Exoskeletons Improve Walking Economy by Steering Muscle Dynamics

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Summary

Exoskeletons reduce whole-body net metabolic rate by modifying limb-joint biomechanics. Yet, muscles, not limb-joints, are the primary consumers of metabolic energy during locomotion. Perplexingly, it is unestablished *how* exoskeletons alter muscle dynamics to improve locomotion economy. We investigated the relationships between the rates of active soleus force, work, and volume to net metabolic rate from participants walking with springy bilateral ankle exoskeletons. Across exoskeleton stiffness (k_{exo}) values, rates of soleus force, work, and active muscle volume explained 50.9, 16.1, and 54.1% of the change in net metabolic rate, respectively (p=0.006). Thus, we suggest that exoskeletons improve locomotion economy primarily by affecting rates of active muscle volume rather than muscle work.

Introduction

Numerous exoskeleton designs are purported to reduce net metabolic rate during walking (improve walking economy). Typically, engineers design wearable devices to improve walking economy via reducing limb-joint moments or powers. This is despite the fact that limb-joint and muscle dynamics are often disassociated, primarily due to in-series compliance. We contend that exoskeletons improve locomotion economy by improving the contractile dynamics of muscles; the primary consumers of net metabolic energy during locomotion [2]. Further, the literature suggests that walking economy may well-corresponds to the rate of active muscle volume because it depends on both muscle force production and length change dynamics. Based on this notion, we hypothesized that exoskeletons primarily alter walking economy by altering active muscle volume.

Methods

10 participants completed the IRB approved protocol. Each participant performed 5, 1.25 m/s walking trials on a force-instrumented treadmill with bilateral ankle exoskeletons. We varied exoskeleton ankle-joint rotational stiffness (k_{exo}) from 0-250 Nm/rad. Following habituation, we collected kinetic, kinematic, B-mode ultrasound, and metabolic data. We performed inverse dynamics and analyzed soleus ultrasound images [1] to determine stride averaged rates of active fascicle force, work, and volume for each condition. We extended [2]'s rate of active muscle volume calculation by accounting for following additional factors: effective mechanical advantage, muscle pennation angle, passive force, force-length and force-velocity relationships. We performed an ANOVA to evaluate the effect of k_{exo} on soleus fascicle dynamics. Finally, we determined how each biomechanical parameter related to net metabolic rate following the approach in [2].

Results

k_{exo} altered rates of active soleus force (p=0.042) and volume (p=0.034), but not work (p=0.190) (Fig. 1). Across k_{exo} conditions, rates of active soleus force and volume explained 50.9 and 54.1% of the change in net metabolic rate, respectively, whereas soleus work rate only explained 16.1% (p=0.006).

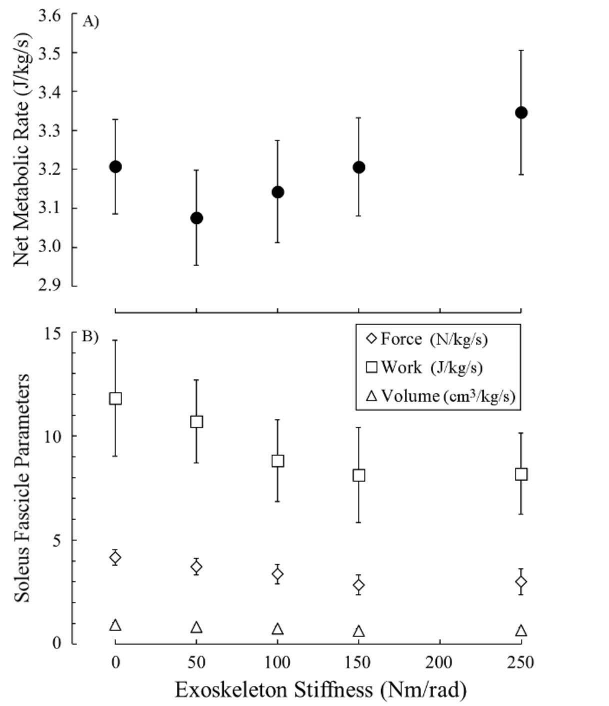

Figure 1 A) Net metabolic rate vs. exoskeleton stiffness (k_{exo}). B) Rates of active soleus force, work, & volume vs. k_{exo}. Error bars=SE.

Discussion and Conclusions

Overall, rates of active muscle volume and force corresponded to net metabolic rate >3 times better than the rate of muscle work (>50 vs. 16%). Yet, our results do not fully support our hypothesis because the rate of active muscle volume numerically, but not statistically, corresponded better to net metabolic rate than active muscle force rate (Bonferroni-adjusted α=0.017; p=0.032). In summary, exoskeletons may primarily reduce net metabolic rate by steering active muscle volume, opening the door to devices that use feedback controllers that incorporate muscles dynamics in-the-loop.

References

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