A Lower Extremity Soft Robotic Exoskeleton

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1 Introduction

Humans and other animals walk in a way that minimizes energy consumption. We take advantage of inertial passive dynamics and elastic energy storage and return to create a walking pattern that is extremely economical [1]. A reduction in energy consumption during walking might be achieved by supplying external mechanical power to the joints of the lower limbs. With additional mechanical power applied to the joints, a human could engage in physical activity for longer durations of time before fatigue sets in. This same concept could be applied for rehabilitation purposes to supplement mechanical power for impaired muscles [2].

A host of robotic exoskeletons have demonstrated that it is possible to add mechanical power to the lower limbs of humans [2, 3]. Most robotic exoskeletons add substantial mass to the wearer and constrain the range of motion of some joints. Exoskeletons often alter the user's natural dynamics and a poorly designed exoskeleton can actually lead to an increase in energy consumption [4]. Recent research by Malcolm et al. has shown that it is possible to reduce a wearer's metabolic cost during walking by using a single joint exoskeleton [5]. It might be possible that a wearer's metabolic cost could be further reduced using a robotic exoskeleton made from lightweight, soft materials to supply power to the wearer's ankle.

A soft exoskeleton could rely on the existing skeletal structure of the wearer to transmit forces across the actuated joint. This design would result in a lightweight exoskeleton that does not rely on heavy rigid components. The soft materials of the exoskeleton could also be compliant. Compliance could maintain the wearer's natural range of joint motion. A soft exoskeleton's mechanical output is likely limited in comparison to a rigid design because a soft exoskeleton would transmit forces directly to the human body. However, a soft exoskeleton might be able to produce sufficient mechanical assistance to substantially lower the wearer's energetic cost of locomotion.

Several research groups around the world have previously tried to build soft exoskeletons for assisting human movement. Most of the research has focused on prototype devices with limited human subject experimentation [6–8]. Conner Walsh's group at the Wyss Institute for Biologically Inspired Engineering has recently demonstrated that a soft exoskeleton could minimize the use of rigid, hard materials in the support frame [9]. In their work, Walsh et al. proposed the idea that anchor points and webbing straps within the exoskeleton could strategically transfer tensile forces throughout the system. Key anchor points are locations at which the exoskeleton transfers forces to the skeletal structure. These locations are points on the body that are know to readily support loads and include the feet, hips, and shoulders. Virtual anchor points are locations on the exoskeleton that are not directly connected to the wearer, but do not move relative to the body during motion. Virtual anchor points direct tensile forces along desired lines of action via webbing straps. The anchor points are also used to connect actuators to the soft exoskeleton. Using their developed concept of anchor points, Walsh et al. have been able to supply mechanical power to the ankle using a soft exoskeleton design [9, 10].

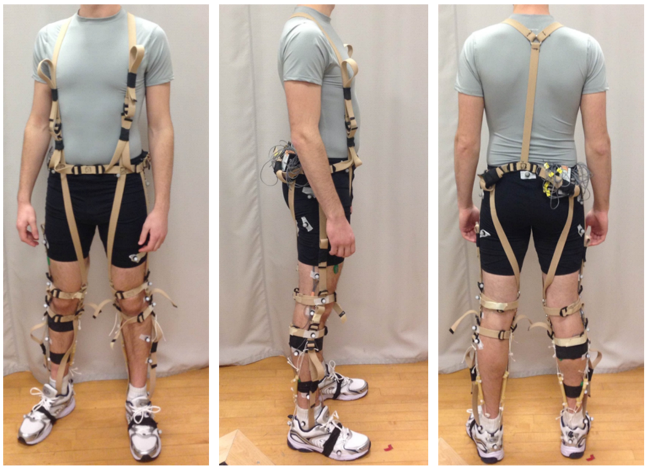

Figure 1: A prototype soft exoskeleton during pilot testing. The exoskeleton was made from cotton webbing straps, plastic adjustment buckles, and metal D-rings. For this test, passive springs are used in place of actuators. The subject was equipped with a full lower limb marker set for motion capture and six electromyography electrodes on one lower limb to record muscle activity.

The goal of our project is to test the feasibility of using a soft exoskeleton with pneumatic actuators to reduce the metabolic cost of walking. We propose to extend on Walsh et al.'s previous findings by developing a systematic design methodology that allows for optimal placement of key and virtual anchor points. We also plan on demonstrating a systematic process of optimal control inputs [5] for a soft exoskeleton with active plantar flexor assistance.

2 Current State

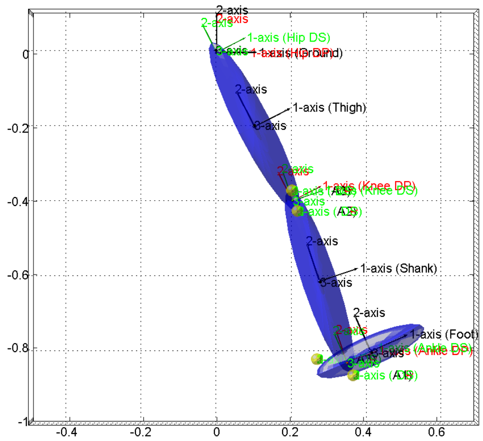

Figure 2: Our anthropometric lower extremity model under a forward kinematic simulation of human walking. An optimization scheme determined optimal anchor point locations by minimizing the relative displacement between locations during gait. The yellow spheres in the model were the calculated optimal anchor point locations for the subject used in our pilot study.

We will present a software tool that computes the optimal placement of virtual and key anchor points in a soft exoskeleton design. Using an anthropometric lower extremity model (Fig. 2) and a forward kinematic simulation of human walking, we will predict the relative displacement between anchor points as a function of time. Such displacements create slack, lead to a saturation in power output, and result in an overall inefficient design. We aim to minimize this relative displacement through an optimal choice of key and virtual anchor point locations. We have parametrized anchor point placements and established a cost function that is a weighted sum of the integrated relative anchor point displacements. We have determined anchor point locations via numerical optimization in order to minimize our developed cost function of single stride dynamics for level-ground walking.

Based on our simulation results, we developed a prototype of the soft exoskeleton out of cotton webbing straps, plastic adjustment buckles, and metal D-rings (Fig. 1). The current prototype weights 1.7 Kg and can be adjusted to fit subjects ranging from 172 - 190 cm in height. We have tested the exoskeleton in a pilot study using passive springs in place of actuators to study how the exoskeleton moves relative to the body when under tension. The springs supplied approximately 10% of our subjects normal ankle torque during plantar flexion. The subject wore electromyography electrodes to measure muscle activity in lower limb muscles. The data from this pilot study is currently being analyzed.

3 Best Possible Outcome

We will conduct a second pilot study to analyze the effects of high actuation forces on the exoskeleton and investigate how the soft exoskeleton affects energy consumption of users during walking. We plan to replicate the testing procedures set forth by Malcolm et al. [5] to compare results with a soft exoskeleton relative to a rigid ankle-foot orthosis. We will also expand upon the design methodology described above to account for pneumatic actuation of the soft exoskeleton. Moving away from a purely kinematic simulation, we will include forces and elastic deformations in our model in order to predict how the exoskeleton will behave under tensile forces that will assist with the wearer's plantar flexion. This will allow us to quantify user comfort and to assess efficiency by evaluating power dissipation caused by soft-body motion. The model will be based on the results of the user testing described above. Given that this pilot study and model show promising results, we expect to use our soft exoskeleton for future rehabilitation studies.

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