A new muscle model with implications for actuation and control

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1 Introduction

The widely accepted theory of muscle contraction, known as the "sliding filament - swinging cross-bridge" theory, explains muscle contraction as resulting from the interaction between two motor proteins, myosin and actin, which are arrayed in thick and thin filaments within muscle sarcomeres (Fig. 1). Overlap between the sliding filaments determines the active muscle force (Gordon et al. 1966). When a muscle is activated, myosin cross-bridges bind to actin, hydrolyze ATP, and undergo a deformation (swinging) that translates the thin filaments (Huxley 2004), resulting in muscle contraction.

Despite decades of intensive research, many important properties of muscle remain unexplained by this theory (Herzog et al. 2008), and the goal of predicting how muscle forces change during natural movements remains elusive (Sandercock & Heckman 1997; Brown & Loeb 2000). Experiments using constant-velocity stretch and shortening (e.g., Sandercock & Heckman 1997) illustrate the non-linear viscoelastic properties of muscle; specifically the time-dependence and history dependence of muscle force output (Fig. 2). During constant velocity stretch, muscle force increases faster in the first 20 ms than during the next 50 ms of the stretch. After stretch, there is a long-lasting increase in force. Similar results are observed for constant velocity shortening. By adjusting their stiffness instantaneously to changes in load, muscles themselves control interactions between body and environment, and manage interactions between antagonistic muscles, which interact via their loads (Nishikawa et al. 2012).

2 The winding filament hypothesis

We recently developed a "winding filament" hypothesis for muscle contraction (Nishikawa et al. 2011, 2012; Monroy et al. 2011) that builds upon the sliding filament - swinging cross-bridge theory. In this hypothesis, the giant protein titin is "activated" mechanically by Ca^{2+} influx (Fig. 3), and is wound upon the thin filaments by the cross-bridges, which not only translate but also rotate the thin filaments (Fig. 4). Unlike the sliding filament theory, the winding filament hypothesis provides a plausible mechanism that can account for the non-linear, history-dependent properties of muscle that provide intrinsic stability to perturbations in load (Monroy et al. 2007; Nishikawa et al. 2007).

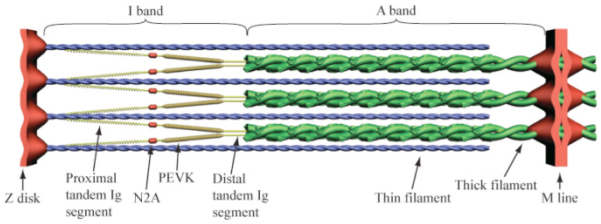

Fig. 1: Schematic diagram of a skeletal muscle half-sarcomere. Titin (yellow) is bound to the thin filaments (blue) in the I-band, and to the thick filaments (green) in the A-band.

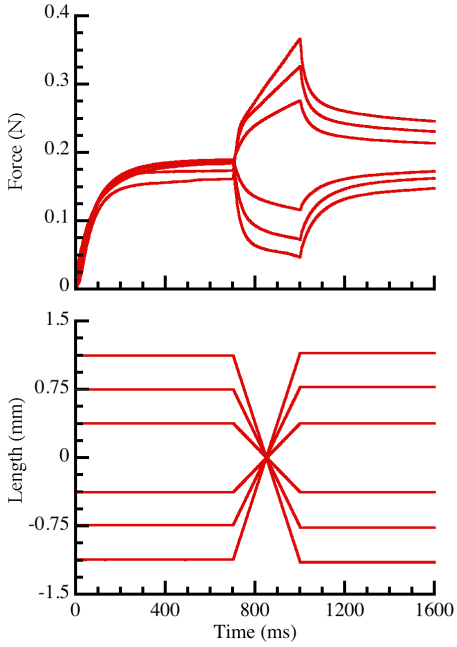

Fig. 2: Muscle force (above) and length (below) recorded during isovelocity experiments on an intact mouse soleus muscle.

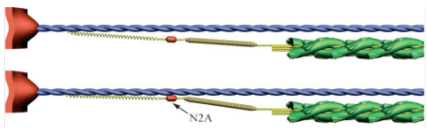

Fig. 3: Ca^{2+}-dependent binding of titin to thin filaments engages the titin spring. Above: Resting sarcomere at low [Ca^{2+}]. Below: Upon Ca^{2+} influx, titin binds to the thin filaments (blue), which shortens and stiffens the titin spring in active sarcomeres.

3 Computer simulations

We developed a computer simulation of the winding filament hypothesis (Fig. 5) in collaboration with Andy Ruina (Cornell University) and Dinesh Pai (University of British Columbia). The modeling and simulations were performed by Sang Hoon Yeo. In our model (Fig. 5), a Ca^{2+}-activated contractile element (CE) turns a pulley, which stretches an exponential spring. A ratchet resists unwinding by the spring during shortening. The contractile element (CE) represents the myosin cross-bridges, the pulley represents the thin filaments, the exponential spring represents the titin protein, and the ratchet represents electrostatic forces between titin and the thin filaments that resist unwinding.

We compared the performance of the winding filament model to that of a conventional Hill-Zajac model (Fig. 6), which represents the widely accepted sliding-filament, swinging cross-bridge theory. The winding filament model performs well at predicting non-linear muscle force output, including both depression of force with shortening and enhancement of force with stretch. These simulations demonstrate the ability of the winding filament model to account for the non-linear history-dependent viscoelastic properties that endow muscle with intrinsic stability to load perturbations. In contrast, the standard Hill-Zajac model fails to account for depression of force with shortening and enhancement of force with stretch (Fig. 6).

4 Bench model linear actuator

We developed a bench model linear actuator (Fig. 7) based on the computer model (see Fig. 5). In the linear actuator, Spring A represents titin and Spring B represents a tendon-like serial elastic element. The servo-controlled ratchet represents the N2A region of titin, which increases titin stiffness by binding to the thin filaments upon activation. The pulley attached to the DC Motor controls the position of the servo-controlled ratchet on the linear bearing, and thus the tension in Spring A and Spring B. A dual-mode force-lever (Fig. 8) is used to change the length of the system and measure the force output. A polymer cord is used to connect the components.

To control the actuator, a micro-controller (ATMega328) generates a pulse-width-modulated (PWM) signal, amplified by a dual H-bridge motor driver and sent to control the motor. The dual-mode force-lever senses the position of the lever and sends an analog signal to the AD converter of the micro-controller. The micro-controller can use the length signal for feedback control as needed, depending upon the particular experiment.

A simple experiment (Fig. 9) emulates the instantaneous automatic adaptation of force output during isovelocity shortening and lengthening (see

Fig. 4: Cross-bridge cycling winds titin on the thin filaments (arrow indicates direction of rotation), storing elastic potential energy during isometric force development.

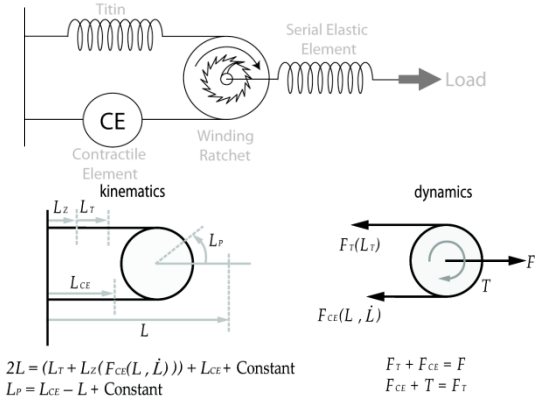

Fig. 5: Winding filament model (above) and constitutive equations.

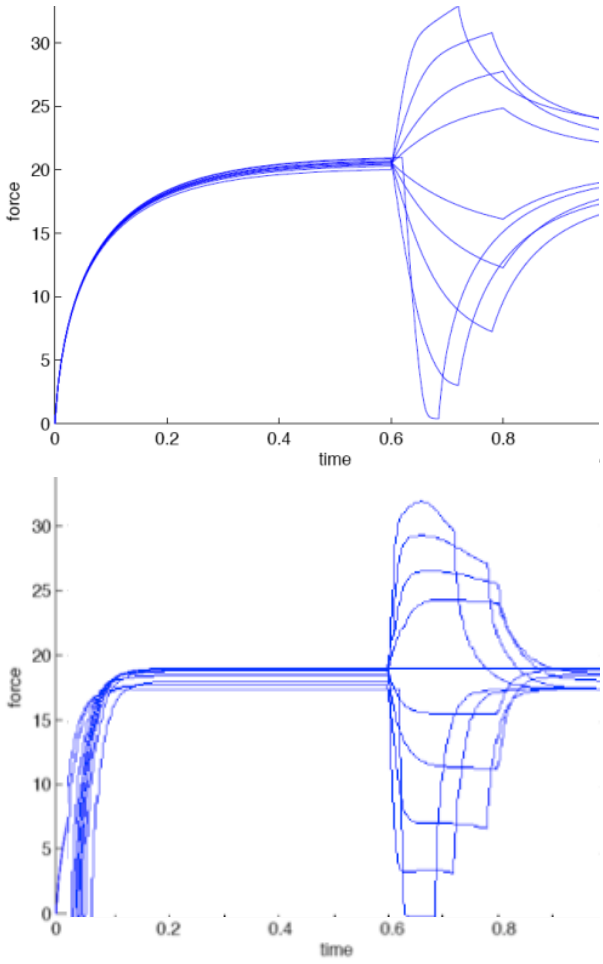

Fig. 6: Simulations demonstrate that the winding ratchet model (above) outperforms the Hill-Zajac model (below) at predicting non-linear force output in isovelocity experiments (compare to Fig. 2 top).

Fig. 2 for muscle data and Fig. 6 for simulation results). The procedure is to establish a pretension force in the system by winding the DC motor until a force value is measured at the dual-mode force-lever. The ratchet is activated once the initial tension level is achieved. This action establishes tension levels at both Spring A and Spring B. The dual-mode force-lever is then commanded to perform a rapid displacement of given amplitude and rate, and the torque at the dual-mode force-lever is measured before, during and after the displacement.

The results of isovelocity stretch and shortening experiments using the bench model are shown in Fig. 9. The shapes of the force output of the actuator in response to isovelocity stretch and shortening are similar to those of active muscle, especially compared to the force output of the Hill-Zajac model under the same conditions (see Fig. 6). The bench model shows similar time dependence (initially stiffer with time-dependent softening) and long-lasting force enhancement that persists after lengthening has stopped, as well as long-lasting force depression that persists after shortening has stopped. These features, including time dependence, force enhancement, and force depression are the precise features of muscle behavior that confer automatic, instantaneous adaptation to load perturbations. The results provide proof of concept that a relatively simple actuator design consisting of a DC motor embedded in a variable-length, passively stable architecture inspired by the winding filament model can reproduce the automatic, instantaneous adaptation of force output observed in muscles.

5 Open questions

What are the strengths and weaknesses of the winding filament model? Is the concept potentially useful for improving actuation and control of prostheses, orthoses and robots? What factors would limit the applicability of the hypothesis to human-engineered devices?

References

Monroy, J.A., Powers, K.L., Gilmore, L.A., Uyeno, T.A., Lindstedt, S.L., & Nishikawa, K.C. (2012). What is the role of titin in active muscle? *Exerc Sports Sci Revs*: Epub ahead of print.

Nishikawa, K.C., Monroy, J.A., Uyeno, T.A., Yeo, S.H., Pai, D.K., & Lindstedt, S.L. (2011). Is titin a winding filament? A new twist on muscle contraction. Proc Roy Soc B 297:981-990.

Nishikawa KC, Monroy JA, Powers KL, Gilmore, LA, Uyeno TA & Lindstedt SL. 2012. A molecular basis for muscle intrinsic properties: implications for motor control. *In*: Progress in Motor Control VIII (Richardson M, Riley, M & Shockley K, eds.) Springer, Basel. In press.

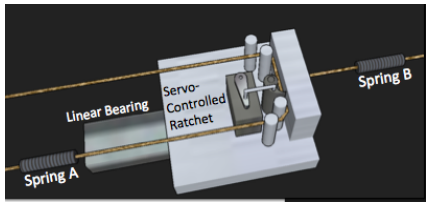

Fig. 7: Linear actuator design based on winding filament model (see Fig. 5).

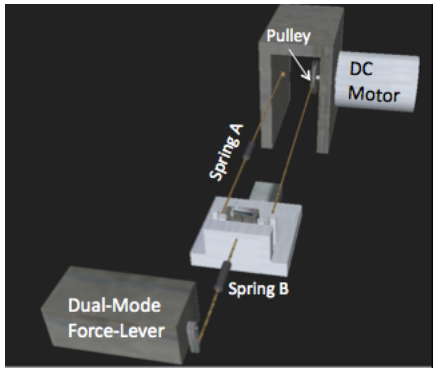

Fig. 8: The dual-mode force-lever is used to change the length of the actuator and measure the force output.

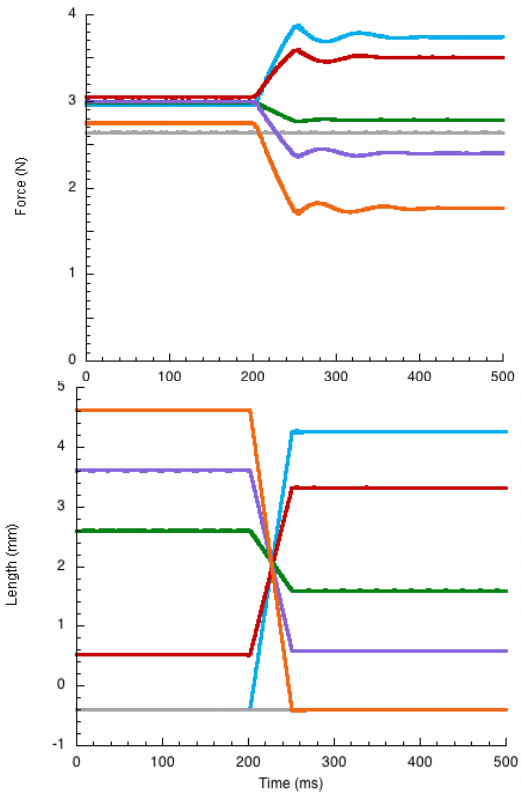

Fig. 9: Length (top) and force (bottom) traces from isovelocity experiments using the bench model actuator with no feedback control.