Title: Heuristic-based co-adaptation of ankle exoskeleton assistance during human walking

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Introduction

Effectively assisting human locomotion with exoskeletons is much harder than it may seem, due, in large part, to the complexity of the neuromusculoskeletal system, the broad range of responses different users can have to the same assistance strategy, and the time-varying dynamics that users exhibit as they learn to walk with exoskeleton assistance. Human-in-the-loop optimization, which systematically varies device behavior in response to measured changes in the user so as to maximize human performance, can overcome many of these challenges [1], but there is still room for improvement. Our goal was to develop a human-in-the-loop control strategy that addresses some limitations of current approaches by slowly and continuously responding to changes in biomechanical outcomes thought to encode the user's needs, thereby enabling co-adaptation between the device and the user.

Methods

We developed a heuristic-based algorithm that uses online measurements of muscle activity and joint kinematics to guide the evolution of a desired ankle exoskeleton torque profile. The driving heuristics were: 1) soleus muscle activity, which acts cooperatively with the exoskeleton, indicates the user wants more torque; 2) tibialis anterior muscle activity, which acts antagonistically to the exoskeleton, indicates the user wants less torque; and 3) a lack of reduction in average soleus muscle activity and significant deviations from nominal ankle kinematics indicate the user is having trouble adapting, therefore torque growth should slow or stop.

We conducted an experiment to evaluate the effectiveness of the algorithm at discovering torque profiles that improve whole-body locomotor economy. Ten able-bodied participants walked with bilateral exoskeletons on a treadmill at 1.25 $m \cdot s^{-1}$ for 30 minutes while torque evolved based on the described heuristics. We measured soleus muscle activity and whole-body metabolic rate.

Results

The algorithm led to evolved torque profiles that significantly reduced soleus muscle activity and metabolic rate (Fig. 1). Metabolic rate was, on average, 22% below that measured during walking with the exoskeletons in a zero-torque mode ($p = 1 \cdot 10^{-4}$, Fig. 1B).

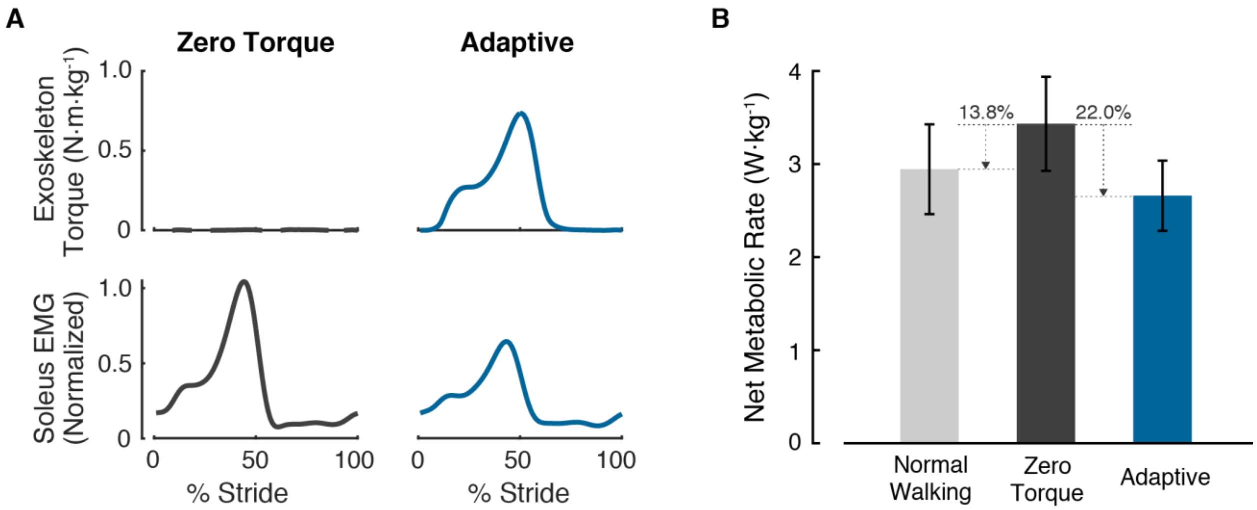

Figure 1. (A) Average exoskeleton torque (*top*) and soleus muscle activity (*bottom*) in the zero-torque (*left)* and adaptive (*right*) conditions. (B) Metabolic rate across walking conditions.

Discussion

The discovered pattern of exoskeleton torque was effective at reducing whole-body metabolic rate through the intermediate step of supplanting a significant portion of soleus muscle activity. Torque grew relatively slowly, which may be beneficial for motor learning, while still seeming to converge quickly. The control strategy can discover any pattern of torque governed by measured muscle activity, making it generalizable to other joints, and it likely scales well, providing the framework for a full lower-limb exoskeleton assistance strategy.

Acknowledgments
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References
[1] Zhang, J., et al., (2017). *Science*. 356, pp.1280-1284.