Mechanics and energetics of incline walking with powered ankle exoskeletons

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INTRODUCTION

Our previous results indicated that when bilateral ankle exoskeletons produce ~65% of ankle joint power, the metabolic cost of level walking decreased by 13% (Sawicki et al., 2007). Because level, steady speed walking requires no net mechanical work over a stride, substituting biological muscle work with artificial muscle work may yield larger reductions in energy expenditure during locomotor tasks that require substantial positive muscle work. The objective of this study was to determine the effects of increasing surface incline on the metabolic cost of walking with robotic exoskeletons. We hypothesized that as surface gradient increased, ankle exoskeletons would deliver more mechanical power and users would save more metabolic energy.

METHODS

Nine healthy subjects walked on a treadmill at 1.25 m/s with bilateral powered ankle exoskeletons under soleus proportional myoelectric control (**Fig. 1**). After three thirty-minute practice sessions on level ground, subjects completed 7 minute bouts of unpowered and powered walking at four surface inclines (0%, 5%, 10% and 15% gradient) in a random order. Subjects rested for 3 minutes between trials. We recorded oxygen and carbon dioxide flow rates using a metabolic cart, artificial muscle forces from series load transducers, and joint kinematics using reflective markers.

To quantify exoskeleton mechanical assistance, we used artificial muscle forces and moment arm lengths along with ankle joint angular velocity to compute the average mechanical power delivered by the exoskeletons over a stride. To assess energy expenditure, we converted gas flow rates from minutes 4-6 of each trial using the Brockway equation and subtracted the energy required for quiet standing to calculate net metabolic power. Theoretically, if exoskeletons directly replaced positive muscle work, reductions in metabolic cost should be four times the amount of delivered exoskeleton positive power (i.e. muscular efficiency of 25%). To evaluate exoskeleton performance, we multiplied changes in net metabolic power by 0.25 and then divided by average exoskeletons positive mechanical power. A performance index of 1.0 would indicate that exoskeletons directly replaced biological muscle work.

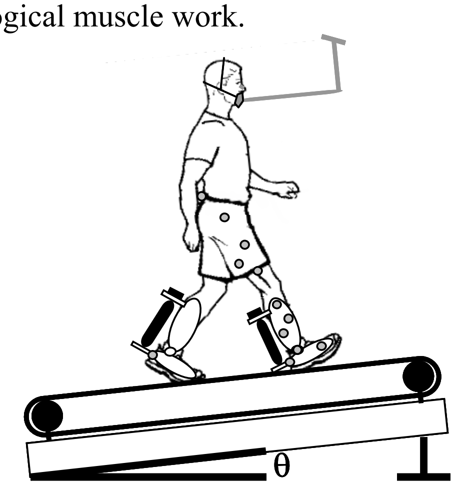

Figure 1. Subjects walked at 1.25 m/s on four different surface inclines while wearing powered bilateral ankle exoskeletons controlled by their own soleus muscle activity.

We used a repeated measures ANOVA to test for differences in positive exoskeleton power across gradients, and net metabolic power between unpowered and powered walking.

RESULTS AND DISCUSSION

Net metabolic power was significantly lower in the powered walking trials for each level of surface incline (**Fig. 2**) (ANOVA, $p < 0.001$). The decrease was between 10% and 13% for all gradients. Exoskeleton average positive mechanical power was significantly higher across surface gradients (0.23 ± 0.19 W/kg (mean ± s.e.) at 0% grade and 0.37 ± 0.03 W/kg at 15% grade) ($p<0.001$) (**Fig. 3A**). As a result, absolute decreases in net metabolic power were larger on steeper slopes and reached a maximum of -0.98 ± 0.12 W/kg at 15% grade (**Fig. 3B**). Exoskeletons performance index increased from 0.47 for level walking to ~0.65 at the two highest grades (**Fig 3C**).

These findings indicate that although powered ankle exoskeletons perform greater mechanical work during incline walking than during level walking, the relative savings in metabolic cost is similar across gradients. However, the increase in exoskeleton performance index indicates that added mechanical power replaces a larger proportion of biological muscle work at higher inclines. The explanation for this discrepancy is likely that the hip and/or knee musculature performs a greater percentage of the total external mechanical work on inclines than on the level.

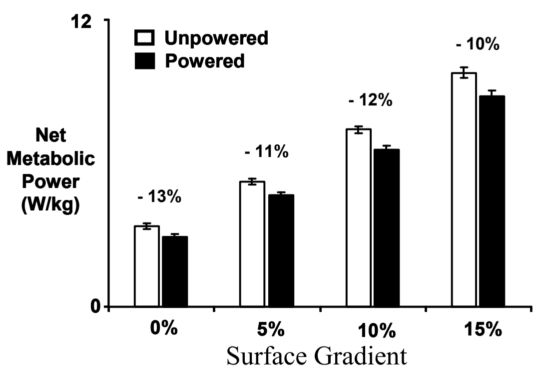

Figure 2. Net metabolic power normalized by subjects' body mass for exoskeleton walking at four different surface gradients (0-15%). Numbers above bars indicate percentage reductions due to mechanical assistance.

CONCLUSIONS

As the demand for positive mechanical power increases with surface gradient, robotic ankle exoskeletons replace a larger proportion of ankle extensor work. However, because of the reduced importance of the ankle on inclines, relative metabolic savings remains independent of surface gradient.

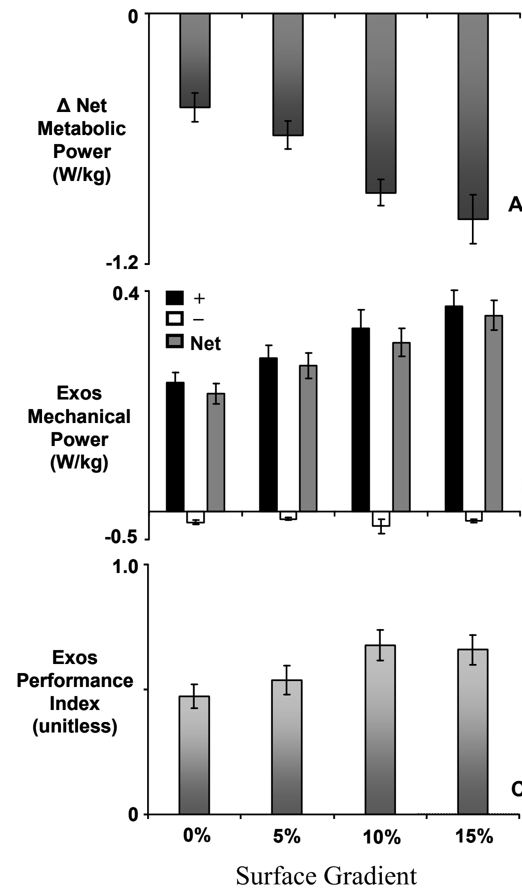

Figure 3. (A) Reduction in net metabolic power (B) exoskeletons average mechanical power (+ black; – white, net gray) and (C) exoskeletons performance index for powered walking at the four surface gradients. All power values are normalized by subject mass. Bars are mean ± s.e.m. A performance index of 1.0 indicates reductions in net metabolic cost that are four times the average positive mechanical power delivered by exoskeletons.

REFERENCE

Sawicki, G.S., Ferris, D.P. (2007). *Proceedings of 31st Annual Meeting of American Society of Biomechanics.*

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