Effect of Elastic Ankle Exoskeleton Assistance on Soleus Muscle Dynamics during Walking

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INTRODUCTION

Unpowered exoskeletons that place intermediate stiffness springs in parallel with the human plantarflexors can reduce the metabolic demand of walking [1]. Exoskeleton stiffness above and below this 'optimal' value results in increased metabolic cost. The physiological mechanisms underlying this U-shaped trend are not completely understood. Proposed mechanisms include compensation at proximal joints, increased co-contraction around the ankle, and unfavorable muscle fascicle contractile conditions (*i.e.*, force-length (FL) or force velocity (FV) operating point) [1].

Research in our lab has begun to address changes in muscle fascicle dynamics due to exoskeleton assistance and the relationship to metabolic cost. In hopping with a spring-loaded ankle exoskeleton, we observed large reductions in metabolic cost, but no difference in soleus muscle mechanical power output. Exoskeletons reduced biological muscle force requirements but also increased fascicle excursion leaving muscle workload unchanged [2]. Our computer models indicate that this altered fascicle behavior may extend to walking as well, where stiff exoskeletons lead to decreased force but increased excursions in muscle fascicles [3], conditions that would exact a penalty due to the increased metabolic cost of rapid muscle shortening. The purpose of the current study is to make direct measurements of ankle plantarflexor muscle dynamics during walking elastic exoskeleton assistance and relate these findings to changes in joint and whole body mechanics and metabolic energetics. We hypothesize that the stiffest ankle exoskeletons alter muscle FL and FV contractile dynamics, and offset the benefits of decreased fascicle force, leading to suboptimal improvements in metabolic cost.

METHODS

We used an exoskeleton emulator to apply a range of ankle exoskeleton rotational stiffnesses to the user. The emulator provided torque from benchtop motors to the ankle exoskeleton through a Bowden cable transmission. We tested five exoskeleton stiffnesses (0, 50, 100, 150, 250 Nm/rad) applied across 3 walking speeds (1.25, 1.5, 1.75 m/s). Following an initial training day where subjects walked for 95 minutes, mechanics data were collected for each condition. Inverse dynamics analysis was performed by combining high speed motion capture (VICON) and GRFs from an instrumented treadmill (BERTEC). B-mode ultrasound images of soleus fascicle length changes were captured using a low profile ultrasound system (TELEMED) and were digitized to extract length change patterns [4]. Data have been collected on 9 subjects and full data analysis performed for one subject at the 1.25 m/s walking speed.

RESULTS AND DISCUSSION

Exoskeleton torque increased with exoskeleton stiffness and resulted in a concomitant decrease in biological moment and muscle-tendon unit force (Fig. 1, middle two panels). Viewed independently, the decrease in biological muscle force would have positive whole body metabolic benefit. However, our initial data suggest that isometric fascicle dynamics during mid-stance, typically associated with large stretch in the Achilles' tendon (*i.e.*, 'catapult mechanism), are disrupted when high stiffness exoskeleton assistance is applied. In the stiffest condition, during mid-stance, we found a 10% increase in avg. fascicle length (not shown) and ~x4 higher fascicle shortening velocity (Fig. 1, bottom, red vs. purple). These altered fascicle dynamics likely result in less economical force development (*i.e.*, reduced force per unit activation) and act to counter the metabolic benefit derived from reduced force requirements.

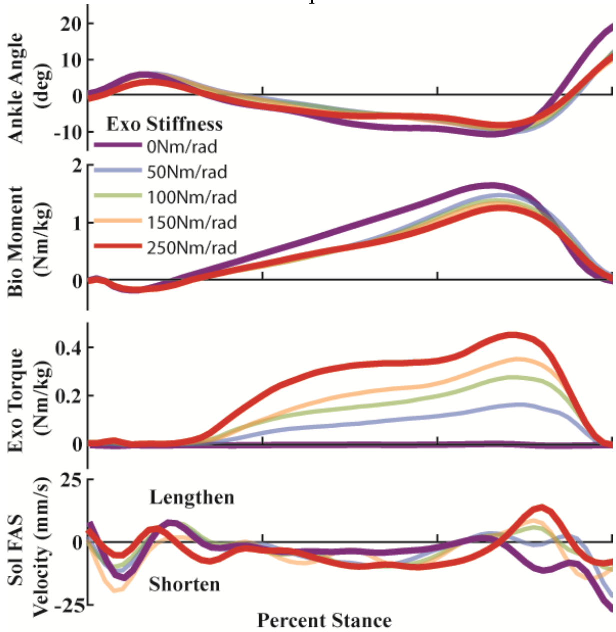

Figure 1: Ankle joint and soleus muscle fascicle dynamics resulting from application of bilateral elastic ankle exoskeleton assistance during walking at 1.25 m/s.

CONCLUSIONS

Design of wearable robots intended to reduce metabolic effort need to account for unintended changes in muscle contractile dynamics of the user. This is especially true for devices intended to assist joints with compliant muscle-tendon architecture, where the muscle fascicle length changes are inherently decoupled from joint kinematics.

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REFERENCES

1. Collins SH, et al. *Nature*. 2015 Apr 1.
2. Farris DJ, et al. *J Appl Physiol*. 2013; **115(5):**579-85.
3. Sawicki G et al. *IEEE Trans Biomed Eng*. 2015 Oct 15.
4. Farris DJ, Lichtwark GA. *Comput Methods Programs Biomed*. 2016 May;**128**:111-8