More Is Not Always Better: Consequences of Exoskeleton Assistance in a Compliant Muscle-Tendon System

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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 [1]. Achieving a 'tuned' state in a compliant muscle-tendon unit (MTU) depends on optimal interaction between the frequency and amplitude of muscle activation, material properties of series elastic tissues, and actuation properties of the biological muscle (e.g. activation dynamics, force-length, and force-velocity). Maximizing elastic energy storage and return in complaint tissues allows series muscles to remain nearly isometric, reducing metabolic demand with little effect on MTU power output [2, 3]. It is not surprising, then, that humans prefer to use neuromuscular control strategies during cyclic movements that allow their muscles to operate with near-isometry when coupled with a series elastic tendon [3-5].

In recent years, there has been rapid progress in the development of wearable robotics designed to assist/enhance human movement [6, 7]. Despite technological advances, few studies have examined the effects of parallel mechanical assistance on underlying MTU interaction dynamics. Because it is difficult to make direct measurements of in-vivo MTU behavior, we developed a model of assisted human hopping to address key questions regarding human physiological response to wearable robotic assistance provided via a spring loaded exoskeleton (Exo). We hypothesize that 1) the coupled Exo-MTU system can produce periodic mechanical power output by trading off increased Exo stiffness with decreased muscle activation and that 2) the MTU will continue contracting with near-isometry under these conditions resulting in reduced CE power and force production.

Methods

The biological MTU in this model is comprised of a single Hill-type muscle, or contractile element (CE) in series with a Hookean tendon-spring, or series elastic element (SEE) operating with a fixed mechanical advantage on a mass under constant gravitational load. We based our muscle-tendon properties (F_{max} = 6000 N, v_{max} = .45 m/s, l_0 = .055 m, k_{CE} = 90,000 N/m, k_{SEE} = 180,000 N/m, l_{slack} = .237 m) and activation dynamics (*duty* = 10%, τ_{act} = .011 s, τ_{deact} = .068 s) on data documented for the human triceps surae-Achilles tendon complex [8]. We chose parameters for the load (M = 35 kg, in/out lever arm length ratio ~.33) to reflect realistic body weight and mechanical advantage seen at the ankle joint of a single limb during two-legged hopping.

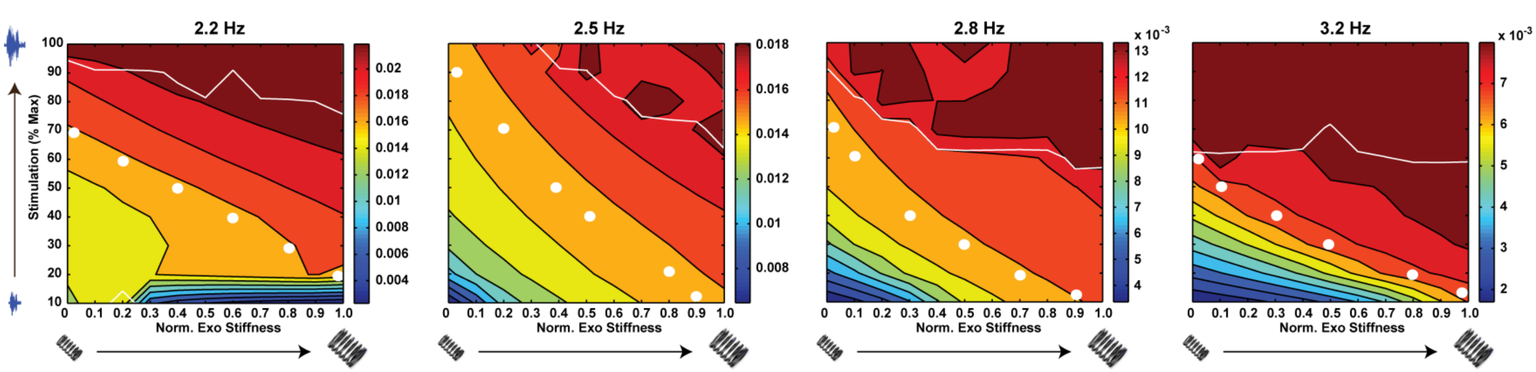

Figure 1: Plots of average positive power produced in the Exo-MTU system for each of the four operating frequencies over the full range of stimulation amplitude and exoskeleton stiffness. Exoskeleton stiffness is normalized to k_{MTU} and Power production to F_{max}*v_{max} for the CE. Contour scaling for each operating frequency is indicated by the colorbar to the right of each graph. Regions exhibiting non-periodic behavior are bordered in white, and points selected for further analysis are indicated by white dots. MTU and Exo component data for each dot can be seen in **Figure 2**.

To drive muscle force generation, we used a purely feed-forward neural control signal. The modeled muscle-tendon system was stimulated over a range of muscle activations (10-100% of maximum) and frequencies (2.2, 2.5, 2.8, and 3.2 Hz). We chose these operating frequencies because they reflect observed human behavior, and exhibit near-isometry for in-vivo and modeled conditions in the absence of assistance [4]. To model the effects of a wearable passive Exo at the ankle, we provide parallel assistance with a linear spring that has a slack length equal to the combined optimal muscle fascicle length (l_0) and series tendon slack length (l_{slack}). Modeled exoskeleton stiffness ranged from 0-100% of the stiffness of the purely passive MTU (k_{MTU} = 60,000 N/m). By varying activation amplitude, frequency, and coupled Exo-MTU stiffness we were able to explore how the addition of a passive linear spring in parallel with the human triceps surae-Achilles tendon complex affected the naturally efficient mechanics of the MTU.

Results/Discussion

At all frequencies, a majority of stimulation amplitude/Exo stiffness combinations resulted in mechanics that were periodic with stimulation. Non-periodic behavior was observed at every frequency for high Exo stiffness and high stimulation amplitude (**Figure 1**). The Exo was able to make significant contributions to MTU-Exo power and force production, particularly for low stimulation amplitude and high stiffness conditions (**Figure 2**). We observed contours of equal power production for the Exo-MTU system that spanned stiffness-stimulation parameter space at all frequencies by trading increasing exoskeleton stiffness for decreased muscle activation, in support of hypothesis 1. Power output from the CE was frequency dependent, increasing dramatically at the lowest frequency and decreasing only slightly at the highest with system power output held constant (**Figure 2**). Despite reductions in CE peak force and rate of force along these contours, there were consistent increases in CE average operating length/velocity and passive force. This indicates a loss of isometry and previously efficient MTU mechanics, contradicting hypothesis 2. All of these variations in mechanics will affect both metabolic cost and injury risk; what that effect will be, however, cannot be determined based on model results. Future experiments in humans will test model predicted variations in MTU mechanics when assistance is applied, and attempt to determine what, if any, mechanical aspects of assisted hopping drive metabolic cost and human preference.

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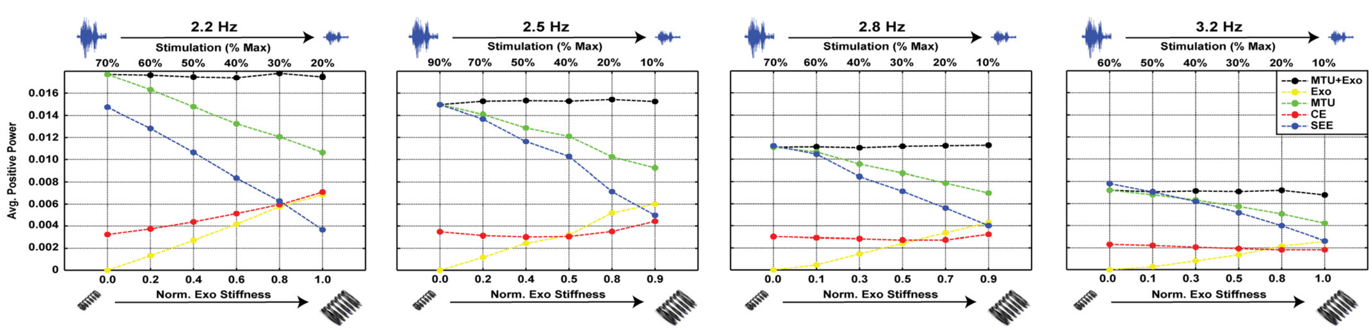

Figure 2: Plots of average positive power over a cycle of stimulation for each component of the MTU system. Each point corresponds to a white dot in the MTU-Exo average positive powers plotted in **Figure 1**, horizontal axes are not to scale. Moving from left to right decreases stiffness and increases activation.