Design of a Portable, Lightweight Ankle-Foot Orthosis (AFO) to Reduce Metabolic Cost of Walking

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1 Introduction

Lower extremity robotic exoskeletons can provide mechanical assistance to improve mobility for neurologically-impaired individuals [1]. The metabolic cost of using an exoskeleton to perform a desired task is a crucial performance measure for determining the effectiveness of the device. However, to our knowledge, there is currently no portable leg exoskeleton that reduces the metabolic cost of walking when compared to normal conditions.

While the relationship between joint mechanics and metabolic cost is difficult to ascertain, there are important principles that may guide exoskeleton design. During normal walking, the ankle joint performs more positive work than both the knee and hip joints, especially during pushoff [2]. This work is required for steady-state walking dynamics due to negative work from heel collision to redirect the body center of mass. Studies have shown that the step-to-step transition is linked to metabolic cost for walking [3-4], so perhaps the ankle joint is a good place to providing mechanical assistance via an orthosis. Another design parameter that affects locomotion energetics is the mass of the assistive device. Experiments have shown that adding mass to the body exacts a proportional increase in metabolic energy during walking, with increasing energy change as the mass is moved distally from the body center of mass [5-6]. Actively-powered exoskeletons are typically bulky and require large motors or pneumatic/hydraulic systems [1], which likely inhibits the energetic advantage of using these devices. Recent studies on ankle joint mechanics suggest that passive mechanical components (e.g. springs, dampers) may be a successful alternative to active force control for providing assistance to the lower limb [7-8]. The purpose of this project is to design a portable, lightweight ankle-foot orthosis (AFO) that decreases the metabolic cost of normal walking.

2 Methods

Mechanical Design

We built a lightweight and minimally constraining AFO for use in locomotor experiments on metabolic energy expenditure. A schematic of the device outlining the important components is illustrated in **Figure 1** alongside an isometric view of the CAD model. The device interfaces with the biological leg on the upper shank and at the heel and contacts the ground near the toes. One of the primary design goals is the reduction of interaction forces between the AFO and the biological limb, so the connections near the knee and toes were placed as far from the ankle joint as possible without restricting normal knee and foot motions. The struts along the shank and foot are made from a lightweight composite and include cutouts to reduce the mass while maintaining strength requirements. A pin joint near the toe and a vertical slot at the shank contact improve flexibility in the desired regions and minimally constrain normal joint kinematics. The shank and foot of the exoskeleton are connected via springs that operate in parallel to the biological muscle and provide mechanical assistance during pushoff. The springs are controlled by a one-way passive clutch so that deflection only occurs when desired (in this case, as the ankle dorsiflexes during midstance). We will determine spring torque characteristics *a priori* to estimate the reduction of biological ankle joint work per stride.

Experimental Study Design

The goal of the initial study is to determine the performance characteristics of the AFO described above using able-bodied subjects walking on a treadmill. Subjects will be tested under three conditions: (A) not wearing the exoskeleton, (B) wearing the exoskeleton but without any mechanical assistance, and (C) wearing the exoskeleton with mechanical assistance. Measured parameters will include gait kinematics, ankle torque, muscle activity (e.g. soleus and gatrocnemius), and metabolic energy expenditure. We will compare assisted and unassisted walking to characterize orthosis performace and test the hypothesis that the addition of spring torque results in reduced biological ankle torque. In addition, we will explore the effect that varying parameters such as spring stiffness, step length, and gait speed have on performance. We hypothesize that the spring stiffness can be modified so that assisted walking results in similar gait kinematics and overall ankle torque compared to normal walking, but with decreased muscle activity and metabolic cost.

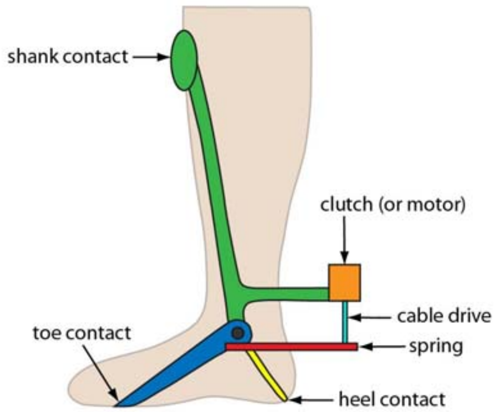

Figure 1: AFO illustration showing orientation on the leg and outlining important mechanical components (top); Solidworks model of the AFO alpha prototype with a passive clutch mounted to the shank strut (bottom).

3 Discussion

The most important design criteria for this device are the overall mass and spring stiffness. The total mass is approximately 0.6 kg per leg, which should result in a negligible increase on the energy cost of walking. The springs were selected by observing empirical ankle moment-angle curves for normal walking and, assuming linearity, choosing the maximum stiffness that would not generate an unnatural ankle moment pattern. This selection relies on the assumption that the spring will replace, rather than add to, the ankle torque produced by the muscles. Regardless, as discussed above, we think it is important to perform experiments that explore the relationship between varying spring parameters and metabolic cost.

While this AFO design is specifically geared toward the use of a clutch for passive control of ankle joint mechanical assistance, the design may also be useful in experiments on active force control using offboard motors or another source of actuation. Long-term studies includes coupling the AFO frame with an external motor to investigate various control methods with the goal of improving motor adaptation of impaired subjects (e.g. stroke patients) during gait rehabilitation exercises.

4 Acknowledgments

This research is conducted in collaboration with G. Sawicki and B. Wiggin (NCSU/UNC Joint Dept of BME), who are designing the passive clutch that will be used with our lightweight AFO frame.

5 Open questions

While we do not yet have experimental results to discuss, I would like to network with other researchers to determine what mechanical changes might make the design better and what results we might expect regarding human response to mechanical assistance from the orthosis.

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