Study of the contribution of negative work assistance at the ankle with a multi-articular soft exosuit during loaded walking

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Summary

Of the recent exoskeletons that successfully reduce the metabolic cost of walking, some deliver mostly positive joint work assistance, while others deliver a combination of positive and negative joint work assistance. There is no consensus about the contribution of negative joint work assistance on the metabolic cost of walking. The aim of the present study is to investigate the contribution of negative work assistance at the ankle with a soft exosuit. We tested eight participants who walked with a soft exosuit that uses an off-board actuator to assist with both plantarflexion and hip flexion through a multi-articular suit architecture. In four active conditions, we provided different rates of negative work assistance. All active conditions significantly reduced metabolic rate by 11 to 15% compared to wearing the exosuit powered off. On average there was a trend toward higher reduction in metabolic rate with higher rates of negative work assistance, but this was not significant.

Introduction

Recent studies have shown that it is possible to reduce the metabolic rate of walking using robotic ankle exoskeletons. Some studies achieved this result with mostly positive work assistance (Malcolm et al., 2013; Mooney et al., 2014). Another study achieved this result with a combination of negative and positive work assistance (Collins et al., 2015). Furthermore, we recently achieved a net reduction in metabolic cost during loaded walking with an autonomous soft exosuit compared to wearing the inactive exosuit with effective mass removed by using a combination of negative and positive work assistance at the ankle and hip (Panizzolo et al., in review). Despite these exciting recent results, there is no consensus about the isolated contribution of negative work assistance on metabolic cost of walking. The aim of the present study is to investigate the contribution of negative work assistance at the ankle with a soft exosuit.

Methods

We tested eight participants (26 ± 5 y., 80 ± 10 kg, 1.78 ± 0.06 m) during walking at 1.5 m s^{-1} with a 23-kg backpack. An off-board actuation system generated assistive forces, and Bowden cables transmitted the forces to a soft exosuit at the ankle. The exosuit assisted plantarflexion and hip flexion through a multi-articular load path specified by a textile architecture (Lee et al., 2016). We used a load cell (Futek) and two gyroscopes (ST Microelectronics) per leg to collect real-time data. To provide negative work assistance around midstance the actuator held the cable at a fixed position, and force was passively generated as the wearer dorsiflexes. We call this phase *pretension*. To provide positive work assistance, the motor retracted the Bowden cable when the ankle angular velocity

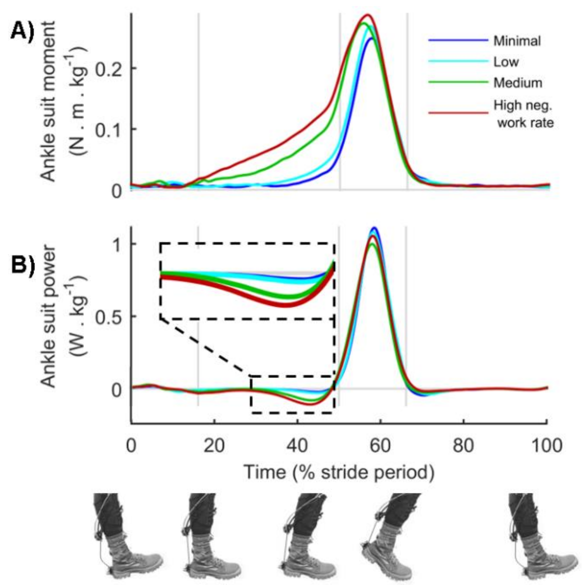

Figure 1 Ankle suit actuation. (A) Moment. **(B)** Power.

changed its sign. Since the biological ankle exerts a plantarflexion moment during the entire part of stance after initial forefoot contact we know that when ankle angular velocity crosses zero subsequent actuation will provide positive work assistance. In four *active* conditions, we provided different rates of bilateral negative work assistance, ranging from 0.015 to 0.037 W kg^{-1}. In all conditions, we maintained a fixed rate of total positive work assistance of 0.19 W kg^{-1}. Participants also walked in a *power off* condition, wearing the exosuit without assistance engaged. We measured metabolic cost (Cosmed) and kinematics and kinetics (Vicon and Bertec).

Results

Ankle suit *pretension* moments ranged from 0.04 ± 0.01 up to 0.16 ± 0.01 N · m kg^{-1} (Figure 1A). We maintained total ankle suit positive work rate independently from the negative work rate (Figure 1B). However, higher negative work rate conditions required higher peak assistive moments to keep positive work rate constant. In all *active* conditions, metabolic rate was significantly reduced by 11 to 15% (p values are 0.003, 0.003, 0.002 and 0.007 respectively for the *minimal* to *high* negative work rate condition) compared to the *power off* condition (Figure 2). There was a trend toward higher reduction in metabolic rate with higher rates of negative work assistance. Every Joule of bilateral negative work assistance generated on average 8.8 Joules metabolic reduction, but this trend was not significant ($p = 0.083$).

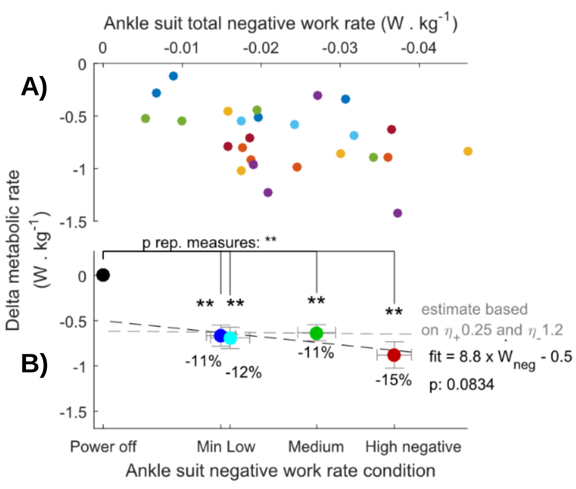

Figure 2 Metabolic rate. (A) Change in metabolic rate versus total ankle suit negative work rate. Colors are different participants. **(B)** Dots are condition averages. Error bars are s.e.m. Percentages are percent metabolic reduction relative to *power off*. Dashed black line indicates linear fit. Dashed grey line indicates estimated trend assuming positive and negative work efficiencies corresponding to Margaria (1968). ** is $p \leq 0.01$.

Discussion

A possible reason why we found no significant effect of negative work assistance could be that the magnitude of the positive work assistance was much higher and also has a variable effect on metabolic cost. As such it could be that the effect of the negative work assistance was confounded by the variability in the effect of positive work assistance. A similar experiment where negative work assistance varies, with no positive work assistance whatsoever, may generate a clearer trend, though such an experiment would be less relevant to produce large metabolic reductions. Related, we were only able to vary negative work assistance over a small range. It is possible that negative work can be varied over a bigger range with a different controller.

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