EFFECT OF SPEED ON THE MECHANICS AND ENERGETICS OF WALKING WITH AN ELASTIC ANKLE EXOSKELETON

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INTRODUCTION

Our previous research indicates that bilateral elastic ankle exoskeletons with intermediate stiffness springs placed in parallel with the human calf-Achilles' tendon complex reduce the metabolic demand during level walking at 1.25 m/s by 7% [1]. However, whether this same parallel stiffness is optimal at other walking speeds has yet to be determined. Previous work suggests that the quasi-stiffness of the ankle in able-bodied subjects increases with increasing walking speed [2], thus we theorized that optimal stiffness of assistive devices should scale with walking speed.

We hypothesized that 1.) an optimal ankle exoskeleton stiffness exists for each speed, where metabolic demand is reduced relative to no assistance and 2.) as walking speed increases the optimal stiffness should also increase.

METHODS

We recruited eleven healthy, young adults (7M, 4F; mean:27.5y, 74.2kg) to complete the IRB approved protocol over a four-day testing period. Participants walked at three walking speeds (1.25, 1.5, 1.75 m/s) while we applied five ankle exoskeleton rotational stiffness conditions (k_{exo}=0, 50, 100, 150, 250 Nm/rad). We delivered mechanical assistance using a custom exoskeleton emulator consisting of bilateral ankle exoskeletons driven by a benchtop motor and transmission, using a control system that imposed a torque-angle relationship to emulate an elastic device providing rotational stiffness.

The order of the four testing days, the purpose, and measurements collected were:

1. Training – 95 minutes (Metabolic Demand)
2. Gait Mechanics (Inverse Dynamics, EMG, B-Mode Ultrasound of Soleus)
3. Steady State Metabolic Demand
4. Stiffness Sweep (Instantaneous Metabolic Demand)

We recorded kinematics using reflective markers (Vicon), muscle activity in the medial and lateral gastrocnemii, soleus, and tibialis anterior using surface EMG (Biometrics), soleus fascicle lengths using B-mode ultrasound (Telemed), and whole body metabolic power with indirect calorimetry (OxyCon Mobile).

We performed a mixed-model ANOVA with a first (k_{exo}) and second order term (k^2_{exo}) to determine the effect of exoskeleton stiffness on metabolic demand. We then ran a post-hoc pairwise t-tests at each speed to compare the condition that yielded the largest reduction in metabolic cost against the no assistance condition($p<0.05$).

RESULTS AND DISCUSSION

For all walking speeds, exoskeleton torque increased and biological ankle moment decreased with increasing exoskeleton stiffness (Fig 1A). Compared to the no assistance condition (0 Nm/rad), for the stiffest condition (250 Nm/rad) we observed a reduction in average (peak) biological moment of -11% (-29%) at 1.25 m/s, -9% (-22%) at 1.5m/s, and -8% (-22%) at 1.75 m/s. Interestingly, in early stance (0-40%) exoskeleton assistance enhanced total ankle moment while biological moment decreased only slightly. Conversely, in late stance (40-60%) the exoskeleton primarily offset the biological contribution and total ankle moment remained nearly constant or decreased slightly. These changes in ankle joint mechanics were accompanied by systematic decreases in soleus muscle activation across all exoskeleton conditions at all speeds (Fig 1B). At the stiffest condition, we observed on average across speeds a reduction of 17% in integrated soleus EMG during stance phase of walking.

Across speeds, we observed a decrease in relative exoskeleton contribution as walking speed increased. From the slowest to the fastest walking speed, peak exoskeleton torque decreased by 20% at the highest stiffness despite a 12% increase in peak total ankle torque. This reduction in exoskeleton assistive torque is explained by a decrease in peak ankle dorsiflexion with increased walking speed, suggesting that efficacy of passive devices may be limited by natural ankle joint kinematics especially at fast walking speeds.

Exoskeletons reduced metabolic cost of walking only at the slowest (-4.2% at 1.25 m/s) and fastest (-4.7% at 1.75 m/s) walking speed, and the optimal stiffness did not increase with speed (50 Nm in each case) (Fig 1C). Surprisingly, for walking at 1.5 m/s, exoskeletons increased metabolic cost across all stiffness conditions.

CONCLUSIONS

Currently we are analyzing ultrasound images of the soleus muscle captured for each stiffness and speed. These data may provide insight into how exoskeletons can disrupt 'tuned' ankle dynamics and counteract decreases in biological force and activations offsetting potential metabolic benefits. We are particularly interested in the changes in muscle mechanics at the intermediate speed where we were unable to achieve a reduction in metabolic demand.

The most compliant spring proved effective at both the slowest and fastest, but not the intermediate walking speed. However, the exoskeleton did not respond to added demands of faster walking in a manner similar to that of biological plantarflexors. Counter to our hypothesis, the optimal elastic ankle exoskeleton spring stiffness did not increase with walking speed.

The metabolic reductions we report here (~5%) still do not approach reductions seen in the most successful active devices (~23%) [3]. Despite this, passive devices remain advantageous given their minimal weight and simplified design in comparison to active systems. In fact, our results suggest that a single compliant exoskeleton spring can achieve metabolic reductions across a range of walking speeds. Furthermore, elastic systems, like the one tested here, may simplify prescription of devices intended to restore structural stiffness to joints in specific populations (*e.g.* older adults).

REFERENCES

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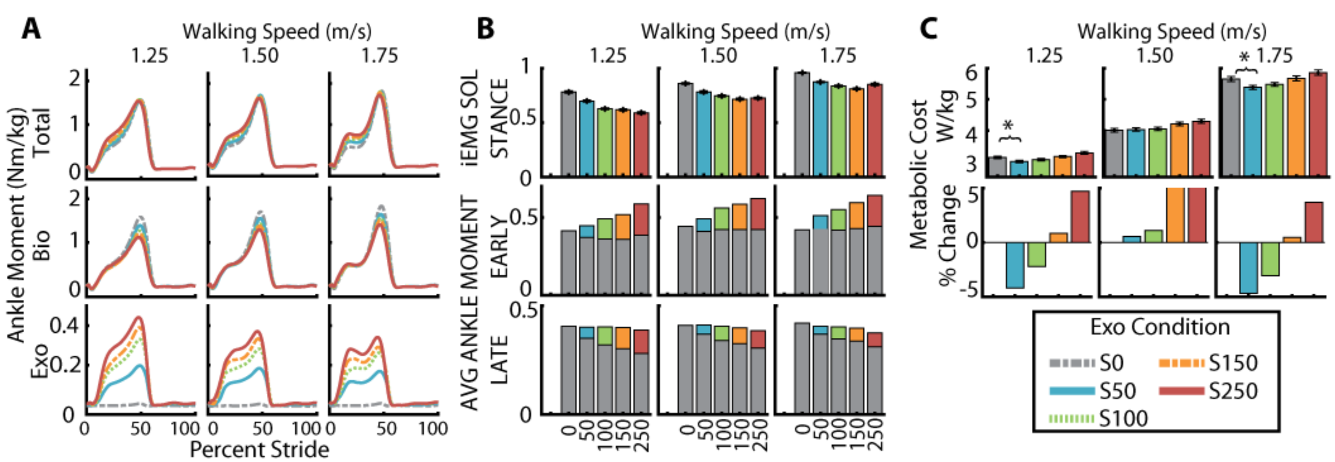

Figure 1: Joint dynamics, neuromuscular activation, and whole body metabolic cost changes resulting from applying exoskeleton assistance over a range of walking speeds. **A:** Total, Biological and Exoskeleton Torque **B:** Soleus integrated EMG and average biological moment. Gray bars represent biological contribution and colored bars are exo contribution. **C:** Exoskeleton assistance reduced metabolic demand at the lowest level of assistance for the slowest (1.25 m/s) and fastest (1.75m/s) walking speeds ($p<0.05$).