Optimized Hip-Knee-Ankle Exoskeleton Assistance at Different Speeds

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Introduction

Exoskeletons have led to significant reductions in user energy expenditure during walking [1]. However, these studies are typically limited to one speed, whereas an effective autonomous device will need to assist at a variety of speeds. Optimal exoskeleton assistance at different walking speeds may mimic biological responses such that joint torque, angle excursion and power increase with speed [2]. To investigate the relationship between walking speed and ideal exoskeleton torque, we optimized assistance with a hip-knee-ankle exoskeleton [3] while participants walked at slow, medium and fast speeds.

Methods

We optimized multi-joint exoskeleton assistance to reduce user energy expenditure at three speeds with human-in-the-loop optimization [4]. One participant (male, 90 kg, 188 cm) walked with assistance for slow, medium and fast walking (1.0 m/s, 1.25 m/s and 1.5 m/s respectively), while we measured metabolic expenditure, exoskeleton joint angles and ground reaction forces.

Results and Discussion

The participant experienced a 30% reduction in metabolic energy expenditure for slow walking and a 50% reduction for both medium and fast walking. The participant saw the largest absolute reduction at fast walking (Fig. 1 A and B).

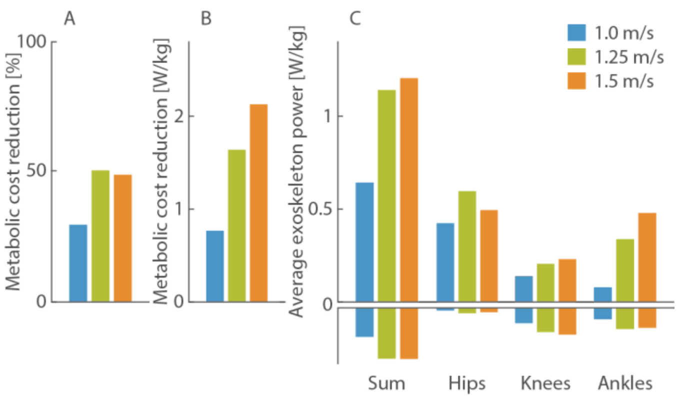

Figure 1: Metabolic reduction and exoskeleton power after optimization at all three speeds. (A) Metabolic reduction normalized to metabolic cost of walking with the device turned off. (B) Absolute metabolic reduction relative to walking with the device turned off. (C) Average positive and negative joint power at the hips, knees, ankles, and sum of all three. The y-axis scale for C is half the scale of B.

Ideal exoskeleton power did not linearly increase with speed like biological power. The exoskeleton provided the least amount of power for slow walking and similar amounts of power for medium and fast walking (Fig. 1 C). In contrast, the absolute reductions in metabolic cost increased with speed. This suggests that exoskeleton power cannot fully explain reductions in energy expenditure.

Unlike biological torques, optimized exoskeleton torques did not increase monotonically with speed (Fig. 2 B). Ankle plantarflexion and knee flexion torque at toe off (60% of stride) were the smallest for slow walking, and all other torque magnitudes were similar for all three speeds. Effective torques may work at a range of speeds, but it seems that push-off torque should be lower at slower speeds.

Biological joint angle excursion linearly increases with speed, but the joint angle excursion with assistance did not follow that trend (Fig. 2 A). The hips and ankles saw increased excursion greater than biological around toe-off. With assistance, the knee was relatively straight during stance. However, biological knee excursion during stance increases with speed to reduce the impact from heel strike.

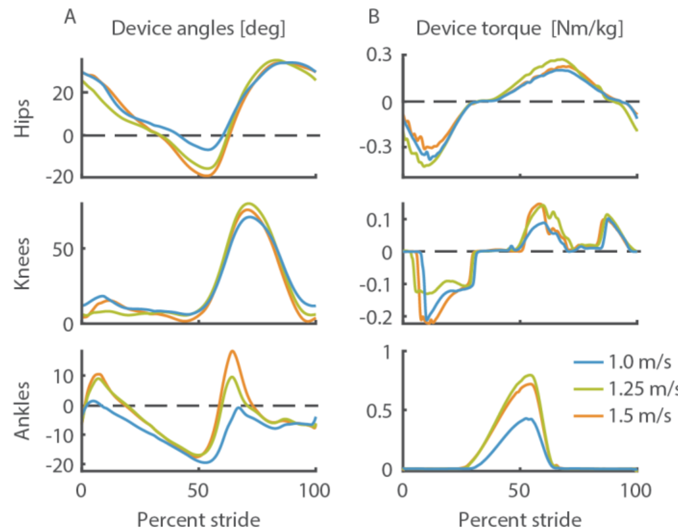

Figure 2: Average exoskeleton joint angles and optimized, exoskeleton torques. (A) Average hip, knee and ankle device angles during optimized torque application. (B) Average applied hip, knee and ankle torque. The applied torques at the hip and ankle are torque- time profiles, and the applied torque at the knee is defined by a virtual spring during stance, time based flexion near toe off a virtual damper during late swing.

Significance

Exoskeletons can reduce the metabolic cost of walking at a range of speeds, with largest improvements seen at faster speeds. Assistance may reduce energy expenditure by replacing positive work done by the muscles, but the positive device power does not fully explain the metabolic reductions.

Acknowledgments

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