Modeling muscle cross-bridge dynamics for movement simulations

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Introduction

Hill-type muscle models are poor at predicting muscle-tendon behavior during dynamic conditions.

1. Force generation is determined experimentally by measuring force-length (FL) and force-velocity (FV) relationships during static conditions.
2. These relationships are not necessarily generalizable to force generated during movement or in response to imposed stretch3
3. Force outputs only vary with length, velocity, and activation level, therefore lack history-dependent behaviors and transient muscle properties that emerge during eccentric contractions, such as short-range stiffness

Cross-bridge models exhibit short-range stiffness and history-dependent behaviors4 but are not typically implemented in muscle-tendon unit (MTU) simulations.

1. Acto-myosin interactions are responsible for FL and FV relationships2
2. Cycling activity in the cross-bridges also produces transient force responses that are affected by prior movement and activation4
3. Transient force responses due to cross-bridge attachment could influence energy storage within the tendon during locomotion

Our goal is to develop a simple cross-bridge model to be implemented in hopping simulations to study the effects of history-dependent force generation during rapid lengthening and shortening.

Objectives:
1. Confirm the model produces Hill-type FL and FV relationships5
2. Verify it produces transient cross-bridge behaviors, such as negative forces before detachment, that are not typically included in the Hill-type model
3. Confirm a biphasic tension response during eccentric conditions, i.e. short-range stiffness
4. Characterize the history-dependent behaviors in response to the same length and velocity inputs

Cross-bridge Model

Single half-sarcomere with a population of 6.9 x 1016 cycling cross-bridges in a two-state system

1. Detached
2. Attached

Force-length behavior

Early transients in cross-bridge force during shortening

Rapid, small-scale length changes stretch the attached cross-bridges without causing detachment4

Biphasic tension response during stretch

Scales with velocity in latter phase of stretch6,7,8

History-dependent force generation in the cross-bridges

Active Forces

Force responses are time-dependent when length and velocity are held constant

Discussion and future directions

Cross-bridge model produces FL and FV relationships that are scalable to Hill
1. FL and FV follow a similar shape but parameters must be tuned to real muscle and Hill parameters
2. Characteristic cross-bridge properties are captured by the model that are not present in Hill-type models
3. Cross-bridge dynamics are important for understanding force generated in a muscle during imposed length changes, such as those that occur in locomotion
4. Movement-history dependent changes in stiffness (referred to as thixotropic stiffness changes) may be important to dynamic and cyclic behaviors

Future directions:
1. We have integrated the cross-bridge model into the active muscle component of the hopping model to examine features of movement, such as energy storage and settling time, in stable and perturbed conditions

References:

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