CONTROLLING COMPLIANCE: FEED-FORWARD STIMULATION PATTERN INFLUENCES ELASTIC TUNING DURING CYCLIC MUSCLE-TENDON CONTRACTIONS

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INTRODUCTION

Years of research on the mechanics and energetics of locomotion have established that compliant tissues (i.e. tendon and aponeurosis) are crucial in shaping efficient and stable locomotion. When muscle-tendon (MT) interaction dynamics are optimally 'tuned', series elastic tissues stretch and recoil accounting for much of the overall MT length change (Figure 1). Maximizing elastic energy storage allows in-series muscles to remain nearly isometric, reducing metabolic demand with little effect on overall MT power output (Roberts et al., 2011).

While the benefits of an optimally 'tuned' MT interaction are clear, the role of the nervous system in coordinating the timing and magnitude of muscle stimulation to optimize elastic energy storage and return is unclear. We hypothesize that stimulating a compliant muscle-tendon system at its passive resonant frequency will (1) maximize MTU force generation (2) minimize muscle contractile work and (3) maximize elastic energy storage and return. The combination of these outcomes would indicate and optimally tuned muscle-tendon control strategy.

METHODS

To investigate the effect that feed-forward neural control has on mechanical energetics (i.e. force and power production) we developed a simple mathematical model of a compliant muscle-tendon unit (MTU). The model includes a Hill-type muscle, or contractile element (CE) in series with a Hookean tendon-spring, or series elastic element (SEE) (Zajac, 1989) operating across a lever on a mass under constant gravitational force. We based our initial muscle (τ_{act}=0.03 s, τ_{deact}= 0.09 s, F_{max}=65 N, V_{max}=0.12 m/s, l_o=0.01 m, k_{CE}=7000 N/m) and tendon (k_{SEE}=7000 N/m, l_{slack} = 0.07 m) properties on data collected from bullfrog plantaris muscle-tendon units. We chose parameters for the

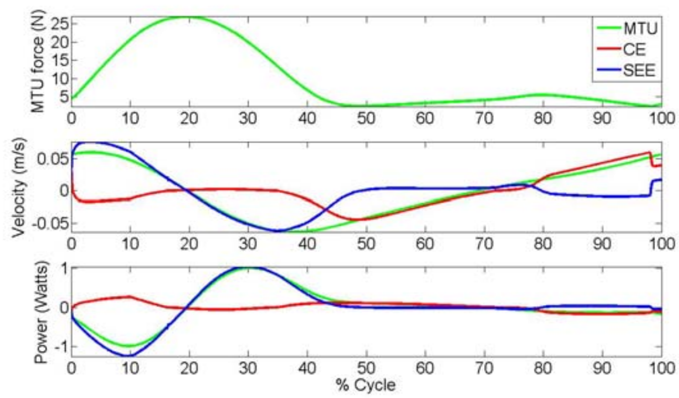

Figure 1. Force, velocity, and power generated during a single cycle with a stimulation of 100% and a period of 3Hz. Stimulation is from 0-10% of the cycle. Note significant elastic energy storage and return in the SEE.

load (mass=0.1 kg, in/out lever arm ratio = 0.1) to get a resonant natural frequency, ω_n= ~2.5 Hz, for the passive system without muscle activation. This simple model should scale well with muscle-tendon dynamics at distal joints of the lower-limb (e.g. ankle) of a wide range of terrestrial animals, including humans. To drive active muscle force generation we used a feed-forward neural control signal with no reflex feedback. This was achieved by stimulating the modeled muscle-tendon system over a range of amplitudes (20-100%) and driving frequencies about ω_n (2.0-4.0 Hz). By varying these parameters, we were able to systematically investigate the role that feed-forward neural control plays in effective energy storage and return in the SEE of a simple, compliant muscle-tendon system.

RESULTS

Every control strategy (i.e. amplitude + frequency combination) we used exhibited stable, periodic behavior after a short transient. A sample output showing MT dynamics from a single steady cycle with 100% stimulation at 3 Hz can be seen in Figure 1.

We decided on two key factors for determining the effectiveness of different neural control strategies. The first was average positive mechanical power generated over a stimulation cycle. In particular we examined how overall MTU power generation was distributed between individual components - the muscle (CE) and the series elastic tissues (SEE) (Figure 2). We consider small ratios of CE to total MTU average positive power to be an important indicator of system efficiency for a given frequency of stimulation. We found that maximum MTU and CE average power outputs occurred at the lower stimulation frequencies (Figure 2). Furthermore, the ratio of muscular (CE) to overall MTU positive power output was minimized at a value of ~20% over a range of driving frequencies spanning ~2.6-3.0 Hz.

The second key factor we examined was peak force generated by the *active* component of the contractile element over a cycle. As was expected, peak active force increased in proportion with stimulation amplitudes for all frequencies (Figure 3.). Active force generation depends on several well-known properties of muscle, including the force-length-velocity relationships that are accounted for in this model. In line with these properties, peak active force occurred when the muscle was at optimal length (~l_o) and velocity (~0) at the time of stimulation onset. As can clearly be seen in Figure 3, this occurred at ~3 Hz.

DISCUSSION/CONCLUSIONS

From our investigation of feed-forward neural control strategies, several important conclusions can be drawn. First, contrary to our hypotheses, maximal force and minimal contractile element positive work did not occur at the resonant frequency of our passive system (2.5 Hz), but at a range of frequencies above it. This is likely due to the non-linear contribution of active muscle to the overall stiffness of the system during dynamic contractions. Secondly, while *overall* MTU power output scaled well with stimulation amplitude, it had little effect on *within* MTU dynamics. Finally, while lower frequencies produced higher overall MTU power outputs, they required large amounts of work from muscular (CE) components and had minimal contribution from SEE's. This is in stark contrast to the bandwidth of tuned frequencies, where ~80% of positive power is produced by SEE recoil.

Future work will extend the model to include feedback pathways, and consider how optimal force generation/power production is influenced by both passive and active parallel mechanical assistance. This may provide insight into how feed-forward and feed-back control signals are modulated to re-tune MTU force/power generation when mechanical assistance is present.

REFERENCES

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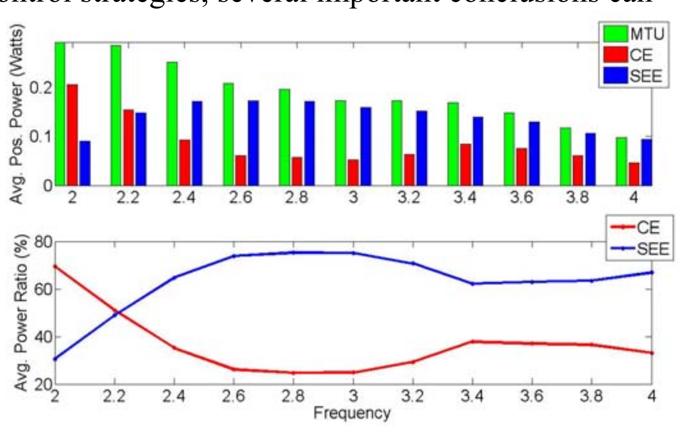

Figure 2. Graphs of (top, bars) average positive power output of the muscle-tendon unit (MTU), contractile element (CE), and series elastic element (SEE) and (bottom, lines) Power Ratios - CE/(CE+SEE) and SEE/(CE+SEE) versus stimulation frequency calculated over a single contractile cycle.

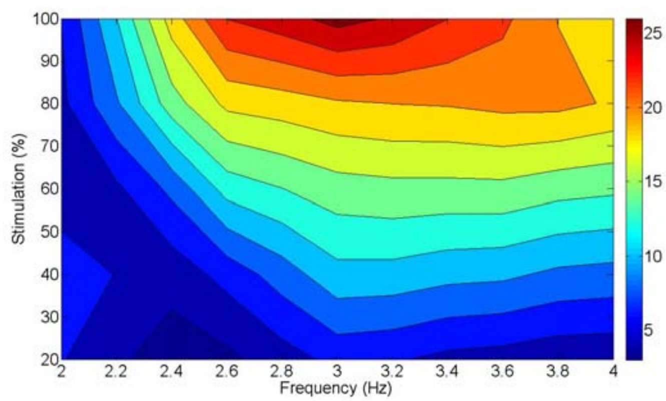

Figure 3. Contours of peak *active* contribution to contractile element force (Newtons) as a function of both magnitude and frequency of muscle stimulation. Note that peak active muscle force occurs when stimulated well above the natural frequency of the passive system (~2.5 Hz).