Estimated changes in muscle-level dynamics and energetics under different levels of exoskeleton-applied work and torque

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1 Introduction

Assisting human locomotion with ankle exoskeletons is a complicated task, requiring consideration of both biological and device contributions to assisted joint mechanics. Assistance techniques have typically involved some combination of work input and torque support. The complex interaction that arises between the exoskeleton and human neuromuscular system, however, makes it difficult to understand why certain techniques are more effective than others and comparisons have often been confounded by differences other than device behavior. We previously conducted an experiment to study the independent effects of a specific mode of exoskeleton-applied net work and average torque on human mechanics and energetics [1]. We systematically varied net work independently from average torque while subjects walked with a unilateral ankle exoskeleton. We measured metabolic energy consumption, ground reaction forces, joint positions, and muscle activity.

Increasing net exoskeleton work, as delivered in this study, reduced metabolic energy consumption, while increasing average exoskeleton torque, as applied in this study, increased metabolic energy consumption. The reduction in metabolic rate with increasing exoskeleton work seems to have been a result of reduced assisted ankle plantarflexor activity and contralateral knee extensor activity. Based on preliminary electromyographic and kinetic analyses, as net exoskeleton work increased, soleus muscle activity during late stance decreased while peak muscle force remained relatively constant. This may have been due to changes in the timing of muscle activation and force generation as biological ankle torque appears to have peaked and dropped-off earlier with increasing work input. Total assisted ankle push-off work increased with increasing exoskeleton work, which affected overall center of mass mechanics and resulted in reduced effort of the contralateral knee around the step-to-step transition.

The increase in metabolic rate with increasing average exoskeleton torque seems to have been a result of increased contralateral knee extensor activity, likely due to changes in muscle-tendon dynamics at the assisted ankle that affected total exoskeleton-side ankle mechanics and whole body coordination. As average exoskeleton torque increased, biological ankle torque and soleus muscle activity decreased, suggesting reduced muscle-tendon force and Achilles' tendon stretch before push-off. To power push-off, the plantarflexor muscles would have had to contract with higher velocity than normal to compensate for this suboptimal muscle-tendon state. As suggested by relatively constant peak soleus electromyography but reduced biological ankle torque during late stance, the soleus muscle seems to have been operating at a higher velocity with reduced force per unit activation. Due to a lack of direct measurement of muscle-fascicle force and length, these ideas merit further exploration using a musculoskeletal model that estimates changes in muscle-tendon dynamics.

2 Aims and Hypotheses

Our goal is to use OpenSim [2], a musculoskeletal modeling tool, to estimate and explore changes in plantarflexor muscle-tendon dynamics that arise as a result of net work and average torque applied at the ankle with an exoskeleton. We hypothesize that with increasing net exoskeleton work of the described form: 1) soleus muscle activation is decreased while peak force remains relatively constant during late stance, 2) plantarflexor muscle force peaks and drops off earlier in stance, and 3) energy consumed by the soleus muscle is reduced across conditions. We hypothesize that with increasing average exoskeleton torque of the described form: 1) soleus muscle fibers are more stretched leading into late stance, 2) soleus muscle fiber contraction velocity during push-off is increased, 3) soleus muscle fiber force is significantly reduced but activation is consistent during late stance across conditions, and 4) energy consumed by the soleus muscle remains relatively unchanged.

Furthermore, we aim to use OpenSim's metabolic probes to estimate changes in individual muscle energy consumption and verify its predictive capabilities. We hypothesize that the trend and magnitude of the changes in experimentally-observed metabolic energy consumption across the different work and torque conditions will be realized using OpenSim's metabolic simulation.

3 Methods

Experimentally obtained data, i.e. joint positions, ground reaction forces, and muscle activity, are fed into the Open-

Sim software and used to generate musculoskeletal simulations for each work and torque condition. The behavior of the exoskeleton is modeled as equal and opposite external torques applied to the shank and foot segments of scaled, subject-specific musculoskeletal models. Changes in plantarflexor muscle-tendon dynamics are simulated using OpenSim's Computed Muscle Control tool. The simulated kinematic, kinetic, and electromyographic results are then compared to the experimentally observed data. If there is sufficient agreement between experimental and simulated results, muscle level changes occurring across conditions, including magnitude and timing of muscle activation and force generation, muscle-fiber contraction velocity, and tendon length, are examined and analyzed.

Individual muscle metabolic energy consumption is estimated using OpenSim's metabolic probes, based on Umberger's model of human muscle energy expenditure [3]. These estimates are used to predict changes in whole body metabolic rate across the different conditions, and these predictions are compared to experimentally observed changes in metabolic energy consumption.

4 Preliminary Results

Preliminary analyses performed on one subject show reasonable agreement in overall trends between experimental and simulated exoskeleton-side ankle mechanics, but vary considerably in timing and changes in magnitude (Fig. 1).

5 Expected Outcomes and Impact

Musculoskeletal modeling of our experimental results will provide a more developed understanding of the changes in plantarflexor muscle-tendon dynamics that arise under different levels of this mode of ankle exoskeleton work and torque delivery. The findings will help explain why certain assistance techniques are more effective than others and provide insights into what changes in muscle-tendon dynamics are beneficial. Inverting the information gained could result in new methods that prescribe exoskeleton behaviors in order to cause specific, desirable changes in muscle-tendon dynamics.

Iterative simulation and evaluation of predicted metabolic changes using the discussed experimental data will help inform changes to OpenSim's metabolic probes and improve their predictive capabilities. Dissemination of the experimentally-obtained data set to modelers and developers will help validate and improve the accuracy of tracking and predictive musculoskeletal and neuromuscular models.

6 Open Questions

Will the model be able to sufficiently reproduce experimentally-observed changes in kinetic, kinematic, and electromyographic data? Will the metabolic model used in the OpenSim metabolic probes accurately predict the magnitude of the observed changes in metabolic energy consumption or will it just predict the trend?

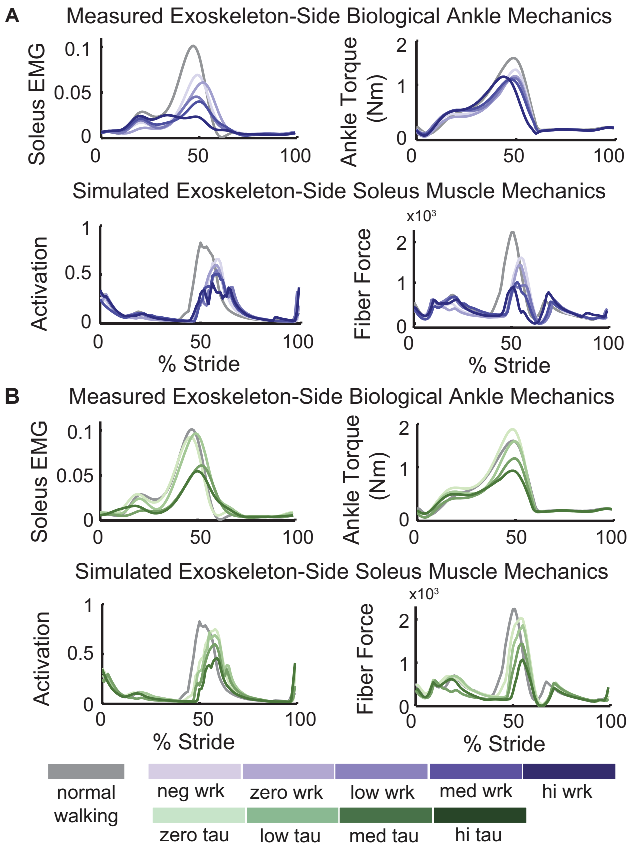

Figure 1: Preliminary results for one subject across A) work conditions and B) torque conditions. Top row of A) and B), from left to right, shows experimentally-measured exoskeleton-side soleus electromyography and biological ankle torque. Bottom row, from left to right, shows simulated exoskeleton-side soleus activation and fiber force. Normal walking is in grey. Work conditions are in purple, torque conditions are in green, and darker colors indicate higher values.

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References

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