Exploring Individual Differences in Metabolic Savings during Exoskeleton Walking: Mechanical and Muscular Factors

Isabella Shih[1], Anthony Chen[1], Gillian Phillips[1], Megan J. McAllister[1], and Jessica C. Selinger[1*]
[1]School of Kinesiology and Health Studies, Queen's University, Kingston, ON, Canada
Email: *j.selinger@queensu.ca

Summary

While exoskeletons are designed to reduce metabolic energy during walking, individual responses vary widely. Here, our purpose was to explore what differences in mechanical and muscular metrics may explain large variations in metabolic cost reductions across participants when walking with an ankle exoskeleton. We compared metabolic cost and lower-limb kinematics, kinetics, and muscle activity when participants walked without (Exo-Off) and with (Exo-On) exoskeleton assistance. We found a wide range of metabolic cost reductions (+0.5% to -21%) across participants. Participants who achieve the greatest metabolic savings with exoskeleton assistance adapt ankle kinetics and muscle activity to accept push-off assistance while maintaining the natural mechanics of non-actuated joints.

Introduction

Ankle exoskeletons are often designed to assist the push-off phase of walking, off-loading plantarflexion muscles, and in turn reducing the whole-body metabolic cost required to walk [1]. However, the mechanisms by which exoskeletons reduce metabolic cost are complex and unclear [2]. This may in part be due to individual differences in anatomy and motor adaptation. Previous exoskeleton experiments have reported large differences between participants' metabolic savings—ranging from individuals who gain little benefit to those that reduce cost by 20-60% [3]. Here, our purpose was to explore what differences in mechanical and muscular metrics may explain large variations in metabolic cost reductions across participants when walking with an ankle exoskeleton.

Methods

Ten healthy adults (6F and 4M, 20.2±0.8 yrs., 75.3±15.0 kg) with no prior exoskeleton walking experience or lower limb impairments wore bilateral ankle exoskeletons (EXO-001, Humotech, USA) that provided assistive plantarflexion torque based on real-time ankle angle (**Fig 1)**. Participants walked at 1.25m/s for two, 12-minute trials: Exo-Off and Exo-On. Lower-limb kinematics were captured using optical motion capture (Oqus 300+, Qualisys, Sweden) and ground reaction forces were recorded from an instrumented treadmill (FIT, Bertec, USA). We measured muscle activity (nine dominant-leg muscles) using surface electromyography (EMG; Trigno, Delsys, USA) and metabolic cost using indirect calorimetry (K5, Cosmed, Italy). We used OpenSim (v4.4) to compute gait kinematic and kinetic outcome measures and custom scripts (MATLAB, R2023b) to process EMG outcome metrics. We compared kinematic, kinetic, EMG, and metabolic cost metrics during the final minutes of the Exo-Off and Exo-On trials. We first evaluated what metrics changed on average across participants between Exo-Off and Exo-On using paired t-tests. Next, we explored what metrics were correlated with reductions in metabolic cost across individual participants using a Spearman's rank correlation (given our low sample size and the potential for non-linear relationships).

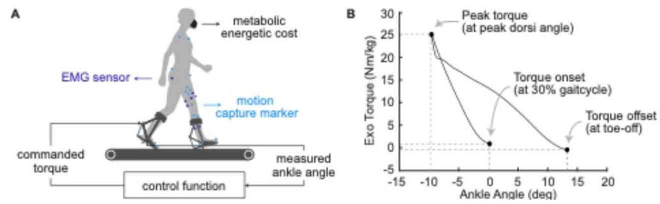

Figure 1. (A) Participant instrumentation and (B) Bézier curve for our angle-based exoskeleton controller.

Results

On average, metabolic cost was reduced by 12.3% ± 7.0% ($p=0.003$) in the Exo-On condition compared to Exo-Off, with a wide range of reductions across participants (+0.5% to -21%). As expected, on average we found decreases in ankle plantarflexion torque ($p=0.014$), power ($p=0.039$), and peak plantarflexor EMG (soleus $p=0.022$, gastrocnemius $p=0.033$) during the push-off phase of the gait cycle. Across participant changes in peak soleus EMG were strongly correlated with reductions in metabolic cost ($r = 0.71$), with higher savers showing greater reductions in activity. We also found that on average participants tended to decrease their peak knee and hip extension torque ($p = 0.06$ and $p = 9.6\times10^{-4}$, respectively) and their peak knee extensor EMG (vastus medialis $p=0.033$) during the loading phase of the gait cycle. Across participant changes in these metrics were negatively correlated with reductions in metabolic cost ($r = -0.77$, $r = -0.50$, $r= -0.78$, respectively), suggesting those with higher savings kept their knee and hip kinetics closer to natural walking.

Discussion and Conclusion

Our findings suggest that participants who demonstrate large metabolic savings when walking in the exoskeletons exhibit two key features. First, they more readily accept device assistance during push off by altering ankle kinetics and muscle activity. Second, they avoid altering the mechanics of other non-actuated joints, potentially preserving the efficient passive pendular dynamics of walking. Our findings may help inform training strategies and feedback metrics to help all users benefit from exoskeleton assistance during walking.

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