Reducing Residual Forces & Moments in a Three-Dimensional Simulation of Running

Samuel R. Hamner[1], Chand T. John[2], Frank C. Anderson[3], Jill S. Higginson[4], Scott L. Delp[1,2]

Departments of [1]Mechanical Engineering, [2]Bioengineering, and [3]Computer Science, Stanford University
[4]Department of Mechanical Engineering, University of Delaware

Introduction

Understanding the actions of muscles during movement is a challenging problem because important variables, such as muscle forces, are generally not measurable. Muscle-actuated simulations of walking have been successfully generated in the past [1]. However, simulating running presents new challenges due to higher speeds, accelerations, and forces. The objective of this project was to create an accurate, three-dimensional, muscle-actuated simulation of running, which allows estimation of muscle forces, in order to gain insight into muscle actions. This was achieved by: (1) examining the effect of modeling arms on reducing residuals, and (2) assessing the effect of reducing residuals on joint torques.

What are residuals?

When creating simulations of movement, dynamic inconsistencies occur due to errors in experimental kinematics, ground reactions, and the model [2]. In other words, Newton's 2nd law does **NOT** hold:

GROUND REACTIONS → $F \neq ma$ ← BODY MOTIONS

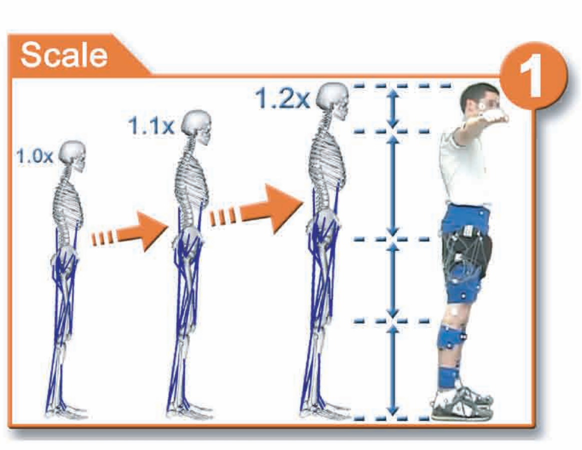
To resolve this, an additional, non-physical force and moment, called **residuals**, are applied to a model segment (e.g., the pelvis):

$$F + F_{residual} = ma$$

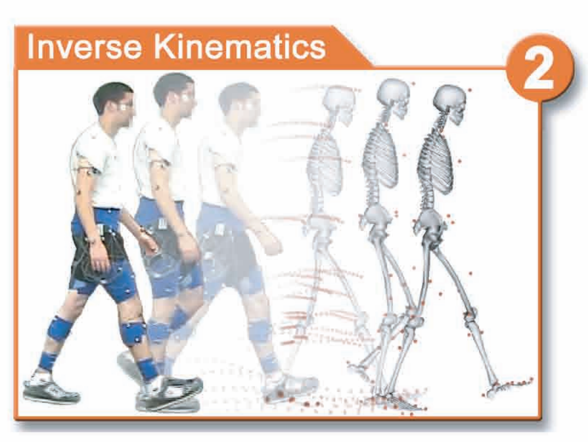
To improve the dynamic consistency of simulations, we applied a residual reduction algorithm (RRA) [3], which slightly adjusts estimated body segment mass properties and experimental kinematics, and significantly reduces the residuals.

Generating a Simulation

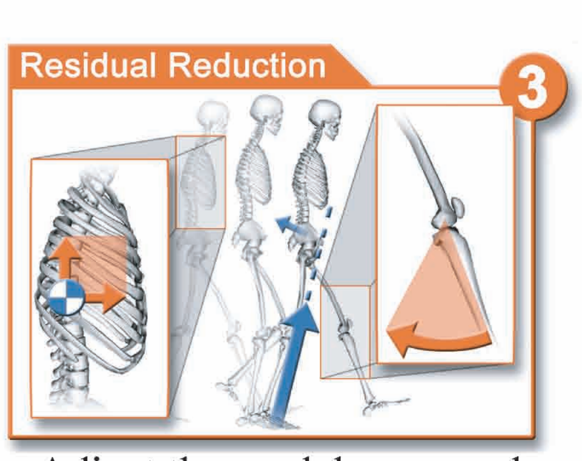
Motion and external forces were measured for a 65.9-kg adult male subject running at 3.9 m/s on a split-belt treadmill. These movements were simulated using the following 4 steps [3]:



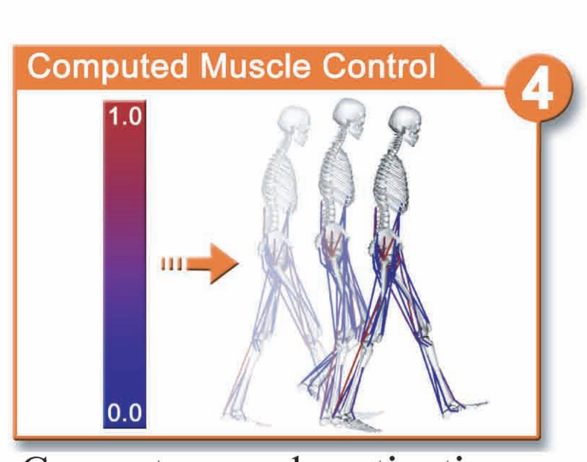
Scale a musculoskeletal model to subject anthropometry.



Find model joint angles that best reproduce the measured marker motion.



Adjust the model mass and motion to improve dynamic consistency.

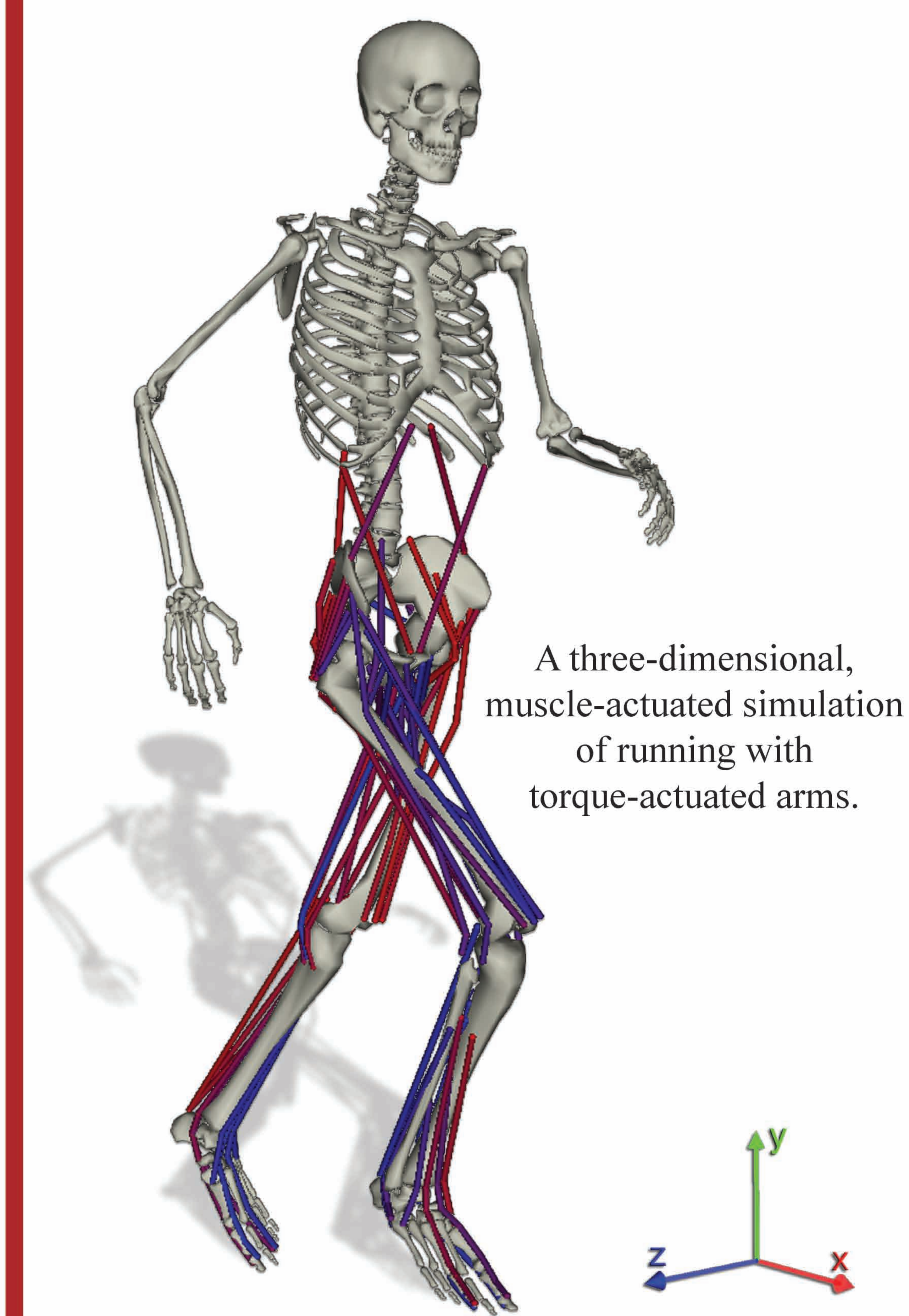


Compute muscle activations that will track the measured motion [4].

Building a Model with Arms

Scaling, inverse kinematics (IK), inverse dynamics, and RRA were applied to a three-dimensional, 10-segment, 21 degree-of-freedom musculoskeletal model with 92 muscles [4,5], which did not include arms.

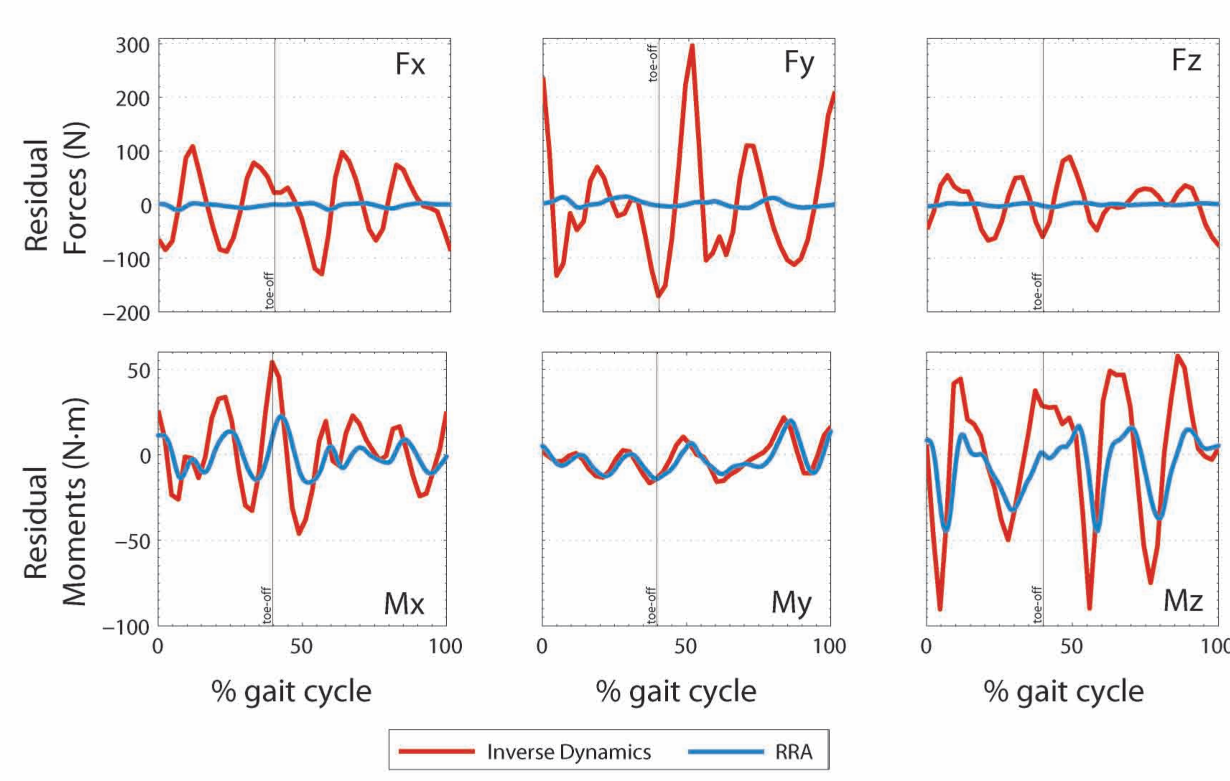
Torque-actuated, 5 degree-of-freedom upper extremities, adapted from [6], were added to the model to further improve dynamic consistency. Scaling, IK, and RRA were then reapplied to the new model with arms.



A three-dimensional, muscle-actuated simulation of running with torque-actuated arms.

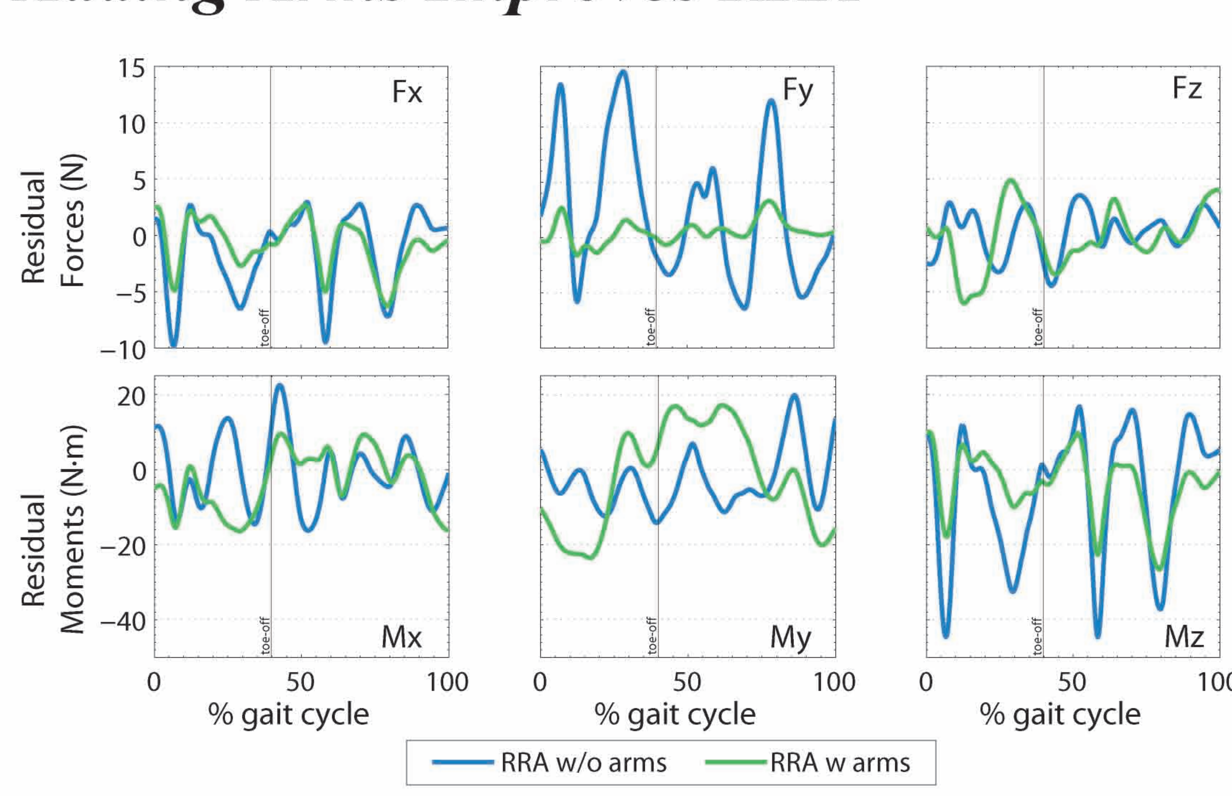
Results

Reducing Residuals without *Arms*



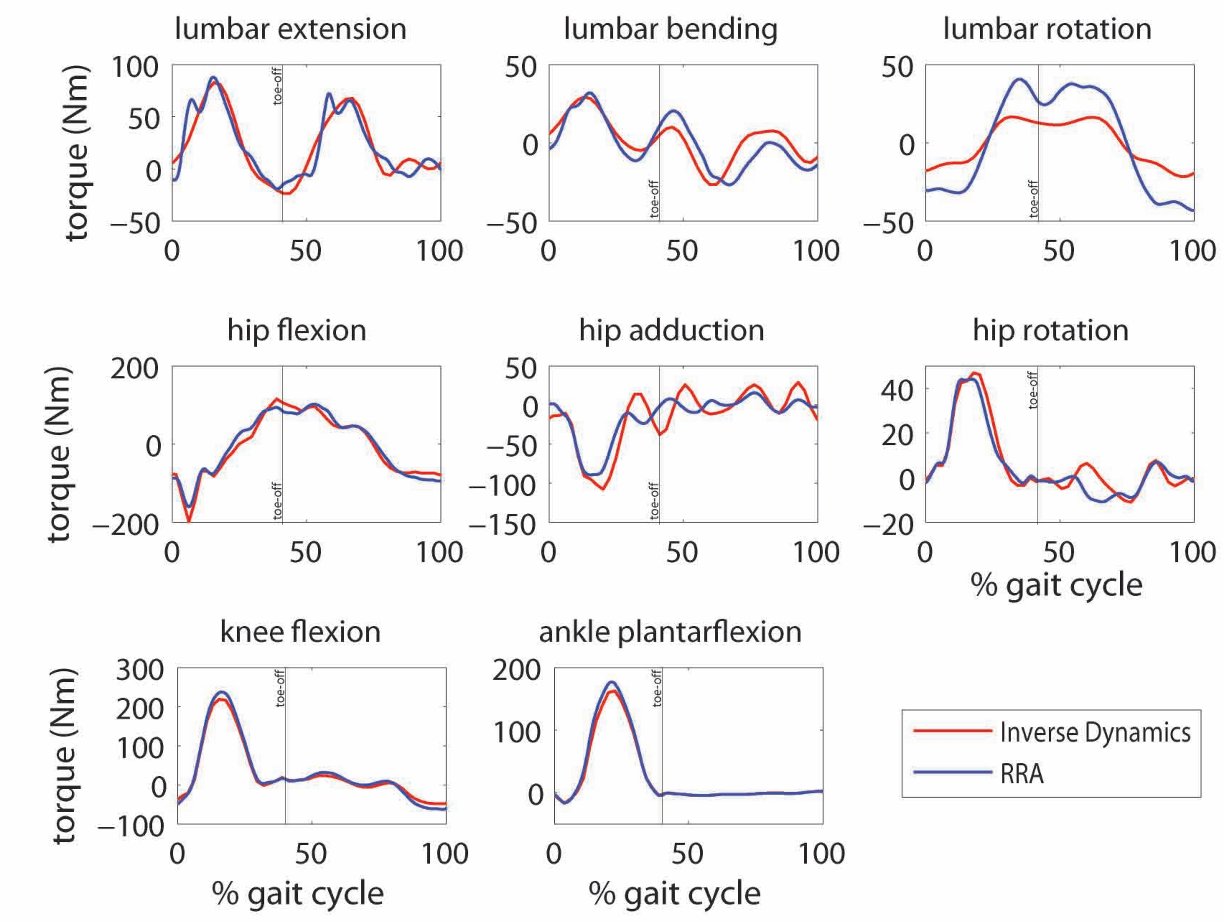
Applying RRA substantially reduced the residual force, which approached ½ body weight in the vertical (F_y) direction when using inverse dynamics. RRA also significantly reduced the frontal (M_x) and sagittal (M_z) components of the residual moment, yet did not appreciably reduce the transverse (M_y) component.

Adding Arms Improves RRA



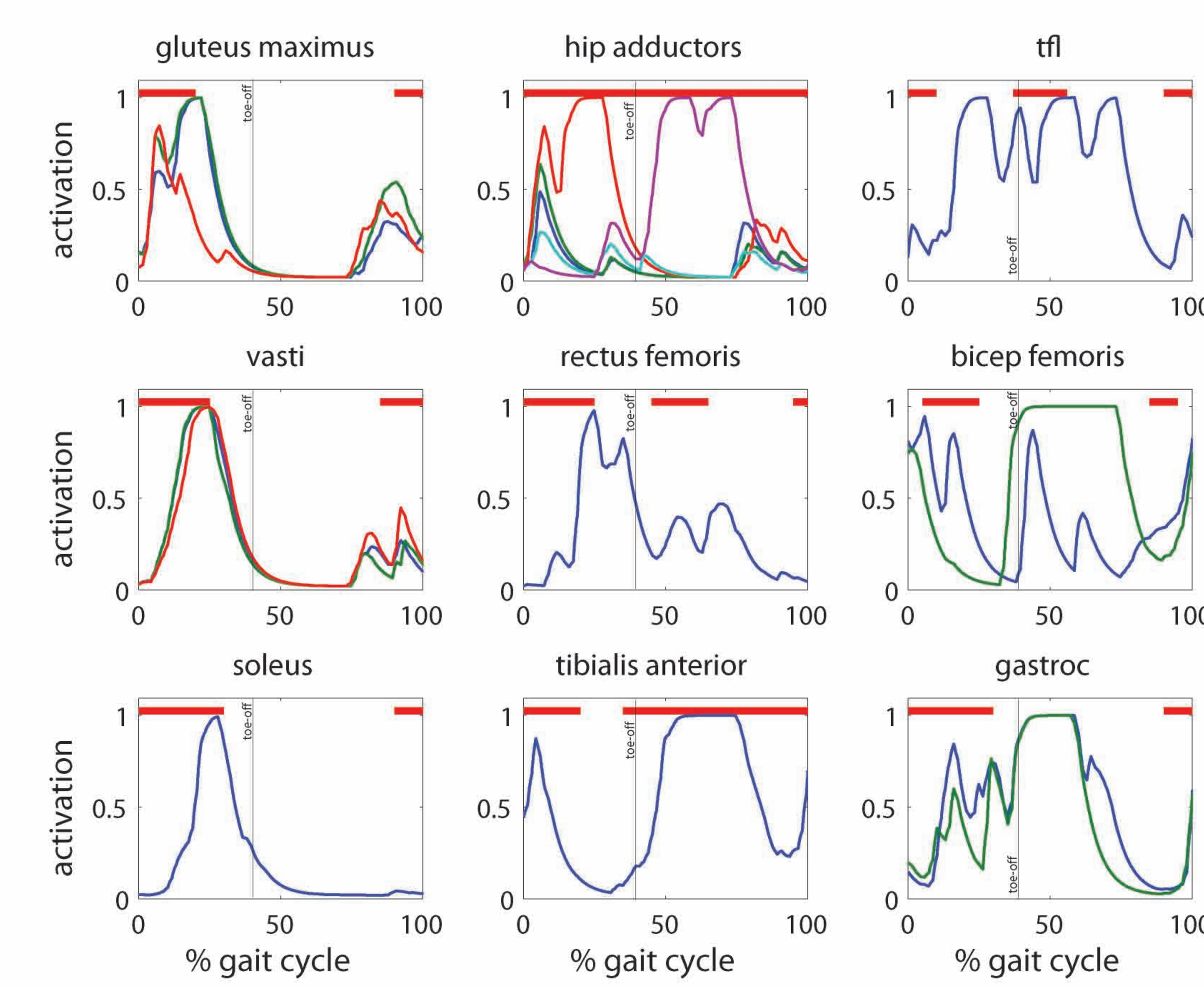
Applying RRA to the model with arms further reduced the residuals. The fore-aft (F_x) and vertical (F_y) components, as well as the frontal (M_x) and sagittal (M_z) components of the residuals were further reduced, while the medio-lateral (F_z) and the transverse (M_y) components were only slightly increased.

Joint Torques Differ with RRA



Peak moments at the knee and ankle increased by about 15 N-m. Changes in hip and lumbar moments were even larger, approaching 40 N-m. This suggests that residual reduction could be important for accurately estimating torques, and thus muscle forces, especially at more proximal joints of the lower extremity.

Validating Muscle Activations



Muscles from the simulation were generally activated during the intervals reported in Cavanagh [7], represented by the red bars in each graph above. However, the simulation was less accurate in predicting activations for biarticular muscles, such as biceps femoris and gastrocnemius, and muscles contributing to hip motion in the transverse and frontal planes, such as gluteus medius and tensor fasciae latae (tfl).

Conclusions and Future Work

We have generated a three-dimensional, muscle-actuated simulation of running over a full gait cycle. When creating simulations of human movement, improving dynamic consistency may be important in order to accurately estimate joint torques and muscle forces, especially at the hip and back. Additionally, we have shown that a simple model of the upper extremities can improve dynamic consistency in simulations of running when using RRA. Future work will use this and similar simulations to investigate muscle contributions to support and progression during running by performing a perturbation analysis similar to [1].

References

[1] Liu et al. (2006) *J Biomech.* [2] Kuo (1998) *J Biomech Eng.* [3] Delp et al. (2007) *IEEE Trans Biomed Eng.* [4] Thelen and Anderson (2006) *J Biomech.* [5] Delp et al. (1990) *IEEE Trans Biomed Eng.* [6] Holzbaur et al. (2005) *Ann Biomed Eng.* [7] Cavanagh (1990) *Biomechanics of Distance Running.*

Acknowledgements

We thank Ayman Habib, May Liu, Ajay Seth, and Jeff Reinbolt. This work was supported by Fellowships from NSF and Stanford, and NIH Grant GM63495.