

Mechanics and energetics of level walking with powered ankle exoskeletons

Gregory S. Sawicki¹ and Daniel P. Ferris¹

¹Human Neuromechanics Laboratory, University of Michigan, Ann Arbor, MI, USA
E-mail: gsawicki@umich.edu

INTRODUCTION

Humans can rapidly learn to walk with a unilateral powered ankle exoskeleton controlled by their own muscle activity (Gordon et al., 2007). Over two thirty-minute practice sessions, individuals alter their soleus muscle activation to command distinct bursts of exoskeleton power during the push-off phase of walking. Substituting biological muscle work with artificial muscle work could reduce energy expenditure during gait. The goal of this study was to determine how much a robotic ankle exoskeleton could reduce the metabolic cost of walking. Muscles produce positive mechanical work with an efficiency of ~25% (Hill, 1938). Therefore, we hypothesized that for every 1 Joule of positive exoskeleton work, the user should save 4 Joules of metabolic energy.

METHODS

Nine healthy subjects walked on a treadmill at 1.25 m/s with bilateral powered ankle exoskeletons under proportional myoelectric control (**Fig. 1**). During three practice sessions, subjects walked with exoskeletons unpowered for 10 minutes, powered for 30 minutes and unpowered for 15 minutes. We recorded (1) O₂ and CO₂ flow with a metabolic cart (2) artificial muscle forces from series load transducers (3) joint kinematics using reflective markers and (4) electromyography (EMG) from surface electrodes at the beginning and end of each session.

To establish baseline joint mechanics, we collected five overground walking trials at 1.25 m/s with exoskeletons unpowered. We used inverse dynamics to calculate the

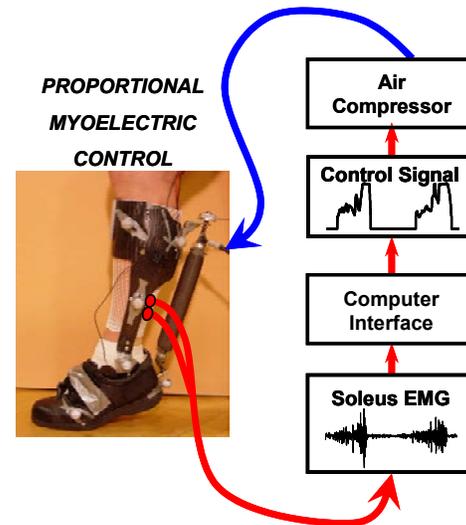


Figure 1. Artificial muscle drives ankle extension using a command from subjects' own soleus EMG

average ankle, knee and hip joint powers over a stride. 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 exoskeletons over a stride. To assess energy expenditure, we converted gas flow rates using the Brockway equation and subtracted the energy required for quiet standing to calculate net metabolic power. To quantify muscle activity, we rectified and high pass filtered (4th Order Butterworth, $f_c=20\text{Hz}$) EMG data and computed the root mean square (RMS) average over the stride. All EMG was normalized to unpowered walking data.

We used a repeated measures ANOVA to determine if there were differences in net metabolic power and soleus RMS EMG between unpowered and powered walking conditions.

RESULTS AND DISCUSSION

Initially subjects walked with increased ankle plantar flexion, but kinematics returned close to normal with practice (**Fig. 2A**). Soleus EMG was 24% lower in the powered condition (ANOVA, $p < 0.001$) (**Fig. 2B**). Exoskeleton average mechanical power was 0.23 ± 0.02 W/kg (mean \pm s.e.); 65% of ankle positive work and 22% of summed joint positive work (**Fig. 2C**). Net metabolic power was significantly lower (-13%) with exoskeletons powered (2.91 ± 0.13 W/kg) versus unpowered (3.36 ± 0.13 W/kg) ($p < 0.001$) (**Fig. 2D**).

Reductions in net metabolic power (13%) were not proportional to decreases in summed joint mechanical power (22%) from powered ankle assistance. Furthermore, for every 1 Joule of exoskeleton work, the user saved only 1.9 Joules of metabolic energy.

CONCLUSIONS

These results suggest that the ankle plantar flexors perform mechanical work during walking with remarkably high efficiency (~51%). Achilles tendon elastic energy storage and return likely contributes to the high apparent efficiency (Ishikawa, 2005). Our findings will be useful in designing powered ankle orthoses and prostheses for improving mobility and reducing metabolic cost in both healthy and patient populations.

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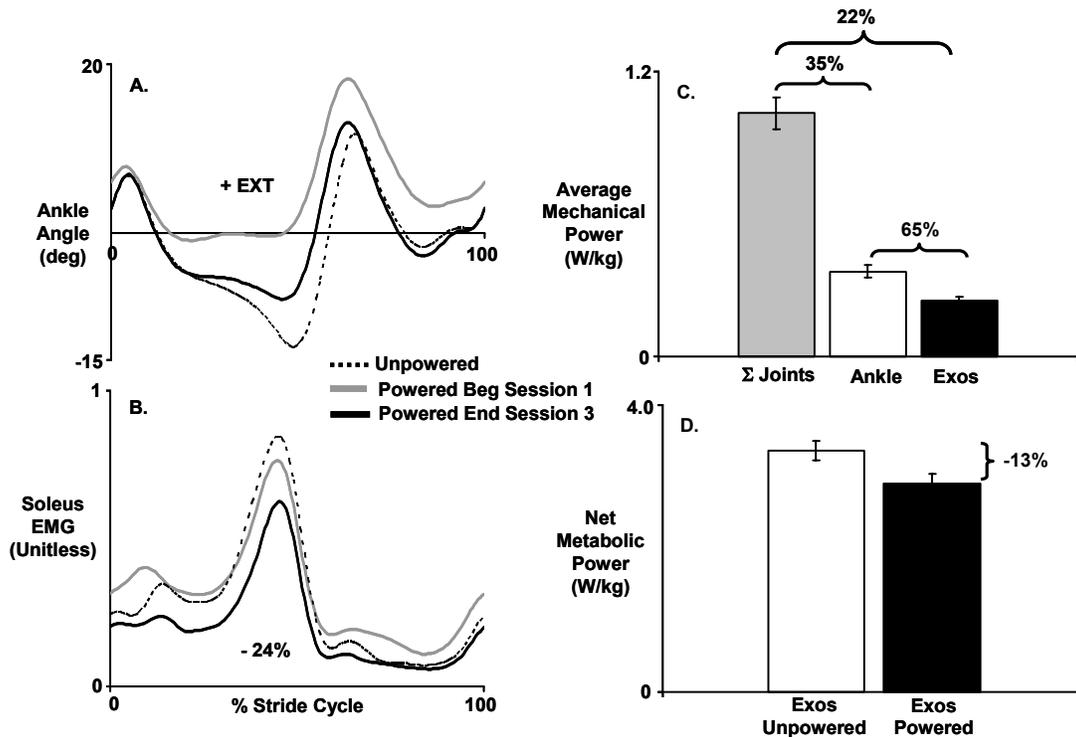


Figure 2. (A) Stride cycle average (heel strike to heel strike) ankle kinematics and (B) normalized linear enveloped (low pass=6Hz, high pass=20Hz) soleus EMG over the practice sessions. Soleus RMS was 24% lower in the powered condition by the end of session 3. (C) Stride average positive mechanical power for ankle joint (white) and ankle+knee+hip joints (gray) during unpowered walking and exoskeletons (black) during powered walking. Brackets indicate right bar as % of left bar. (D) Average net metabolic power for unpowered walking (white) and powered walking (black) during last 3 minutes of practice session 3. Bracket shows % difference. All power values are normalized to subjects' body mass and are mean \pm s.e. for 9 subjects.