# An Algorithm for Generating Muscle-Actuated Simulations of Long-Duration Movement

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## How Movement Is Generated

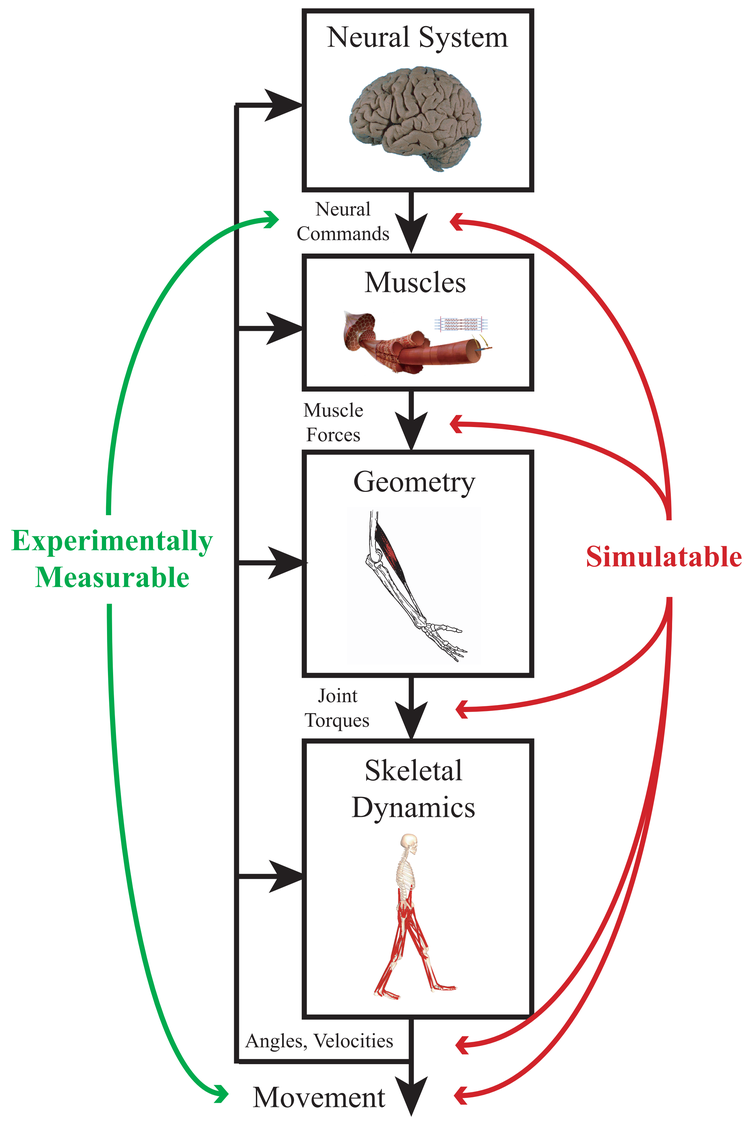


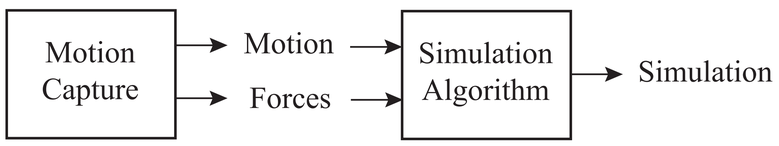

Photo courtesy of Sylvia Ounpuu

Human movement is generated through complex cause-effect relationships that must be understood to optimize athletic performance and treat movement disorders. Experiments cannot capture all of these relationships, but simulations can.

## Objective

Our goal is to enable routine simulation of long-duration movements using motion and force data from motion capture.

## How Movement Is Simulated




Simulations are generated in two stages [2]:

1. **Motion capture:** the motion of a human subject is recorded, and external forces applied to the human by the environment are also recorded.
2. **Simulation algorithm:** a computer program [4] estimates the neural commands, muscle forces, and joint torques that cause a musculoskeletal model [1] of the human to move the way the human did.

## Problem

Unfortunately, when we put the motion and force data into the simulation algorithm, it turns out that $\boldsymbol{F}$ doesn't equal $\boldsymbol{ma}$ [3]! This is due to measurement error in the motion capture data and inaccuracies of the musculoskeletal model.

Forces → $\boldsymbol{F \neq ma}$ ← Body motion

## Previous Approaches

1. Change $\boldsymbol{F}$:

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

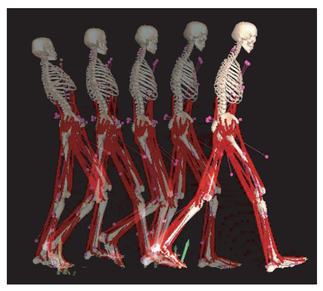
**Limitation:** $\boldsymbol{F}_{\text{residual}}$ may become unrealistically large.

2. Change $\boldsymbol{a}$:

$$\boldsymbol{F = ma'}$$

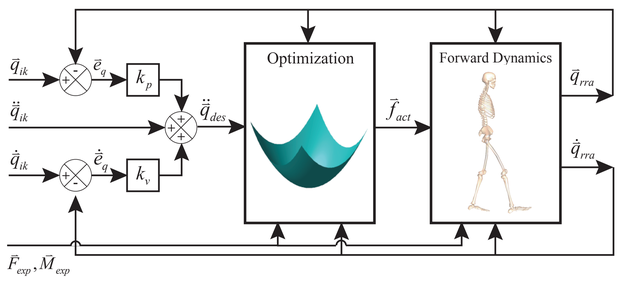
This is called the **Residual Elimination Algorithm (REA).**

**Limitation:** alterations in $\boldsymbol{a}$ can be problematic for movements that are longer than 0.5 s in duration, as shown in this figure.



## Our New Approach

Instead of just changing $\boldsymbol{F}$ or just changing $\boldsymbol{a}$, our **Residual Reduction Algorithm (RRA)** changes both $\boldsymbol{F}$ and $\boldsymbol{a}$ in a controlled way.




RRA starts at the initial time of the movement and repeatedly steps forward in time by an amount $T$. At each time $t$, RRA does the following:

1. **Control:** calculate the values of $\boldsymbol{a}$, represented by $\ddot{q}_{des}$, that would make the model follow the measured body motion.
2. **Optimization:** calculate values of $\boldsymbol{F}$ that minimize an objective function. The first term minimizes changes in $\boldsymbol{F}$ while the second term minimizes changes in $\boldsymbol{a}$.

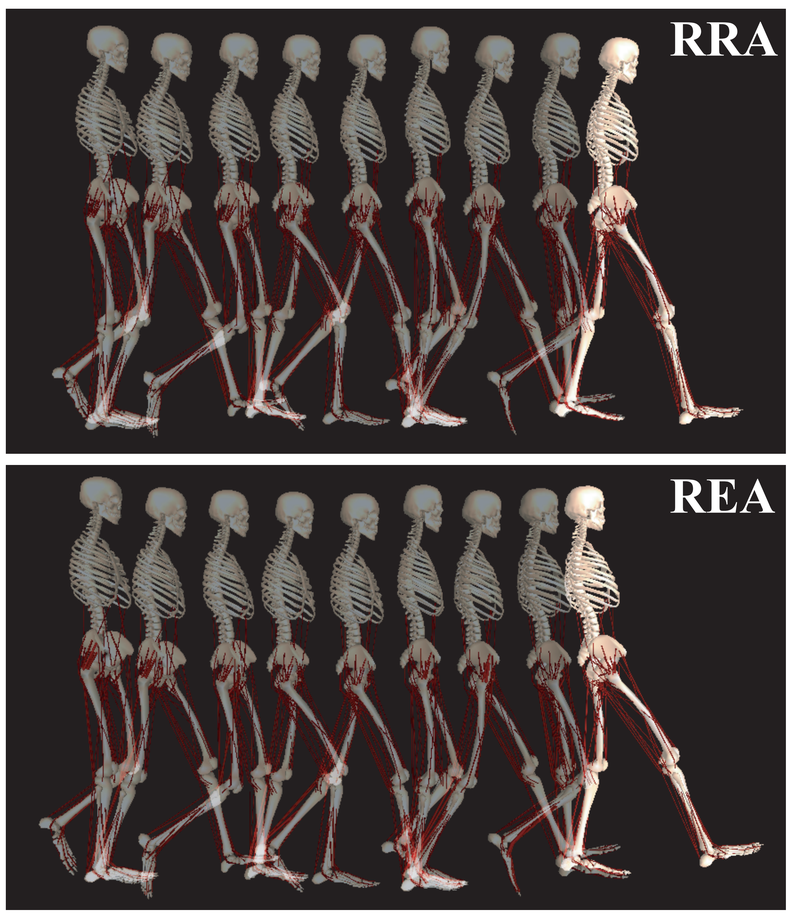
$$J(\vec{f}_{act}(t)) = \sum_{i=1}^{actuators} w_i \left( \frac{f_{act,i}(t)}{f_{act,i}^{opt}(t)} \right)^2 + \sum_{i=1}^{actuators} \omega_i (\ddot{q}_{des,i}(t+T) - \ddot{q}_{rra,i}(t))^2$$

Minimize change in $\boldsymbol{F}$ Minimize change in $\boldsymbol{a}$

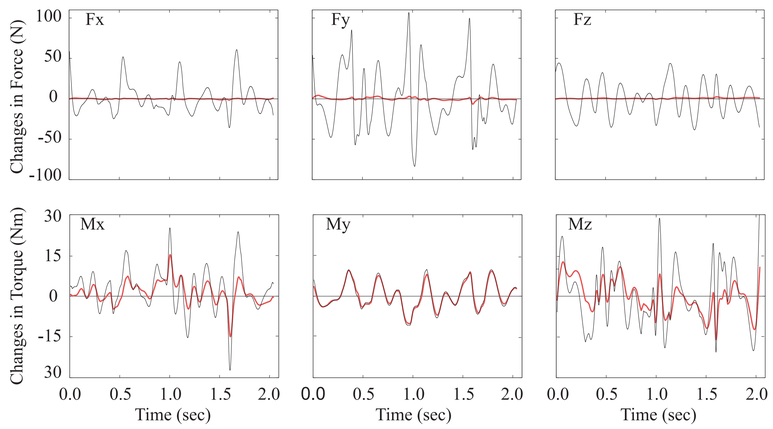
3. **Forward dynamics:** calculate the actual values of $\boldsymbol{a}$, represented by $\ddot{q}_{rra}$, based on the values of $\boldsymbol{F}$ from Step 2.

Does this method prevent both $\boldsymbol{F}$ and $\boldsymbol{a}$ from changing too much? To validate it, we used RRA to simulate a 2.0-s walking movement.

## Results




Changes in $\boldsymbol{a}$ made by RRA were small, while changes in $\boldsymbol{a}$ made by REA on the same movement data were problematic.




Changes in $\boldsymbol{F}$ made by RRA (red) were generally lower, and in some cases significantly lower, than if we had changed $\boldsymbol{F}$ alone (black), as in Previous Approach 1.

## Conclusions

RRA provides a major improvement over both of the previous approaches. We expect that RRA will enable us to simulate even longer movements, and if we can do this routinely for a variety of movements, we will enable a new, powerful way of doing biomechanics research.

### References

[1] Delp et al. (1990), *IEEE Trans Biomed Eng* **37**, 757-67. [2] Delp et al. (in press), *IEEE Trans Biomed Eng*. [3] Kuo (1998), *J Biomech Eng* **120**, 148-59. [4] Thelen and Anderson (2006), *J Biomech* **39**, 1107-15.

### Acknowledgements

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