Title: Ankle Optimization with a Soft Exosuit Reduces Metabolic Cost of Loaded Walking

Authors: Lauren Baker[1,2], Sangjun Lee[1,2], Andrew Long[1,2], Jinsoo Kim[1,2], Nikos Karavas[1,2], Nicolas Menard[1,2], Ignacio Galiana[1,2], Conor Walsh[1,2]
[1] Harvard University John A. Paulson School of Engineering and Applied Sciences, Cambridge, MA
[2] The Wyss Institute for Biologically Inspired Engineering, Cambridge, MA

Background & Purpose: Soft exosuits for gait assistance have shown great promise for improving human walking economy [1, 2]; however, the best control strategy to maximize individual efficiency is still unclear. For ankle assistance, we previously designed a controller that delivers the majority of assistance during the ankle's positive power phase [3]. Despite promising metabolic results [4], the amount of positive power varied across participants, indicating that the original controller may not have been maximizing individual augmentation power at the ankle. To address this, we developed a controller that optimizes actuation timing parameters to maximize the positive power delivered to the ankle. The purpose of this study was to investigate whether the new optimization controller increases the positive augmentation power at the ankle and reduces the metabolic cost of loaded walking compared to the original controller.

***Figure 1**: Components of the soft exosuit*

Subjects: Five healthy males (age 32.8±8.1 years; mass 81.3±8.7 kg; height 1.8±4.6 m)

Methods: Participants walked on a treadmill with the exosuit active at 1.5 $m \cdot s^{-1}$ while carrying a loaded backpack (6.8 kg), actuator (5.9 kg), and battery (2 kg) for a 15-minute online optimization period (Figure 1). The force applied to the ankle was targeted to be 400 N. After optimization, participants completed three 5-minute experimental conditions: loaded walking with exosuit active with original parameters (Original), loaded walking with exosuit active with optimized parameters (Optimized), and loaded walking without exosuit (No Suit). The metabolic cost of walking with and without the exosuit was assessed using indirect calorimetry and calculated using a modified Brockway equation [5].

Results: The force applied at the ankle followed a similar profile for both controllers, with similar peak force and expected varied timing of force delivery (Figure 2). The average positive power delivered to the ankle was 0.178±0.04 $W \cdot kg^{-1}$ for Original and 0.252±0.07 $W \cdot kg^{-1}$ for Optimized, and the average net metabolic reduction compared to No Suit was 11.5±5.8% for Original and 15.3±2.9% for Optimized (Figure 3). Optimized assistance at the ankle reduced the average net metabolic cost of walking with a loaded backpack from 3.67±0.49 $W \cdot kg^{-1}$ during Original to 3.50±0.65 $W \cdot kg^{-1}$ during Optimized. One participant did not follow this reduction pattern from Original to Optimized.
Conclusion: Both controllers reduced the metabolic cost of loaded walking compared to No Suit; however, maximizing delivered power to the ankle with the optimization controller resulted in an overall greater metabolic reduction compared to the original controller.

References:
[1] Panizzolo et al, *A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking,* JNER, 2016
[2] Quinlivan et al, *Assistance magnitude versus metabolic cost reductions for a tethered multiarticular soft exosuit*, Sci Robot, 2017
[3] Lee et al, *Controlling Negative and Positive Power at the Ankle with a Soft Exosuit*, ICRA, 2016
[4] Malcolm et al, *Varying negative work assistance at the ankle with a soft exosuit during loaded walking*, JNER, 2017
[5] Brockway, *Derivation of formulae used to calculate energy expenditure in man*, Hum Nutr Clin Nutr, 1987

Clinical Relevance: These findings will guide future work on customizing joint assistance and maximizing human performance with exosuits.

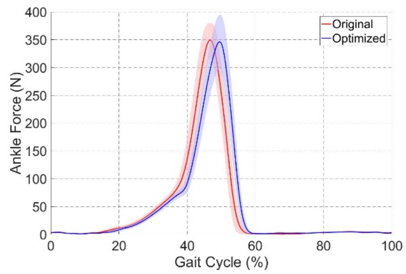

Figure 2*: Average force (N) delivered to ankle of one representative participant over one gait cycle for Original (red) and Optimized (blue). Shaded region represents standard deviation.*

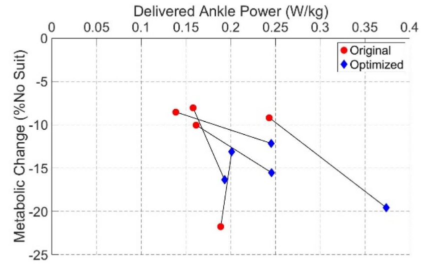

Figure 3*: Net metabolic change from No Suit to Original (red) and Optimized (blue) as a function of delivered ankle power (W kg*$^{-1}$*). Data for each participant is connected to show change from Original to Optimized. Negative values indicate reduction.*

References:
[1] Panizzolo et al, *A biologically-inspired multi-joint soft exosuit that can reduce the energy cost of loaded walking,* JNER, 2016
[2] Quinlivan et al, *Assistance magnitude versus metabolic cost reductions for a tethered multiarticular soft exosuit*, Sci Robot, 2017
[3] Lee et al, *Controlling Negative and Positive Power at the Ankle with a Soft Exosuit*, ICRA, 2016
[4] Malcolm et al, *Varying negative work assistance at the ankle with a soft exosuit during loaded walking*, JNER, 2017
[5] Brockway, *Derivation of formulae used to calculate energy expenditure in man*, Hum Nutr Clin Nutr, 1987