MUSCLE-TENDON MODEL PREDICTS POSITIVE FORCE FEEDBACK LEADS TO SAFER, *NOT* FASTER RECOVERY FROM PERTURBATION

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INTRODUCTION

The task of locomotion in vertebrate animals is enabled by muscular contraction that is orchestrated by the coordination of feedforward planning and reactive feedback. This coupling has made it challenging to accurately model neuromuscular activity in order to fully understand the complex dynamics of locomotion. The mechanical properties of the limbs alone can produce passive motion, but it is clear that reflex action initiated by the spinal cord is also responsible for at least part of the physiological response necessary to induce and maintain locomotion. While multiple models have been produced for examining constant, steady locomotion [1], far fewer have been developed to evaluate responses to perturbations over uncertain terrain. Perturbations in the height or direction of the substrate require some (neuro)mechanical response in order for an animal to maintain balance and orientation.

It has been shown that maintenance of locomotion following a perturbation is enabled through a number of different mechanisms. Natural limb dynamics allow increased energy absorption following a perturbation simply by automatic changes in limb posture. This mechanism allows animals to maintain consistent velocity control even over rough terrain [2]. Improved response to perturbations has also been shown in muscle models which utilize a combination of feedforward (FF) and positive force feedback (PFB) to maintain constant hopping [3]. However, the modeling framework used to evaluate this combinatorial response (FF+PFB) consisted only of a muscle without its series tendon.

Here, based on findings in [3], we aimed to use a model of a compliant muscle tendon unit (MTU) to test the robustness of the hypothesis that a combinatorial feedforward/positive force feedback (FF+PFB) strategy would lead to improved perturbation rejection, as denoted by a faster recovery time to steady-state periodic motions.

METHODS

For this study, we implemented a MATLAB® Simulink Model developed by Robertson et al. [1] and added a positive force feedback mechanism following [3]. This model contained both a massless Hill-type muscle and parallel elastic element (PEE) comprising the contractile element (CE) in-series with a non-linear tendon spring (SEE). The model approximated a human triceps-surae Achilles tendon complex, in which the gastrocnemii and soleus muscles were integrated as a single muscle within the model. The model parameters were tuned such that a stimulation frequency of 2.0 Hz, with a duty cycle of 10% and a 100% stimulation level, produced a stable hopping pattern, with low risk for injury as indicated by the fact that the average positive power output with this setup is primarily produced by the SEE limiting the amount of stretch in the CE.

The perturbation that was added to the model was implemented as a change in velocity within the system's load dynamics. A transient acceleration of $-1.5\ m/s^2$ was added to the derivative of velocity of the mass that was driven by the MTU. This addition to the velocity was initiated only after the first 10 seconds of the simulation had passed, giving the system time to stabilize from the initial conditions, and was applied for a duration of 0.1 seconds of the simulation time. The added velocity was only applied during time when the change in muscle-tendon unit length was positive (*i.e.*, during shortening just before ground contact).

Feedback was incorporated into the system by adjusting two parameters, beta (β) and feedforward (FF) pulse percent contribution. Beta is a factor by which the force level is multiplied to produce the induced positive force feedback, while the FF pulse percent contribution indicates the level at which the 2.0 Hz, 10% duty cycle FF input pulse was set to drive the system. A time delay of 20 milliseconds was added to the force feedback pathway.

The system settling time was determined by evaluating a 10-cycle average of the net CE power at each cycle to determine when the CE cycle power returned to a level below 20% of the maximum 10-cycle average CE power. The number count of cycles following the perturbation that it took for average net CE power to fall below this 20% threshold and remained below it for the duration of the simulation was deemed the settling time.

RESULTS AND DISCUSSION

Simulations were performed for different FF+PFB combinations to study the system response for a perturbation of 40% MTU rest length applied at t = 1.75s. Figure 1 shows a contour plot for the number of cycles the system requires to settle in each of the simulated cases. Results from Fig. 1 indicate that a combined FF+PFB system does not improve recovery time when compared to a 100% FF system. Figure 1 also shows that only particular FF+PFB combinations maintain low settling time values while other combinations of FF+PFB have greatly diminished perturbation rejection capability.

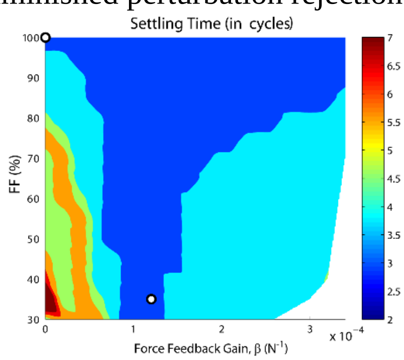

Figure 1: Settling time contours as a function of feedforward (FF) contribution and positive force feedback (PFB) gain, β.

We considered two cases, (circled dots in Fig. 1) in detail to evaluate the differences in system performance between: (1) a 100% FF system with no PFB and (2) a combined FF+PFB system with 35% FF and β of 1.2e-4 N^{-1}. While settling time for both the cases was the same, the MTU dynamics over perturbation rejection varied as observed from the time series plots of the two cases (Fig. 2). The time variation of the absolute lengths shows that the

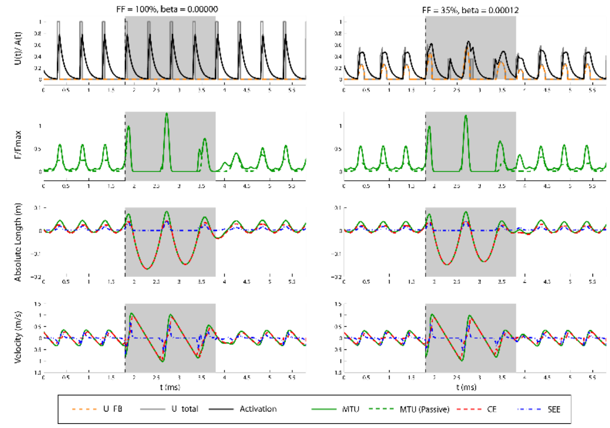

Figure 2: Time series results for points highlighted in Fig. 1.

MTU recovers at shorter CE lengths for the FF+PFB system (Fig. 2(f)) as compared to the 100% FF case (Fig. 2(e)). Observations from the force-length plots for the two cases (Fig. 3(a) and (b)) show that in FF only case, the CE stretches to an extent where it operates predominantly in the injury prone region (large strains) after the perturbation has been applied while the CE spends more cycles at safer, shorter CE operational range for the combined FF/PFB case. Therefore, while we obtain good system stabilization with the 'preflexive' system (100% FF), the hypothesis that the reflex (PFB) reduces settling time is not supported. That is, addition of positive force feedback reflexes to the system affords a safer, yet equally fast return to stable hopping.

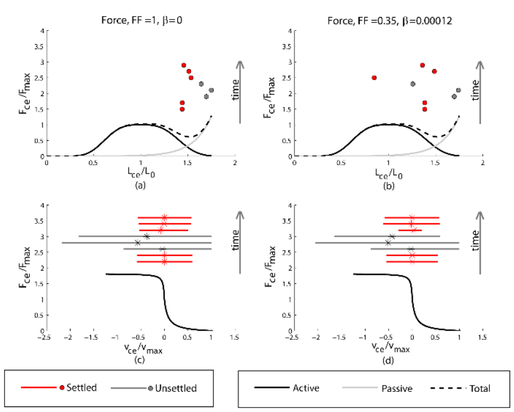

Figure 3: FL-FV regimes for settled and unsettled cycles.

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