POSITIVE FORCE FEEDBACK ALLOWS FOR FASTER AND SAFER RECOVERY TIMES IN PERTURBED HOPPING – AT A COST

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INTRODUCTION

Legged locomotion research has primarily been interested in the study of steady state behaviors – walking, running and hopping. Several groups have taken a modelling and simulation approach, including some previous work in our lab, to study such behaviors [1]. However, humans – or animals in general – don't locomote in a flat world at constant speed. They need to be able to reject perturbations quickly and safely.

Bipedal birds achieve this by a proximo-distal gradient in their motor control strategy [2]. However, it's less clear what happens at the individual muscle level – especially in humans. Furthermore, the details of the neural control strategy (*i.e.*, reflex feedback vs feedforward contributions) are not well understood.

Modelling is a powerful approach to tackle this problem as the neuromechanics can be explicitly specified. Previous studies of simulated hopping using a model with a muscle *only*, driven by feedback and feedforward neural commands show that positive force feedback leads to improved response to perturbation [3]. However, most animals have tendons that can mechanically buffer unexpected perturbations and potentially limit injurious muscle strains [4]. We hypothesize that reflex feedback in conjunction with tendinous series elasticity can allow a compliant muscle-tendon system to recover from perturbations both rapidly and safely.

METHODS

We developed a mathematical model of a cyclically stimulated muscle-tendon unit (MTU) (Figure 1). It consists of a massless Hill-type muscle model with a parallel elastic element (PEE) – that together forms the contractile element (CE) – and a nonlinear spring that models the tendinous tissues (series elastic element (SEE)).

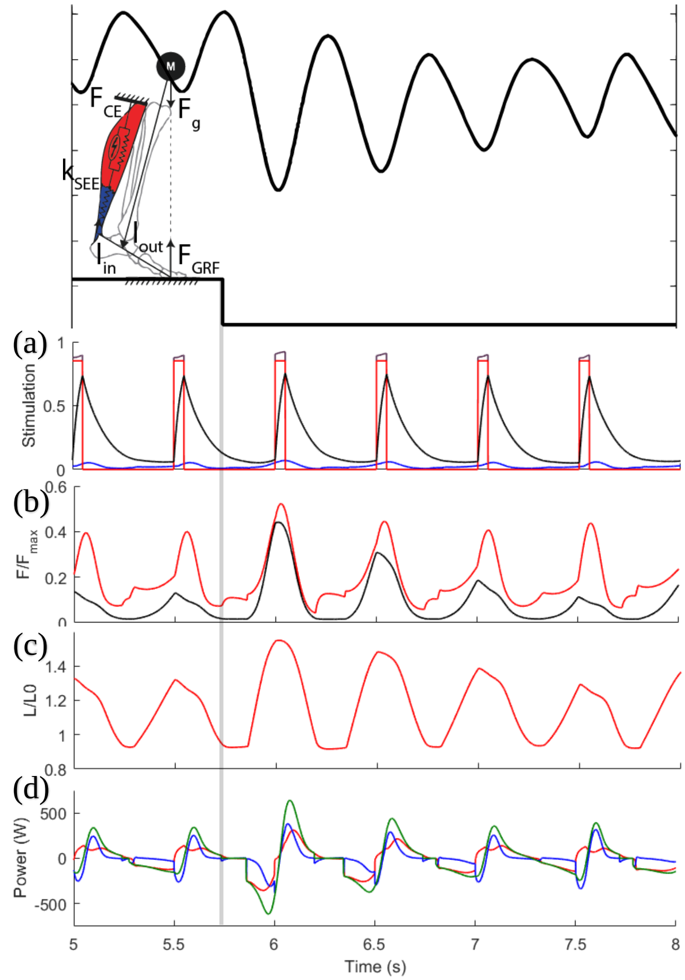

Figure 1: Time series data of (a) **Feedforward**, **Feedback**, **Total** Stimulation and **Activation** (b) **Total** and **Passive** CE Force (c) **CE Length** and (d) **MTU**, **CE** and **SEE** Power for Feedforward Fraction (FF) 0.85 and Positive Force Feedback (PFF) gain $15\text{x}10^{-5}$ N^{-1}

In the current model, a combination of positive force feedback (PFF) and feedforward (FF) signals stimulate the CE:

$$u(t) = FF(t) + (1 - FF(t)).\beta.F_{CE}^{\Delta t}$$

where $FF(t)$ is a square wave with 10% duty cycle and frequency of 2 Hz, β is the feedback gain and $F_{CE}^{\Delta t}$ is the CE force that is fed back with a physiological time delay of 20 ms.

This stimulation gives rise to an activation $a(t)$, which in turn gives rise to active force in the CE in addition to the passive force from the PEE. This total force actuates a point mass in a gravitational field through a mechanical advantage. We apply a perturbation after 10 cycles of hopping to the MTU by virtually moving the ground by $-5cm$ (~20% MTU slack length). We then allow the model to return to steady hopping. We determine settling time as the time point where the difference in peak total energy levels of the system are within 1% of the energy injected into the system. We calculate metabolic cost based on the velocity of the CE, scale it by activation, integrate it and divide that by body mass and total time to get a mass specific average metabolic rate [5]. To address the hypothesis, we simulated the system at many combinations of feedforward fraction (0-1.0) and positive force feedback gains (0-1.8x10^{-6}).

RESULTS AND DISCUSSION

Increased feedback gain or feedback fraction did not necessarily improve settling time. In fact, whether increasing the feedback percentage or feedback gain, the system first gets slower and then faster at returning to steady hopping (*i.e.,* moving vertically or horizontally across Fig. 2(a)). Interestingly, there are many solutions in the parameter space where settling time is lower (2-5 hops) than the pure feedforward case (6 hops – top left corner of contours in Fig. 2).

Increasing either the feedback fraction or increasing feedback gain, resulted in shorter CE strains during recovery from perturbations (Fig. 2(b)). Compared to the pure feedforward case, CE strains are reduced by up to ~10% in cases with high feedback. Thus, positive force feedback potentially acts as a safety mechanism that allows the muscle to maintain shorter and thus safer operating lengths in response to sudden perturbation.

In general, metabolic cost was higher for systems with feedback when compared to purely feedforward control strategies (Fig. 2(c)). For example, the metabolic rate was 20% higher at 0.95 feedforward fraction and 9x10^{-5} N^{-1} force feedback gain than the purely feedforward case (1.3 W/kg and 1.1 W/kg). Increased metabolic demand of feedback based neuromuscular control strategies was a result of more reliance on active rather than passive muscle force contributions (Fig 1(b)).

CONCLUSIONS

Optimally tuned positive force feedback in the context of series compliance within a muscle-tendon unit can facilitate recoveries from unexpected perturbations that are both fast and safe. However, the reduced settling times and safer operating lengths of the contractile element come with a fundamental tradeoff of increased metabolic cost. We have begun to test the predictions of this simple model by examining the behavior of individual muscle-tendon units in both humans (using ultrasound imaging) and on the benchtop (using sonomicrometry) during perturbed cyclic contractions. Insights from these experiments will be used to guide the design of next generation lower-limb robotic devices capable of seamless adjustment to environmental variation.

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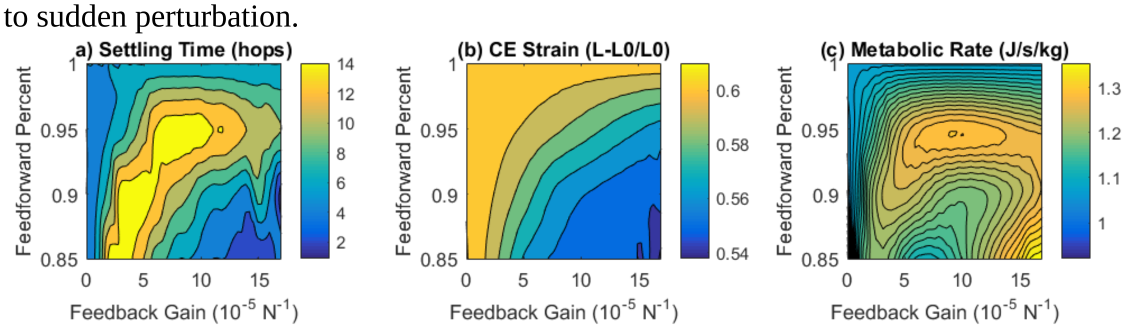

Figure 2: Contours as a function of feedforward (FF) contribution and positive force feedback (PFF) gain for (a) Settling time, (b) Peak strain of CE after perturbation and (c) Mass specific average metabolic rate.