Using a Neuromuscular Model of Human Locomotion to Control Bipedal Robots

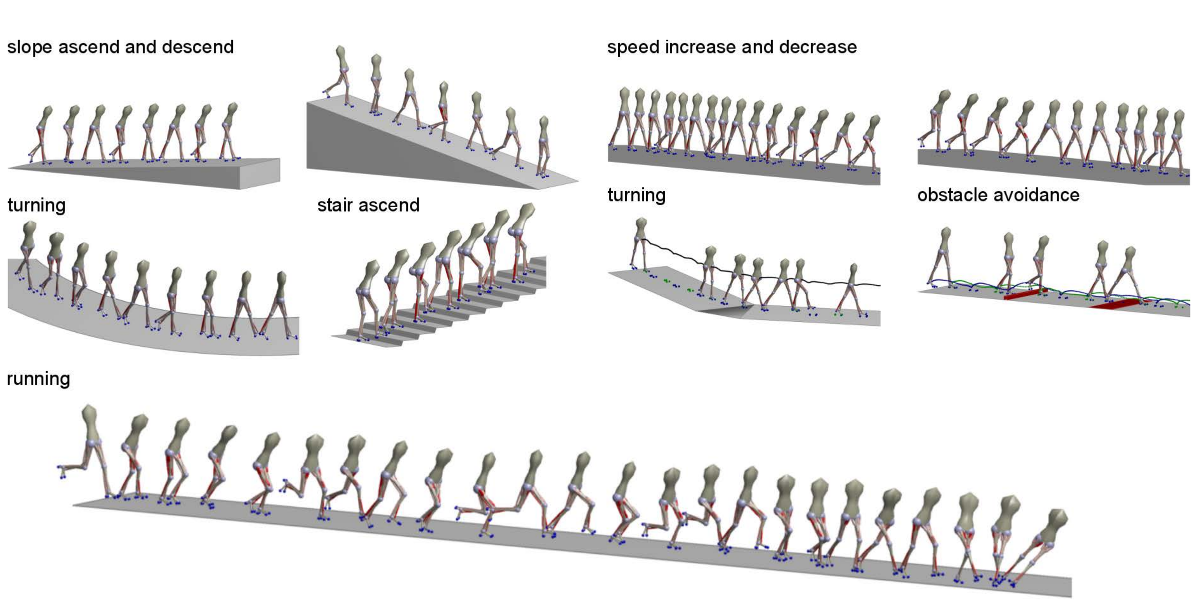
Motivation
Current walking controllers for bipedal robots do not possess the robustness and versatility of human locomotion control. Explicitly imitating the human motor control may transfer its advantages to bipedal robots.

Our Approach
We seek to control bipedal robots with a specific neuromuscular human walking model proposed previously. Here, we present a virtual neuromuscular controller, VNMC, that emulates this neuromuscular model to generate desired motor torques for a bipedal robot.

Current Results and Future Plan
We have shown in simulation that VNMC can generate robust walking for ATRIAS in the sagittal plane. We plan to extend VNMC for robust 3D walking and validate it on hardware.

Neuromuscular Control Model[1]

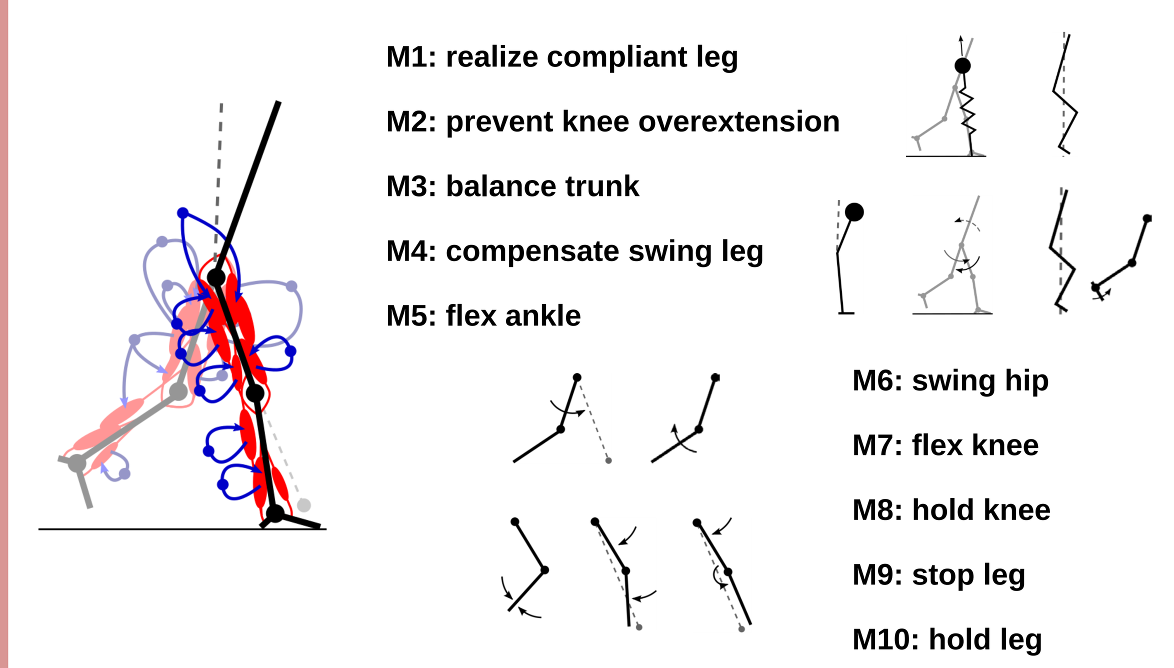
Our neuromuscular control model generates robust and diverse human locomotion behaviors



1. The musculoskeletal system models the human body (inertia properties, muscle dynamics, neural transmission delays are estimated from human physiology). The model does not include internal yaw degree of freedoms which limits it from generating more behaviors (i.e. sharper turns and stable running).

Reflex Control Modules

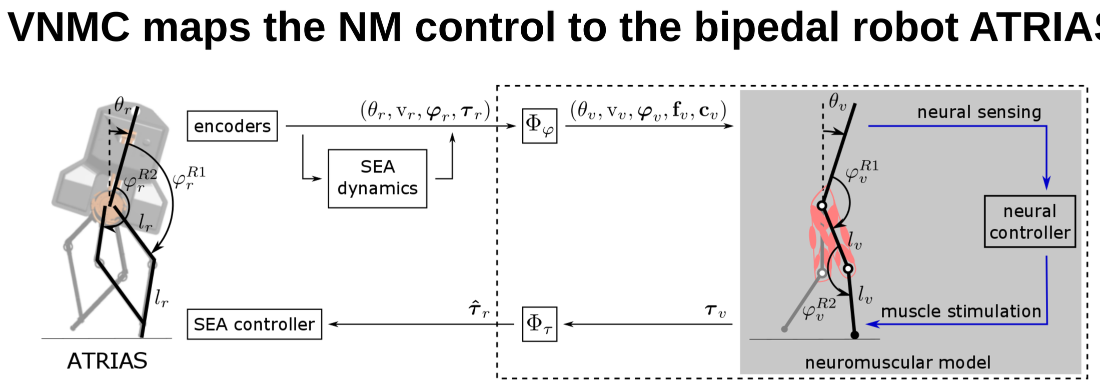
The neural controller consists of 10 reflex modules



2. The control modules compose the spinal control. These modules are modulated by the supraspinal (brain) control through the high-level commands. The current high-level commands are target swing leg placement, swing foot-ground clearance, and trunk lean.

Virtual Neuromuscular Control (VNMC)[2]

VNMC maps the NM control to the bipedal robot ATRIAS



	trunk		upper leg		lower leg		foot		
	COM to hip	mass	length	mass	length	mass	length	height	mass
ATRIAS	10	57.9	50	1.1	50	1.0	-	-	-
human model	35	53.5	46	8.5	46	3.5	20	8	1.25

(unit: cm, kg)

$$\varphi_v^{R1} = \frac{1}{2}\left(-\pi + \varphi_r^{R1} + \varphi_r^{R2} + \varphi_v^{R2}\right)$$

$$\varphi_v^{R2} = 2\sin^{-1}\left(\frac{l_r}{l_v}\cos\left(\frac{\varphi_r^{R2} - \varphi_r^{R1}}{2}\right)\right)$$

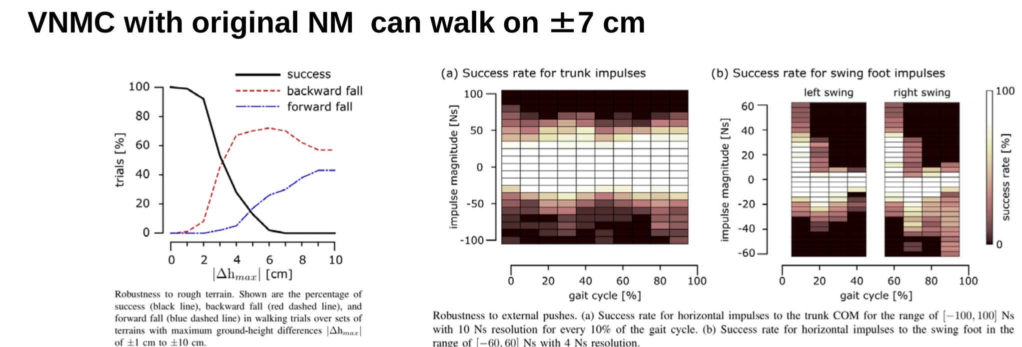
$$\Phi_\tau = \begin{bmatrix} \frac{1+k}{2} & \frac{1-k}{2} \\ k & -k \end{bmatrix} \qquad k = \frac{l_r \sin\left(\frac{\varphi_r^{R2}-\varphi_r^{R1}}{2}\right)}{l_v \cos\left(\frac{\varphi_v^{R2}}{2}\right)}$$

3. An emulated neuromuscular model is mapped to a robot topology to generate desired motor torques.
We use a high-fidelity simulation of the ATRIAS platform constrained in the sagittal plane. The simulation model includes the SEA dynamics, joint frictions, and stick-slip ground contact modes.

Simulation Results

We optimize the control parameters in simulation

VNMC with original NM can walk on ±7 cm



Robustness to rough terrain. Shown are the percentage of success (black line), backward fall (red dashed line), and forward fall (blue dashed line) in walking trials over sets of terrains with maximum ground-height differences $|\Delta h_{max}|$ of ±1 cm to ±10 cm.

Robustness to external pushes. (a) Success rate for horizontal impulses to the trunk COM for the range of $[-100, 100]$ Ns with 10 Ns resolution for every 10% of the gait cycle. (b) Success rate for horizontal impulses to the swing foot in the range of $[-60, 60]$ Ns with 4 Ns resolution.

Such results are not good as the original human NM model.
It is because the optimization finds local minima which does not fully use the original functionalities.
To avoid this problem, we update some reflex control modules to use joint kinematic states of the virtual leg directly instead of estimating it through muscle states.

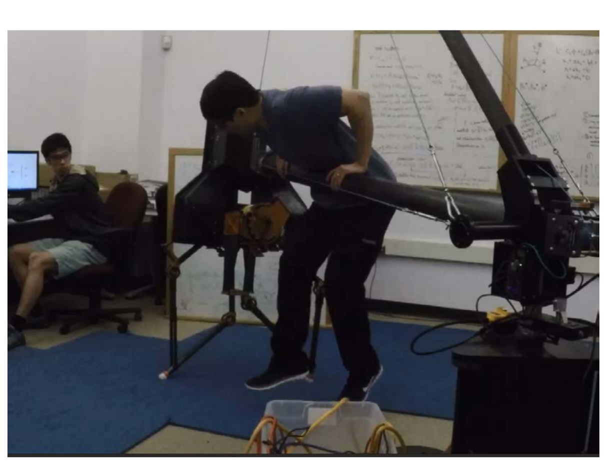
With the above changes, VNMC can walk on ±20 cm.

We have not yet conducted the detail robustness tests on this controller.

4. With the original neuromuscular model, VNMC adapts to 90% of random terrains with height-changes of ±2 cm; and endures 95% of ±30 Ns horizontal pushes on the trunk, and 90% of 8 Ns backward and 4 Ns forward impulses on the swing foot throughout the gait cycle. We expect more robust locomotion with the updated VNMC.

Hardware Experiments in Progress

We are currently testing each control modules on ATRIAS hardware



M1 (compliant leg) works well to adapt to additional weight

Current challenge:

In simulation, we initiate the robot at a pose and velocity that are appropriate for the optimized VNMC to start. This makes it hard to directly run VNMC on the actual robot (which we have not foreseen). Currently, we are developing a temporal controller that allows ATRIAS to initiate walking from standing. Ideally, such controller should be included in the optimization procedure.

5. We have tested most of the stance leg control modules. The swing leg modules are not straightforward to test individually since they depend on the initial states of the swing leg.

Open Questions

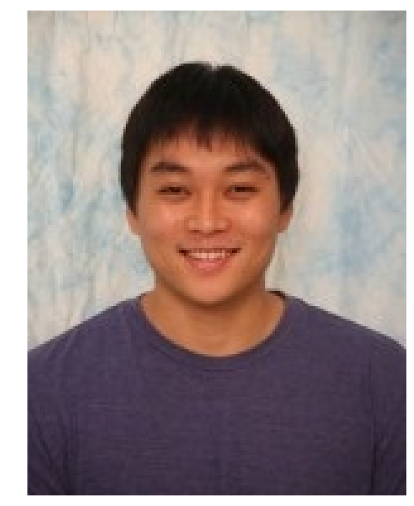
Do humans and animals take advantage of the muscle properties in locomotion? Should robotic controllers capture these properties?

Currently, the virtual muscles in VNMC are identical to those used in the original human model. However, the segment dynamics of ATRIAS are much different from those of humans. How can we tune the muscles specific for the given robot?

In simulation, the neural controller can tolerate about ±20 cm ground height disturbances in both the human and the ATRIAS model in the sagittal plane. This is somewhat unexpected considering that ATRIAS does not have feet. How can we further analyze this result to gain fundamental understanding on the function of the ankle-foot complex?

6. I look forward for interesting discussions. We can setup a meeting during the conference if needed (smsong@cs.cmu.edu).

Poster Day 2

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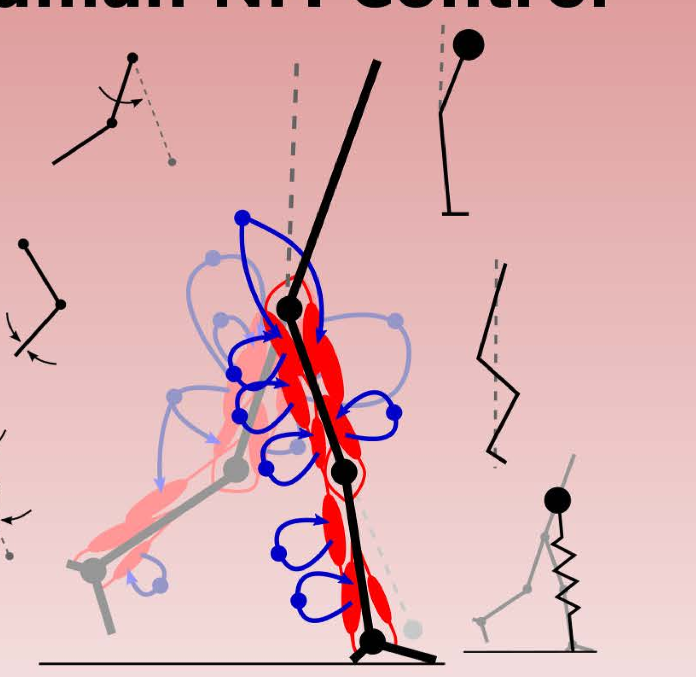
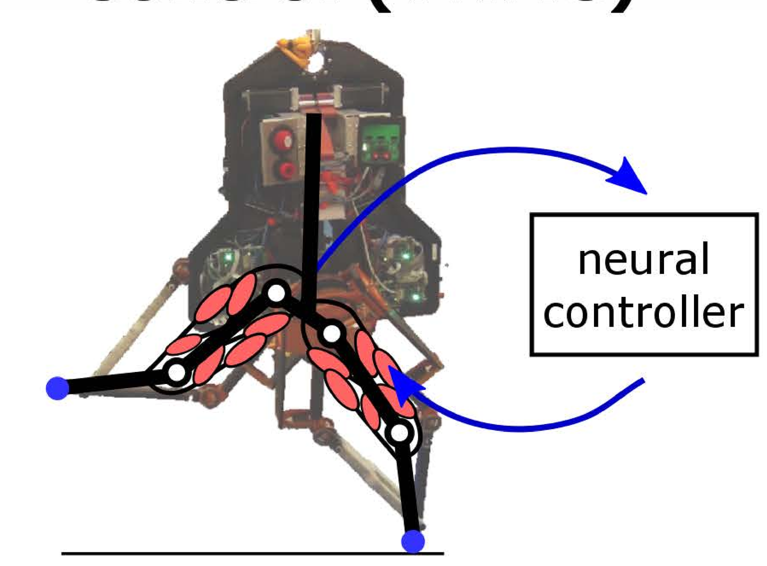
Development Process

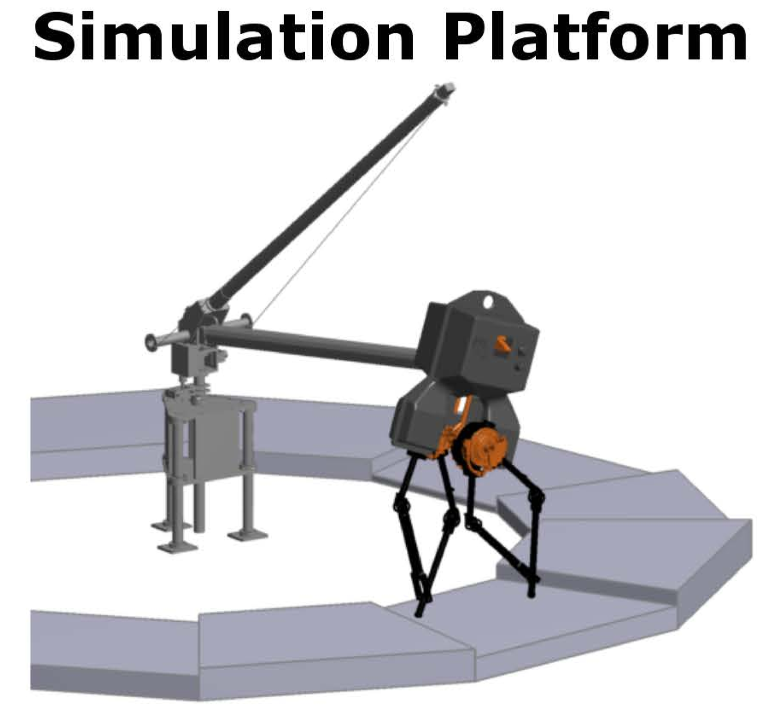
Human NM Control



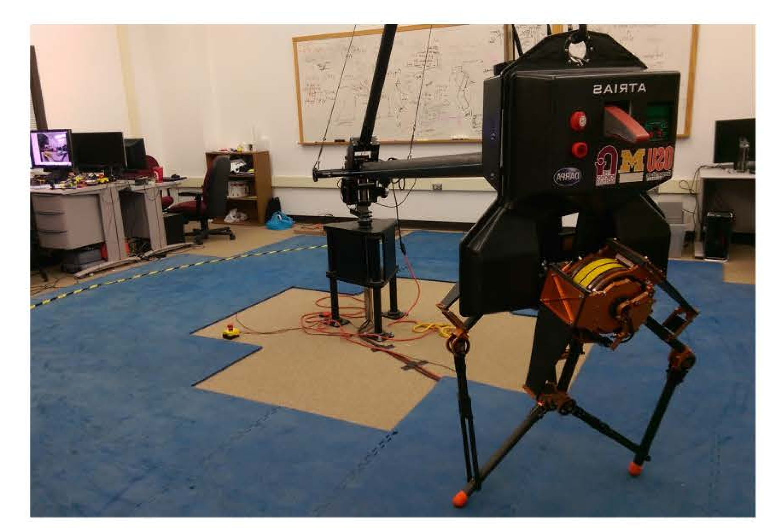
Virtual Neuromuscular Control (VNMC)



Control Optimization in Simulation Platform



Hardware Validation



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[1] S. Song and H. Geyer, “A neural circuitry that emphasizes spinal feedback generates diverse behaviours of human locomotion,” *The journal of physiology*, accepted.
[2] Z. Batts, S. Song, and H. Geyer, “Toward a virtual neuromuscular control for robust walking in bipedal robots,” *IROS 2015*, accepted.

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