A new muscle model for neuro-musculo-skeletal simulations

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1 Motivation

Understanding how the brain controls muscle force is important for treating neuromuscular disease and injury. Yet, our understanding of this process is remarkably incomplete [1]. Why has biology failed to solve to this problem? One explanation is that we do not yet fully understand how muscles work.

2 State of the Art

Zajac [2] provided a muscle model based on the sliding filament theory [3]. Yet, nearly 25 years of attempts to use Hill-Zajac models have ended in failure [4]. We suggest that an incomplete knowledge of muscle contraction has prevented an understanding of neural control of muscle force.

3 Our Approach

We developed a "winding filament" hypothesis for muscle contraction [5] in which the N2A region of titin binds to actin upon Ca^{2+} influx, and titin winds on the thin filaments during force development because the cross-bridges not only translate but also rotate the thin filaments.

4 Current Results

We developed a schematic concept (Fig. 1) that emulates the winding filament hypothesis: a contractile element (CE) turns a pulley (thin filament), which stretches a spring (titin). A ratchet prevents unwinding when energy is to be stored within the muscle.

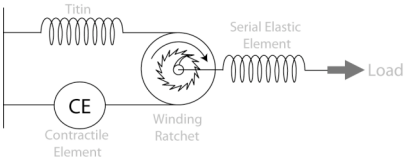

Fig. 1: Original winding filament model.

We used the model to predict force output during isovelocity stretch in soleus muscles of cat and mouse. The model displays force enhancement and depression in isovelocity experiments, and fits with an R^2 value of 0.93 for the experimental force data of isovelocity stretch (Fig. 2). In contrast, Hill-type models ***entirely lack*** history dependence, yielding an R^2 of 0.50. Hill-type models fail to account for force enhancement because springs are in series with the CE. The winding filament model accounts for history dependence because titin is oriented ***simultaneously in parallel and in series*** with the CE.

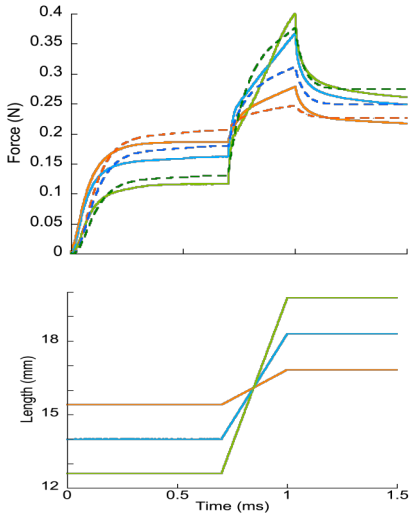

Fig. 2: Observed (solid lines) and predicted (dashed lines) force output (above) and length changes (below) in mouse soleus muscle during isovelocity stretch.

Internal work done by the CE and external work done by applied forces are stored as elastic energy in titin and total force is the sum of the titin force plus CE force. These results are obtained for a linear titin spring. Shortening is more challenging to fit than lengthening, given the linear stiffness assumptions of the first round of simulations. Current and future models will incorporate a nonlinear spring.

5 Best Possible Outcome

If the model is successful at predicting non-linear changes in muscle, it will transform our understanding of the mechanism of muscle contraction. These studies have the potential to improve models of muscle contraction and motor control, and to provide algorithms for controlling powered devices. Such understanding also can lead to entirely new ways to design actuators for dynamic systems that emulate humans.

Acknowledgement

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