AN IN VITRO APPROACH FOR DIRECTLY OBSERVING MUSCLE-TENDON DYNAMICS WITH PARALLEL ELASTIC MECHANICAL ASSISTANCE

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INTRODUCTION

Recent advances in materials science, controls, and raw computational power, have made wearable exoskeletons (Exos) capable of assisting and/or enhancing the power and economy of movement a reality [1]. Despite these advances, little is known about human adaptation and response to assistance at the muscle level [2]. This is of particular importance in compliant muscle-tendon units (MTU) that rely on high forces to store and return energy in series tendon (*e.g.,* the human triceps-surae Achilles tendon complex). Previous human [3] and modeling [4] studies indicate that reducing force demands on the plantarflexors can have energetic benefits [1-3], but that more assistance is not always better [3-4] because biological MTU interactions become 'detuned'.

To better understand how the neural control and biological actuator properties drive emergent mechanics, we developed a hybrid bio-robotic system which implements inertial environment/Exo simulations from previous modeling work [4] on a feedback controlled ergometer. Incomplete models of biological muscle are replaced with the real thing. Based on previous observation, we predicted that the combination of increased Exo stiffness and reduced muscle activation would result in (1) reduced forces in biological tissues [2], (2) constant joint (*i.e.,* combined MTU+Exo) stiffness in both assisted and unassisted conditions [5], (3) reduced energy storage and return in series tendon [2], and (4) increased muscle excursions which, combined with reduced forces, would result in constant average positive mechanical power from active muscle [2]. We further hypothesized that (5) augmenting Exo stiffness would alter emergent phasing dynamics of the MTU+Exo system, driving it away from values ideal for 'tuned' MTU interactions [6,7].

METHODS

Five adult bullfrogs (*Rana Lithobates*) were euthanized, and their plantaris muscle-tendons removed with care taken to preserve the sciatic nerve. Muscles were instrumented with sonomicrometry, a bipolar electrode cuff was placed around the intact nerve, the limb was anchored in a chamber of oxygenated ringers, and the free tendon was attached via friction clamp to a feedback controlled motor.

Muscle activation was controlled with a 'pulsed' rate coding approach shown to robustly modulate force output (p = 0.0002, data not shown). Environment controllers simulated a mass in gravity acting via fixed mechanical advantage on a simulated Exo spring and actual biological MTU (**fig. 1a**). Mass and lever arm ratios were selected to drive the resonant frequency of biological MTU and mass/lever system to 2Hz, ensuring uniform patterns

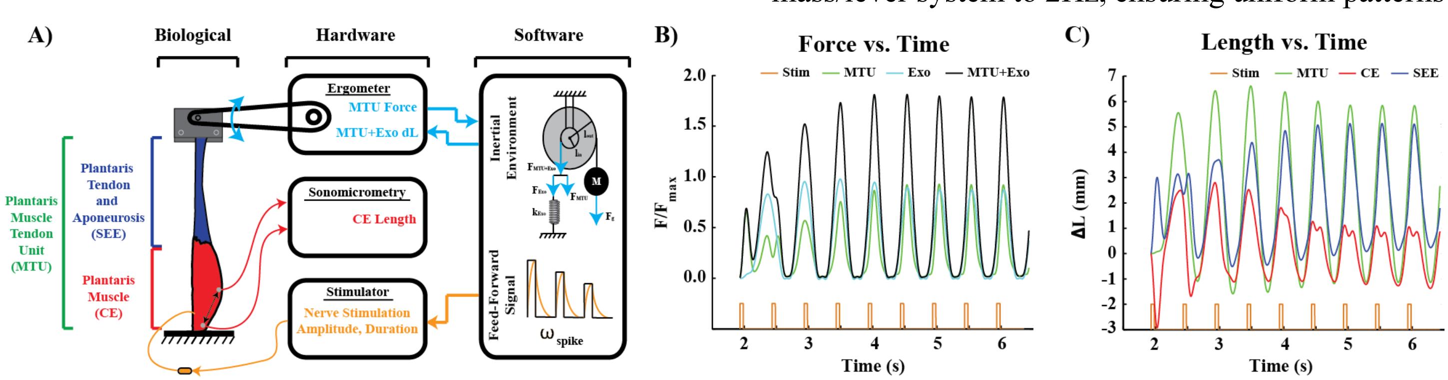

Figure 1 **A)** Schematic of experimental setup and control workflow. **B)** Force vs. time and **C)** length versus time for a representative trial in the 60Hz, 60%k_{MTU} condition.

of neural stimulation were applied in all preparations. Exo stiffness was applied as a percentage of measured passive MTU stiffness. Combinations of neural activation/Exo stiffness were selected based on previous modeling studies [4], and meant to mimic a human response to elastic Exo assistance.

For each preparation, maximal muscle forces (F_{max}) were measured in 300ms fixed-end contractions. Next, a baseline fatigue measurement was taken. Then the passive oscillation frequency of the MTU /environment systems was measured, MTU stiffness was calculated, and mass/mechanical advantage parameters were varied to achieve a natural oscillation frequency of 2Hz. Next, 3 dynamic conditions using predetermined combinations of stimulation frequency and Exo stiffness (applied as a percentage of measured MTU stiffness) were performed in a random order. Conditions used in this study were (100Hz, 0%k_{MTU}), (60Hz, 60%k_{MTU}), and (40Hz, 120%k_{MTU}), and each was performed for 10 contractions. Finally, another fatigue measurement was taken to ensure force declines did not substantially influence findings.

RESULTS AND DISCUSSION

For all conditions explored here, periodic MTU and MTU +Exo behavior was observed after 2-3 cycles of contraction (**fig. 1B, C**). The final five were used in analysis. Study outcomes agreed with our initial predictions, and we observed (1) reduced biological forces (**fig. 2A**), (2) constant MTU +Exo stiffness (**fig. 2B**), (3) reduced energy cycling in series tendon (**fig. 2C**), and (4) increased muscle excursions and constant muscle average positive power (not shown). We are confident that this system reliably mimics the human neuromechanical response to Exo assistance during hopping.

We also observed emergent shifts in phasing of stimulation onset relative to minimum MTU length and peak force, in agreement with (5) (**fig. 2D**). This relationship is known to be critical for efficient MTU function [6]. Previous work showed that driving a biological MTU and lever-mass system at its passive oscillation frequency (ω_0) resulted in emergent frequency-phase coupling favorable to 'tuned' muscle-tendon interactions [7]. The value of ω_0 was predicted by the following equation:

$$\omega_0 = l_{in}/l_{out}\sqrt{k_{MTU}/M}$$

with l_{in}/l_{out}: in-out lever arm ratio, k_{MTU}: passive MTU stiffness, and M: mass of the load [7].

Based on observations from this study and previous findings [7], it is clear that the driving frequency of the biological system relative to the system-level natural oscillation frequency is of critical importance for tuning muscle-tendon interactions. In other words, if too much Exo assistance/stiffness is applied and movement frequencies are not varied in response, MTU mechanics can become 'de-tuned' to the point of detriment. These findings also suggest that it may be possible to 're-tune' limb mechanics around existing patterns of neural control using a passive Exo device. This would be of critical importance in clinical populations where limb/system mechanical properties are altered, and reflex feedback required for 're-tuning' movement patterns around limb physiology is diminished (*e.g.,* stroke, spinal cord injury, aging, obesity).

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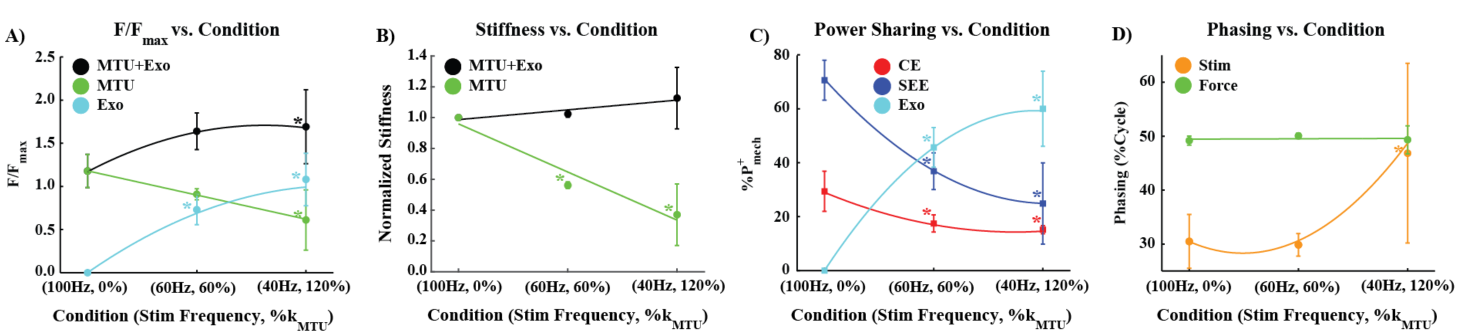

Figure 2 Plots of **A)** Normalized peak force, **B)** Stiffness, **C)** Sharing of average positive power, and **D)** Stimulation and peak force phasing relative to minimum MTU length. A * indicates statistically significant variation relative to the unassisted condition.