Influence of Exoskeleton Compliance and Neural Control Strategy on Ankle Muscle-Tendon Interaction Dynamics During Simulated Human Hopping

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Introduction/State of the Art

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 contractile element (activation dynamics, force-length, and force-velocity). When MTU dynamics are optimally 'tuned' series elastic tissues stretch and recoil, accounting for the majority of overall MTU length change. 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 in a nearly isometric state 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

To investigate the effects of mechanical assistance on compliant muscle-tendon interaction dynamics, we developed a simple mathematical model of the human triceps surae-Achilles tendon in parallel with a passive Hookean spring. 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 across a lever with a fixed mechanical advantage on a mass under constant gravitational load. We based our muscle-tendon properties (maximum active force F_{max} = 6000 N, maximum CE velocity v_{max} = .45 m/s, l_0 = .055 m, k_{CE} = 90,000 N/m, k_{SEE} = 180,000 N/m, slack length 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.

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

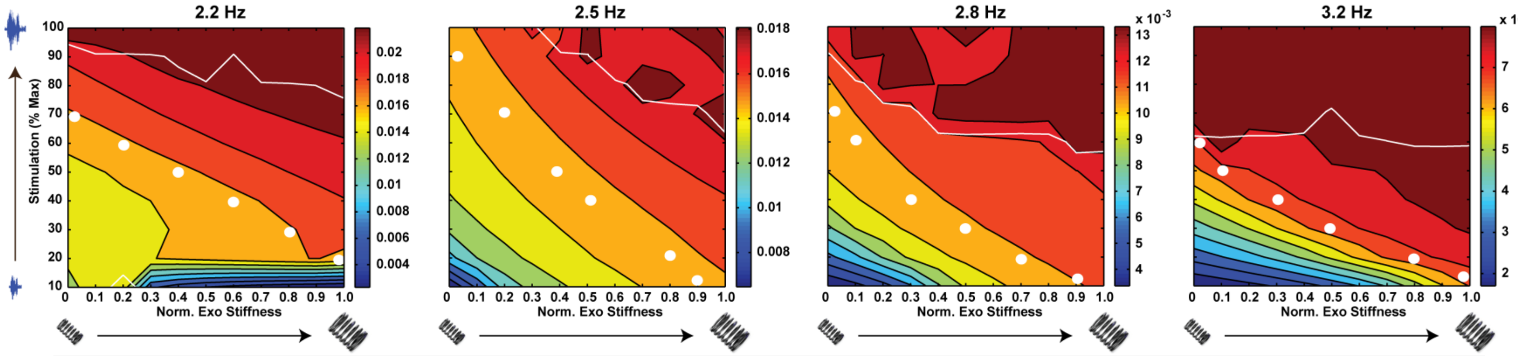

Figure 1: Plots of average positive power produced in the Exo-MTU system for each of the four operating frequencies over the full range of stimulation amplitude and exoskeleton stiffness. Exoskeleton stiffness is normalized to k_{MTU} and Power production to $F_{max}*v_{max}$ for the CE. Contour scaling 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**.

and modeled conditions in the absence of assistance [4]. To model the effects of a wearable passive Exo at the ankle during hopping, we provide parallel assistance with a simple 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 four frequencies, a significant portion of stimulation amplitude/Exo stiffness combinations resulted in mechanics that were periodic with stimulation frequency. Non-periodic behavior was observed at every frequency for high Exo stiffness and high stimulation amplitude. Higher frequencies resulted in larger regions of non-periodic behavior (**Figure 1**). In many cases, 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 (**Figure 1**). These contours traded increasing exoskeleton stiffness for decreased muscle activation while maintaining constant system power output, in support of with hypothesis 1. Despite reductions in CE 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, contrary to our expectation stated in hypothesis 2. For the 2.2Hz operating frequency along a contour of equal MTU-Exo power, decreasing activation and increasing assistance actually *increased* muscle power output. At 2.5 and 2.8 Hz CE power remained nearly constant on a contour of MTU-Exo power, with slight minimums at intermediate levels of stiffness and activation. At 3.2 Hz there was a slight decrease in CE power while decreasing activation, increasing Exo stiffness, and constant MTU-Exo power (**Figure 2**).

Changes in CE power vary across frequency, but average operating velocity increases consistently with greater assistance. CE Rate of force also decreases consistently as assistance is increased. 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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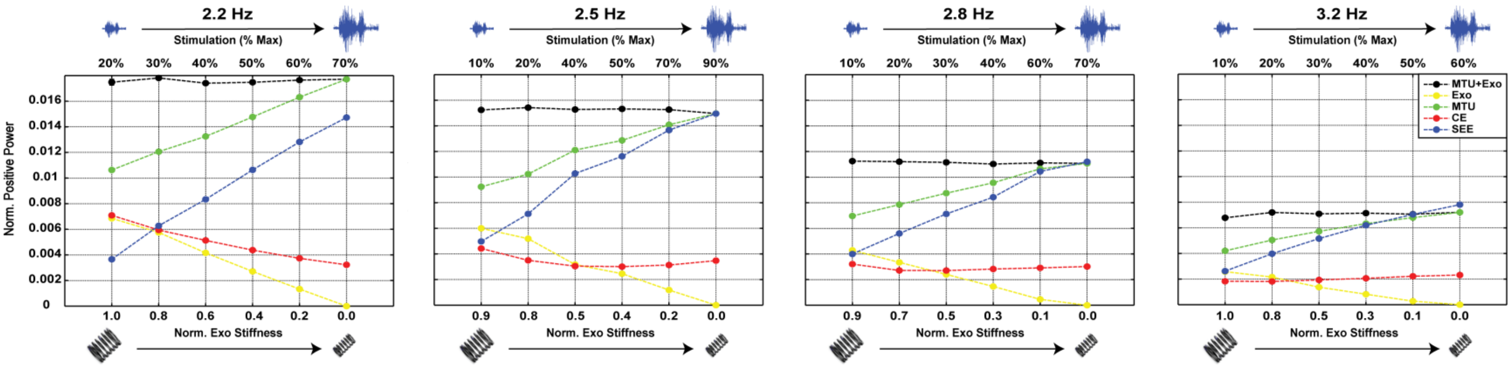

Figure 2: Plots of average positive power over a cycle of stimulation for each component of the MTU system. Each point corresponds to a white dot in the MTU-Exo average positive powers plotted in **Figure 1**, horizontal axes are not to scale. Moving from left to right decreases stiffness and increases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