Optimizing the energy economy of human running with powered and unpowered ankle exoskeleton assistance

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Summary

We used a tethered ankle exoskeleton emulator to simulate and compare the effects of running with powered and passive, spring-like assistance profiles in plantar-flexion. Human-in-the-loop optimization (HILO) was used to identify the best torque profiles for both types of assistance for each user. Optimal powered assistance improved energy economy by 24.7 ± 6.9% compared to zero torque and 14.6 ± 7.7% compared to running in normal shoes. Spring-like assistance was ineffective, improving energy economy by only 2.1 ± 2.4% compared to zero torque. These results suggest success for a portable device with a powered assistance profile.

Introduction

Highly effective running exoskeletons could lead to greater participation in physical activity by decreasing activity intensity and fatigue. Several passive devices and one powered device have demonstrated moderate success with 4 to 8% reduction in energy cost [1-3]. A single-subject pilot study with powered ankle exoskeletons previously resulted in much larger improvements of 27% in running and 24% in walking compared to zero torque [4]. This suggests that assisting the ankle may be more effective than the foot [1] or hip [2, 3].

Spring-loaded exoskeletons that can operate without the added mass of batteries, motors, and complex transmissions may be a preferable method to assist running. Due to the spring-like nature of the legs during running, spring-like assistance profiles might also lead to easier user adaptation [7]. Ankle exoskeleton emulators can be used to simulate various assistance profiles, thus allowing direct performance comparisons between powered and spring-like assistance [8].

Methods

Experimental Protocol. Eleven subjects wore tethered, bilateral torque-controlled ankle exoskeletons while running at 2.7 m/s [8]. Subjects experienced a habituation day in which they were introduced to both controllers in random order. Subjects underwent a day of human-in-the-loop optimization with each controller. On the final day, assistance profiles were compared in a randomized, double-reversed order through a series of validation trials: zero-torque, optimal spring-like, optimal powered, normal shoes, and quiet standing.

Controller parameterization. The optimization algorithm sampled a range of torque assistance patterns by varying the chosen parameters for each controller type through covariance matrix adaptation evolution strategy (CMA-ES). The powered assistance profile was characterized by peak torque magnitude and three time-based parameters: onset time, timing of peak torque, and offset time. The spring-like profile was based on ankle angle and parameterized by the torque at maximum dorsiflexion angle, the angle at which the spring becomes engaged, and a spring shape constant (linear, stiffening, or softening).

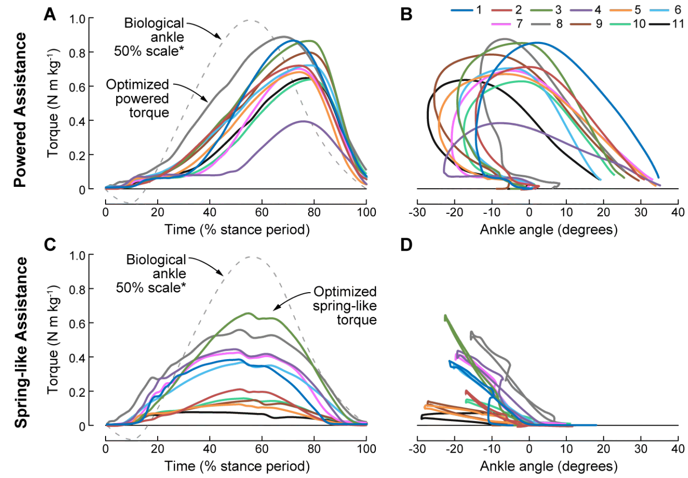

Figure 1: Optimal assistance patterns. **(A)** Optimized torque patterns for the powered assistance strategy are shown for each subject. (**B**) Torque vs. angle curves show large work injection for all subjects in powered condition. (**C**) Optimal torque patterns for spring-like assistance for each subject. (**D**) Torque vs. angle curves show minimal work injection for all subjects in passive spring-like condition. A 50% scale representation of biological ankle torque during unassisted running is shown as a dotted line in **(A)** and **(C).**

Results & Discussion

Optimal powered assistance improved energy economy by 24.7 ± 6.9% compared to zero torque and 14.6 ± 7.7% compared to normal shoes [1]. Spring-like assistance was ineffective, improving energy economy by 2.1 ± 2.4% compared to zero torque and –11.0 ± 2.8% compared to normal shoes. Assistance patterns are shown in Figure 1.

The success of the powered assistance strategy may be due to high peak torques and large amount of net positive work supplied in comparison to the spring-like assistance strategy. However, previous studies have demonstrated that additional power is not always helpful [4], suggesting that this criterion does not always hold. The benefits of powered assistance may also result from the application of high torques in late stance, when force production in the soleus muscle is limited [9].

Results of the spring-like strategy were surprisingly poor. We hypothesize that passive assistance may be more effective when assisting joints that produce near net zero work such as the hip, as demonstrated in [2]. Overall, the results of this experiment have exciting practical implications, suggesting that portable ankle exoskeletons may be capable of sharply improving running performance using a similar powered assistance strategy.

References

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