Multi-articular soft exosuit continually reduces the metabolic cost of unloaded walking with increased assistance magnitude

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Summary

Soft exosuits use structured functional textiles as a lightweight and conformal means to interface to the human body and deliver assistance in attempt to reduce the overall metabolic cost of walking. Here we present a soft exosuit that uses one actuator per leg to assist with both ankle plantarflexion and hip flexion thorough multi-articular suit architecture. To characterize the relationship between the amount of assistance applied by the soft exosuit and the metabolic cost of normal walking, we performed a series of experiments in which the peak force applied to the suit, local to the ankle, was varied from 18.7% to 75.0% of body weight. Results showed that with increasing peak force, the change in net metabolic rate continually decreased within the tested range. When maximum assistance was applied (peak torque of 0.71 Nm kg^{-1} at the ankle and 0.47 Nm kg^{-1} at the hip), the metabolic rate of waking was reduced by 1.02 ± 0.14 W kg^{-1} (mean ± s.e.m.) relative to the powered-off condition, corresponding to a $22.83 \pm 3.17\%$ reduction in metabolic rate.

Introduction

Over the last decade a number of wearable robotic devices have been developed with the purpose of assisting human walking and reducing the metabolic energy consumption of the user. Many of these devices are comprised of rigid linkages that span the entire lower limb and apply torques directly to the wearer's joints; however, such designs were found to increase energy expenditure as they restricted the natural movements of the wearer and added large inertias to limb segments (Gregorczyk et al., 2005; Walsh et al., 2007). Recently, several groups have tried to address these issues by using lightweight components to deliver assistance to a single joint in parallel with musculature, showing promising results (Malcolm et al., 2013; Mooney & Herr, 2016).

Our lab has been developing soft exosuits that apply joint torques via tensile forces in parallel with the muscles in order to reduce the required muscular activation (Asbeck et al., 2015). We have developed both mono-articular and multi-articular exosuits and that have been powered by both offboard and body-worn actuation systems and shown promising metabolic reductions (Ding et al., 2016).

When defining requirements for any wearable robot for walking assistance, it is paramount to maximize the user's metabolic benefit (perhaps by maximizing level of assistance), while also minimizing the metabolic penalty of carrying the additional weight of the system. In line with this, the aim of this study was to isolate and characterize the relationship between the level of assistance applied by the exosuit, the metabolic cost of normal walking, and the underlying mechanics of human locomotion.

Methods

As shown in **Fig. 1**, the soft exosuit used in this study has a single actuator per leg which assists with ankle plantarflexion and hip flexion through the multi-articular load path specified by the textile architecture (Lee et al., 2016). An offboard actuation system was used to generate assistive forces, and Bowden cables were used to transmit the forces to the soft exosuit local to the subject's ankle. On each leg, one gyroscope and three load cells were attached to

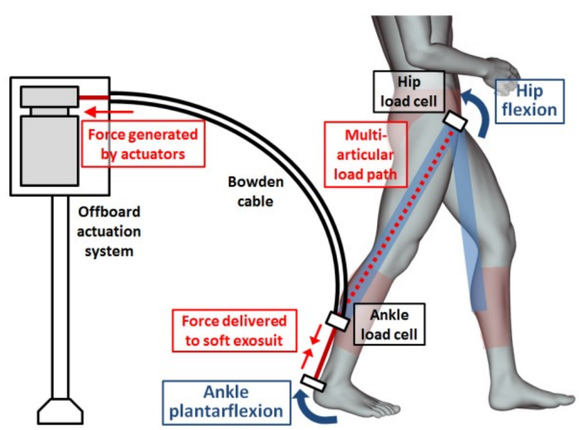

Figure 1. The multi-articular soft exosuit and the offboard actuation system used in this study.

measure data from the suit and the wearer. Using the sensor data, the controller performed a force-based position control to deliver torques similar to the biological ankle moment pattern, considering both kinematics of human walking and exosuit stiffness.

Seven healthy male adults (26.71 ± 4.75 yrs; 68.43 ± 9.46 kg; 1.74 ± 0.06 m; mean ± SD) participated in this study. All participants attended two experimental sessions: a training session and a testing session. In both sessions, participants walked on a treadmill at 1.50 m s^{-1} under five experimental conditions: one powered-off and four active. During the four active conditions, peak assistive force applied at the ankle was scaled based on each subject's body weight: 18.7% (*LOW*), 37.5% (*MED*), 56.2% (*HIGH*), and 75.0% (*MAX*). On average 70% of the force applied at the ankle was transmitted to assist with hip flexion. During the testing session, the order of the five experimental conditions were randomized and grouped into two continuous trials, each 15-minute in length and each containing a powered-off condition for relative comparison of metabolic data. Metabolic rate (Cosmed), lower-limb kinematics (Vicon), and ground reaction forces (Bertec) were measured.

Results & Discussion

Across the four active conditions, the average peak assistive torques at the hip and ankle respectively were: *LOW* 0.201 Nm kg^{-1} and 0.181 Nm kg^{-1}; *MED* 0.302 Nm kg^{-1} and 0.357 Nm kg^{-1}; *HIGH* 0.393 Nm kg^{-1} and 0.540 Nm kg^{-1}; and *MAX* 0.468 Nm kg^{-1} and

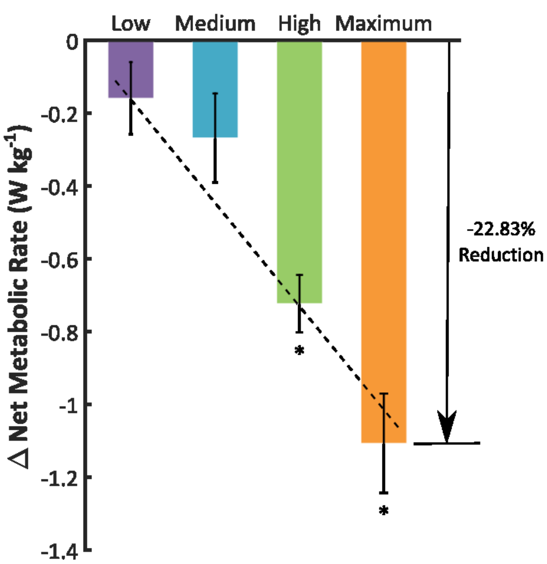

Figure 2. Changes in net metabolic rate in each active condition compared to the powered-off condition (N=7; ANOVA with first-order model; y= -0.1543x+0.1211; y (W kg-1); x (N kg-1); R^2=0.7586; P=5.78×10^{-11}). In the *MAX* condition (orange bar), change in net metabolic rate was -1.017 ± 0.137 W kg^{-1} (mean ± s.e.m.), which corresponds to a 22.83 ± 3.17% reduction. Asterisks indicate significant differences compared to the powered-off condition (paired t-test; P_{HIGH}= 9.44×10^{-5}; P_{MAX}=1.89×10^{-4}).

0.707 Nm kg^{-1}. As shown in **Fig. 2**, with increasing level of assistance, the net metabolic rate continually decreased in the tested range. In the *MAX* condition the metabolic rate of waking was reduced by 1.017 ± 0.137 W kg^{-1} (mean ± s.e.m.) relative to the powered-off condition, which is a reduction of 22.83 ± 3.17% (paired t-test; P=1.89×10^{-4}). With increasing level of assistance, the biological torque and power (total - assistive) were reduced, potentially contributing to the metabolic reduction observed. However, changes in kinematics and total moment and power were also found, indicating changes in the subjects overall way of walking which could also be a contributing factor to the metabolic reduction.

Looking forward, as the metabolic rate continually decreased within the tested range additional studies are needed to determine if this trend continues with higher applied forces or it levels-off as seen in previous parameter sweep studies (Jackson & Collins, 2015; Caputo & Collins, 2014). Additionally, in order to fully understand the trade-off between the amount of assistance an exosuit can provide and its weight, the associated cost for carry an actuation unit capable of each level of force must be taken into account.

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