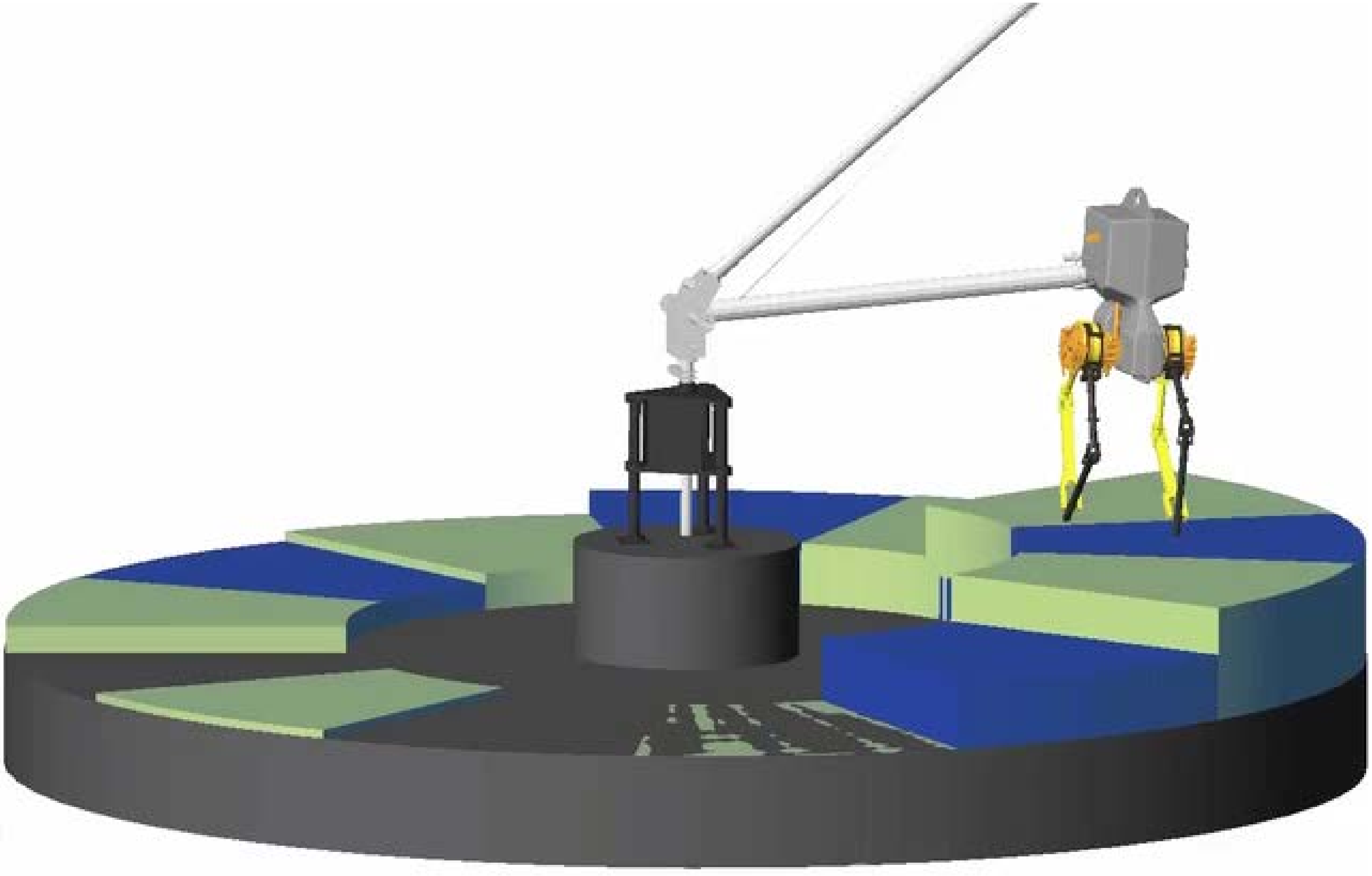
Virtual neuromuscular control (VNMC)



ATRIAS robot

- human size
- trunk mass: 58 kg, leg mass: 2 kg (x 2)
- no foot
- series elastic actuators (SEA)

With VNMC, ATRIAS can walk on a terrain with height changes of ±20 cm in a 2D simulation environment



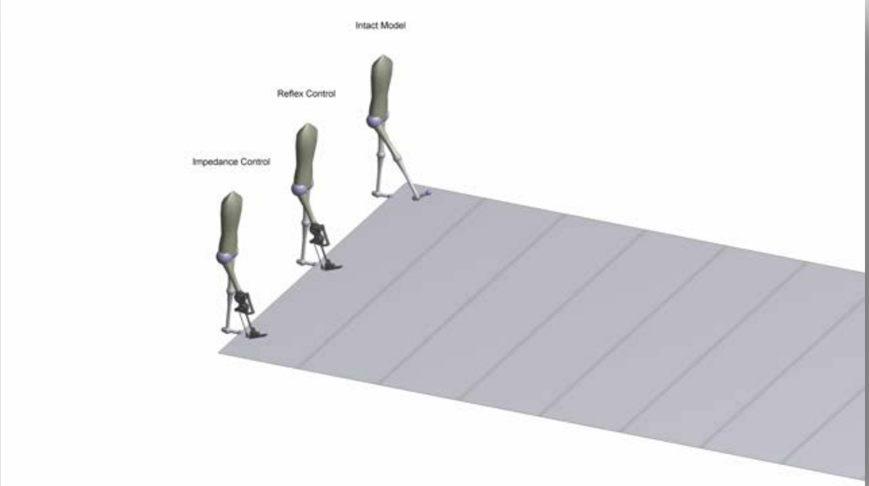
The stance leg control is tested on hardware

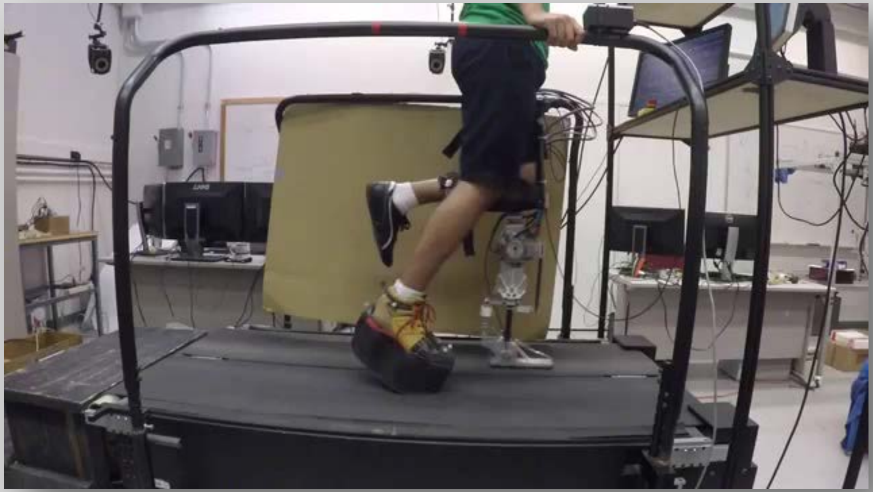
Nitish Thatte

Other Applications

– Controller and simulation testbed for prosthetic legs

N Thatte and H Geyer, Toward balance recovery with leg prostheses using neuromuscular model control, *IEEE Transactions on Biomedical Engineering*, 2015.





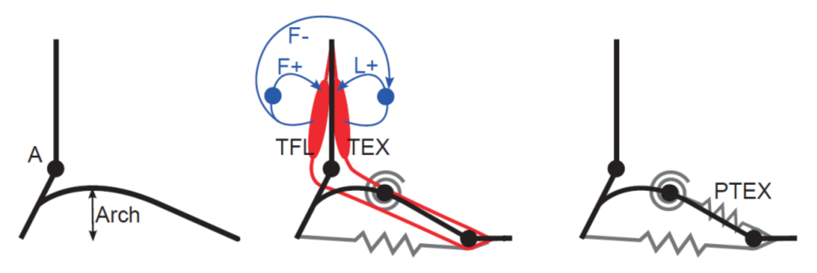
vs. impedance control [Sup EA 2008]

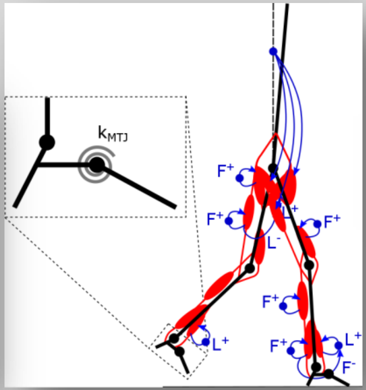
Other Applications

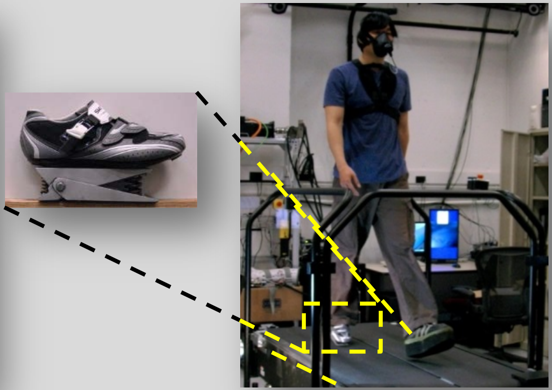
– Simulation testbed for studying foot biomechanics

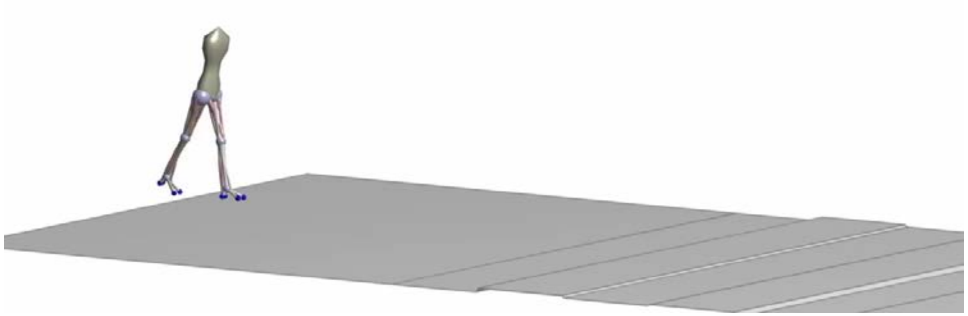
S Song and H Geyer, The energetic cost of adaptive feet in walking, *IEEE ROBIO*, 2011.

S Song, C LaMontagna, SH Collins, and H Geyer, The effect of foot compliance encoded in the windlass mechanism on the energetics of human walking, *IEEE EMBC*, 2013.

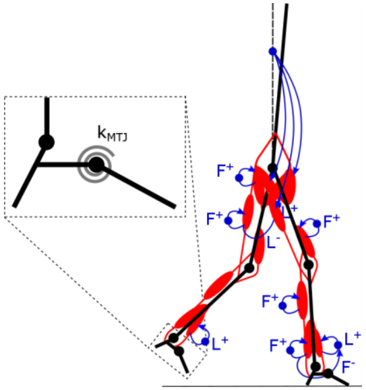


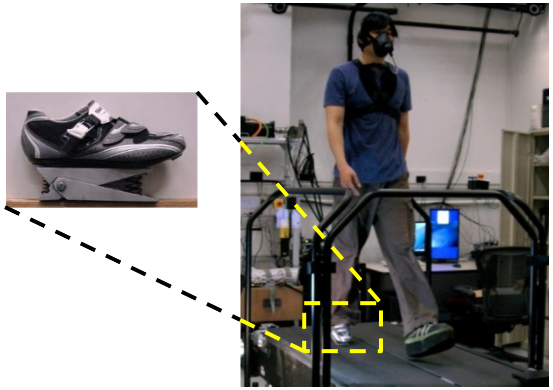




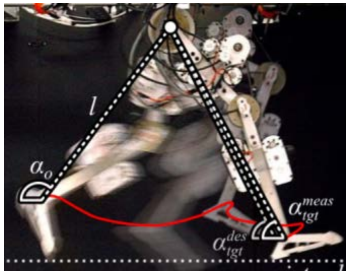


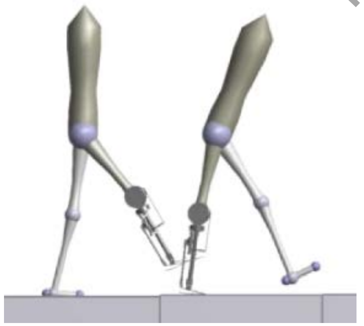
Simulation testbed for locomotion studies





Controller for robotic platforms





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smsong@cs.cmu.edu