Alternative human-in-the-loop exoskeleton assistance strategies: Heuristic-based exoskeleton control for co-adaptive locomotor assistance

Rachel W. Jackson[1,2] and Steven H. Collins[1,3]
[1]Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
[2]Department of Bioengineering, Stanford University, Stanford, CA, USA
[3]Department of Mechanical Engineering, Stanford University, Stanford, CA, USA
Email: rwj1@stanford.edu

Summary

Researchers recently demonstrated that exoskeleton assistance strategies aimed at keeping the human "in-the-loop" can achieve significant improvements in locomotor performance. Given these findings, we sought to develop an alternative human-in-the-loop strategy rooted in the idea of co-adaptation. We formulated an algorithm, based on heuristics about effective interactions between the user and the device, to drive the evolution of an exoskeleton torque pattern. When implemented on bilateral ankle exoskeletons, the algorithm generated patterns of assistance that continuously responded to the changing coordination patterns of each naïve exoskeleton user and significantly reduced whole-body metabolic rate. Similar co-adaptive strategies will likely enable the discovery of effective assistance patterns for new devices and populations.

Introduction

Lower-limb exoskeletons have the potential to enhance mobility in a wide range of individuals. To achieve significant improvements in performance, however, these devices must interact effectively with the complex and redundant human neuromusculoskeletal system. Recent advancements in exoskeleton control strategies have shown that keeping the human "in-the-loop" can help overcome many of the challenges inherent in locomotor assistance. In particular, human-in-the-loop optimization has proven effective at significantly reducing whole-body metabolic rate [1, 2, 3]. Such direct optimization methods, however, often expose users to widely variable and suboptimal exoskeleton conditions and generally hold assistance parameters fixed once the optimization routine is complete. The development of alternative human-in-the-loop strategies, guided by heuristics about effective interactions between the device and the user, could, therefore, be useful for different scenarios, devices, or populations. The goal of this project was to develop a human-in-the-loop assistance strategy that improves locomotor performance by fostering co-adaptation, in which the user and the device continuously respond and adapt to each other.

Methods

We developed a control scheme that uses muscle activity and joint kinematics to drive the evolution of an ankle exoskeleton torque pattern based on three main heuristics: 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) compensatory changes in coordination patterns are indicative of maladaptation and should act to slow or reverse torque growth. We formulated an algorithm to best realize these heuristics and implemented it on tethered, bilateral ankle exoskeletons. To test the efficacy of the approach, we conducted an experiment with ten naïve exoskeleton users. Participants walked on a treadmill for 30 minutes at 1.25m/s while exoskeleton torque evolved based on the driving heuristics (Adaptive). We measured whole-body metabolic rate and soleus muscle activity.

Results and Discussion

Exoskeleton torque evolved independently for each participant and each leg, leading to a wide variety of assistance patterns (Fig. 1A). The shape of the assistance pattern continuously responded to the changing pattern of each user's soleus muscle activity and growth of the assistance pattern slowed when the user did not seem to be adapting. At the end of the Adaptive condition, metabolic rate was, on average, 22% below that measured during walking with the exoskeletons while they provided no torque ($p < 0.05$, Figure 1B).

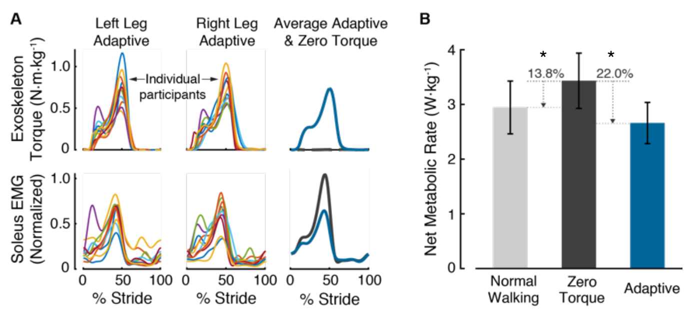

Figure 1: A) Evolved exoskeleton torque profiles (*top*) and resulting soleus muscle activity (*bottom*). Participant-averaged torque and soleus muscle activity in the Zero Torque condition (*dark grey*) are provided for reference. B) Average metabolic rate across conditions.

The results show that the algorithm can discover effective, high-dimensional torque patterns for lower-limb ankle exoskeletons. Furthermore, the algorithm scales well to multiple devices, as demonstrated by the independent application of the algorithm to exoskeletons on the left and right legs.

Conclusions

Co-adaptive exoskeleton assistance strategies can significantly improve locomotor performance. We expect variations of our approach to extend well to new, multi-articular devices and to different populations, particularly those with muscle weakness.

References

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