Recycling Heel-Strike Energy: A Lightweight Foot Exoskeleton for Improved Walking Efficiency

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Summary

This study introduces a novel unpowered foot exoskeleton aimed at enhancing walking economy by recycling heel-strike energy. Trials with eight males showed an 8.25% reduction in walking metabolic cost compared to shoes. The consistent reduction in soleus muscle activity indicated that this exoskeleton is a good walking aid for different subjects.

Introduction

In recent years, the use of lower extremity exoskeletons to assist with walking has received widespread attention[1], [2]. Ankle exoskeletons assist ankle joint with the components across the ankle, which affects their daily wearability. Here, we designed a foot-focused, unpowered foot exoskeleton to improve walking economy by minimizing energy loss at the heel.

Methods

As shown in Figure 1, the exoskeleton was 3D printed using nylon material with 336g per side. The exoskeleton recycles negative mechanical energy of the foot in heel-strike through a torsion spring and transfers the energy to metatarsal-phalangeal (MTP) joints to assist propulsion. The energy release time is controlled by a clutch, which is triggered according to the kinematics of the MTP joints.

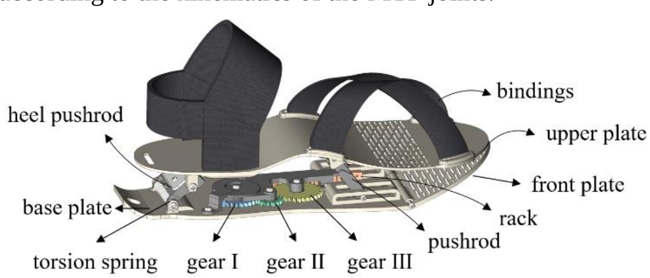

Figure 1: The foot exoskeleton design

Eight healthy males participated in the experiment, providing informed consent. Subjects walked at a self-selected speed of 1.10 ± 0.15 m/s on a defined track, wearing the exoskeleton (EXOS) and shoes (SHOES). An indirect spirometry system (CORTEX, Germany) was used to measure metabolic rate. Subjects first completed a 5-minute quiet standing, followed by 6-minute walking trial, with a 5-minute rest between trials. Data from the last 2 minutes of each trial were used to calculate metabolic cost[3], and paired t-tests were performed using IBM SPSS Statistics 26 (Stanford, America). An electromyographic system (Delsys, USA) was used to measure the muscle activity of soleus. The EMG data was processed[4] in Matlab (R2020a, USA).

Results and Discussion

The net metabolic rates of exoskeletons was 1.65±0.37 W/kg. Compared with the SHOES condition, the metabolic rate of EXOS condition showed an 8.25%±3.84% reduction. The peak EMG reduced range 9.5% to 37% and the mean EMG reduced range 6.9% to 25.2% under EXOS conditions.

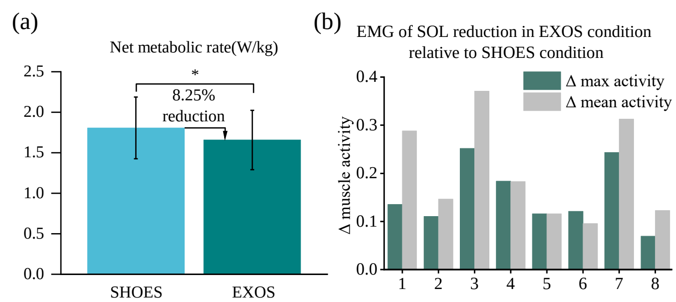

Figure 2: Net metabolic rates and ΔEMG of soleus. N = 8; bars, mean; error bars, SD; Asterisks represent significant differences between two conditions (two-way repeat ANOVA, all $p < 0.004$).

The reduction in metabolic rate and EMG with the foot exoskeleton reflects its effectiveness in enhancing walking economy. The reduction of metabolic rate may be due to that we successfully controlled energy release time by using a clutch[1], efficiently recycling the energy dissipated at heel strike and transferring for propulsion. The reduction of EMG suggests that the exoskeleton does reduce demand on soleus, which applies to most users, reflecting the exoskeleton can assist walking by adapting to individual gait characteristics.

Conclusions

The unpowered foot exoskeleton enhanced walking economy by recycling heel-strike energy to support propulsion, offering a lightweight, user-friendly alternative to traditional shoes. Its ability to adapt to various users highlights its practicality and robustness. These findings suggest that this device has the potential to provide energy-efficient walking assistance, making it a viable option for daily use across a broad spectrum of individuals.

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References

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