A Passive Elastic Ankle Exoskeleton Using Controlled Energy Storage and Release to Reduce the Metabolic Cost of Walking

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1 Introduction

Current exoskeletons fall into two distinct categories- fully-powered [1-4] and purely passive [5]. Fully-powered devices employ motors under high gain force control that can mimic the normal torque output of the lower-limb joints. However, added mass of the hardware most often results in a marked decrease in walking economy during assisted locomotion.

Purely passive devices (e.g. dynamic ankle-foot orthoses (DAFOs)) can store and release elastic energy in rigid, non-hinged frames to assist walking without assistance from motors. This lightweight, simplistic approach has been shown to cause small increases in both walking speed and economy post-stroke [6-8]. However there are downsides to current DAFO designs. First, rigid, non-hinged DAFOs restrict full ankle joint range of motion, allowing only limited rotation in the sagittal plane. Second, and perhaps more crucial- current DAFOs do not allow free ankle rotation during swing, making it difficult to dorsiflex in preparation for heel strike. Inability to dorsiflex freely during swing could impose a significant metabolic penalty, especially in healthy populations [9].

Using a ‘hybrid’ approach (i.e. controlled energy storage and release) our calculations suggest that a parallel spring of the appropriate stiffness could provide *all* of the torque output of the ankle joint during walking- without an external power source [10]. On the other hand, a recent simple walking model with springy ankles predicts that there is an optimal stiffness (not *too* stiff, not *too* compliant) for reducing the metabolic demands of walking [11]. The purpose of this study was to investigate the influence of the parallel spring stiffness of our passive ankle exoskeleton on the mechanics and energetics of walking.

2 Design

In order to take advantage of the key components from both the purely passive and fully powered assistive devices we developed a portable, passive elastic ankle exoskeleton that uses controlled energy storage and release to provide ankle torque [10]. The device works by controlling elastic energy storage and return of a parallel spring used to produce a large portion of the normal torque output of the ankle joint during walking. This concept is analogous to the elastic ‘catapult’ mechanism observed in the human ankle during walking [12, 13]. Our device’s control system works completely off of mechanical position feedback, using a purely mechanical clutching device.

3 Approach

Three study participants trained with the device over three, thirty minute sessions at 1.25m/s walking speed. Sessions occurred over three separate days each with two days in between. Participants trained with the exoskeleton spring stiffness that stored the most elastic energy at 1.25 m/s. Gas exchange, electromyography, inverse dynamics and exoskeleton spring force data were collected on all days. Following training, participants walked in the exoskeleton at 1.25 m/s, for 7 minutes with 5 spring stiffnesses spanning from 110 N-m/rad to 275 N-m/rad (i.e. 30-75% of normal ankle joint stiffness at 1.25 m/s) in order to determine the optimal stiffness for metabolic economy.

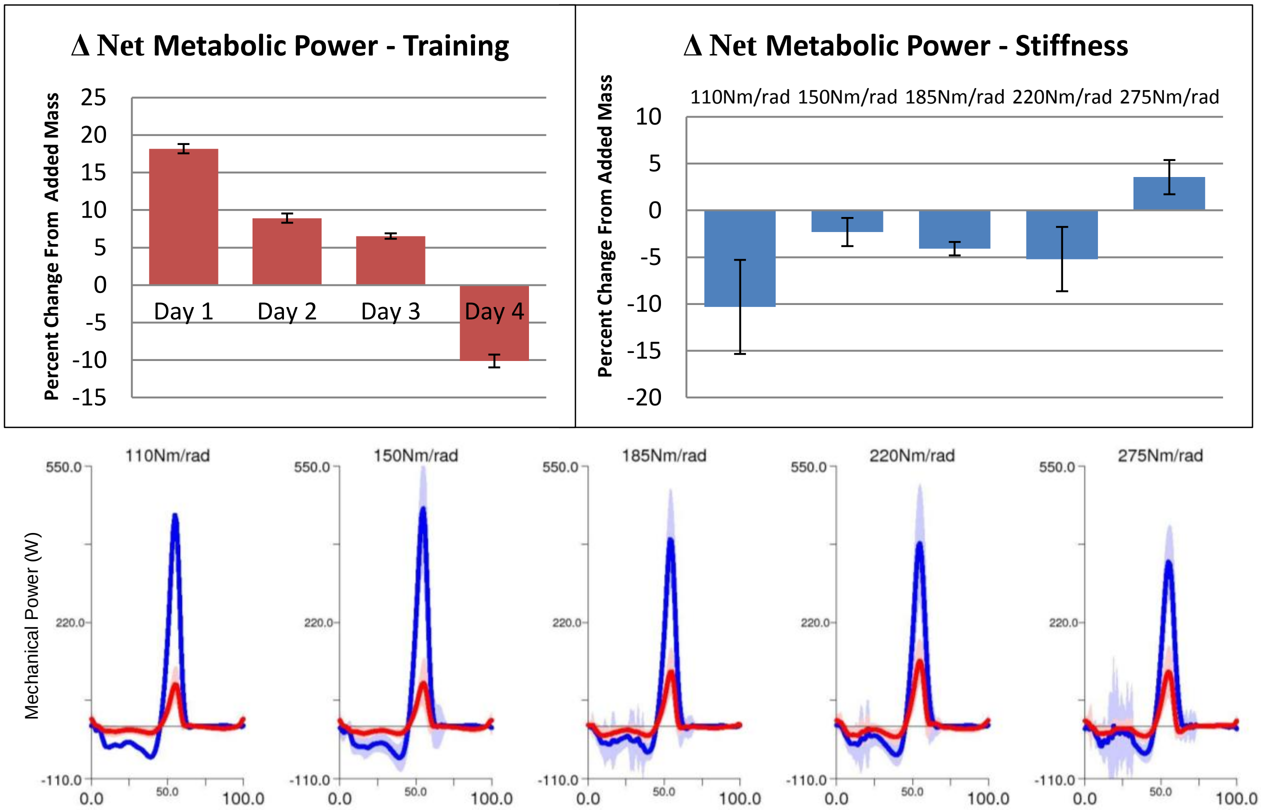
3 Results/Discussion

Our results indicate that training plays a key role in adaptation to an assistive exoskeleton. By utilizing the dynamic energy storage and return of our exoskeleton, study participants were able to reduce metabolic cost on average by 10% below added mass using a parallel spring stiffness of 110Nm/rad (~35% normal ankle stiffness) after training. The 220Nm/rad stiffness spring stored and returned the most energy, providing 35% of total ankle power. However, mechanical performance (i.e. energy stored/exo contribution) did not predict metabolic savings, emphasizing the importance of the timing of trailing limb push-off on COM dynamics [11]. Participants were not able to walk comfortably with stiffnesses larger than 275Nm/rad (~75% normal ankle stiffness). Additional data will build confidence in our results.

4 Open Questions

Can passive dynamic devices be incorporated at other joints to reduce metabolic cost further?

5 Figures



Top Left: Percent change in metabolic cost as a result of training (neg. indicates metabolic reduction).
Top Right: Metabolic change on last testing day using 5 spring stiffnesses at 1.25m/s.
Bottom: Avg. ankle (blue) and exoskeleton (red) power (W). (N=3, avg. mass = 74.8kg, avg. height=1.72m)

6 References

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