Title: Human-in-the-loop optimization of exoskeleton assistance during walking

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Introduction:

Exoskeletons and active prostheses promise to enhance human mobility, but few have succeeded. An overreliance on intuition and specialized hardware may be partially responsible; designs have typically been based on a simplified understanding of the human-robot system and experiments have primarily been conducted using specialized prototypes, limiting exploration to only a small set of potential assistance strategies. Compounding the challenge, differences between individuals can cause divergent responses to the same device and responses can change considerably during adaptation. Methods for automatically discovering, customizing and continuously adapting assistance could overcome these challenges.

Methods:

We are developing methods for systematically varying device characteristics, during use, so as to maximize human performance (Fig. 1A). This is made challenging by lengthy evaluation periods, noisy measurements, and time-varying dynamics, which foil many optimization methods. We recently demonstrated [1] a sample-efficient method of identifying the exoskeleton control parameters that minimize the metabolic energy cost of human walking (Fig. 1B). We used this approach to optimize the pattern of assistive torque applied by an exoskeleton worn on one ankle during walking. We optimized assistance for 11 participants as they walked on a treadmill at 1.25 m s^{-1}. Following optimization, we performed validation tests comparing optimized assistance to a fully passive ‘zero-torque’ mode. Optimized assistance substantially

improved energy economy for all participants, with an average reduction in metabolic rate of 24.2±7.4% (t-test: $P = 1 \cdot 10^{-6}$; N = 11). Optimized assistance patterns varied widely across participants, demonstrating the importance of customization. Three separate factors seemed to be important: discovering a good generic assistance pattern, customizing it to individual users, and facilitating motor learning. The optimization approach was also effective in single-subject tests with exoskeletons worn on one or both ankles, during a variety of walking conditions, during running, and when optimizing muscle activity.

Discussion:

The evolutionary strategy we used was more effective than other methods we tried, but improved techniques seem likely. Such methods could be applied to variable locomotor conditions, or to the optimization of speed, endurance or balance. In daily life, proxy measures such as heart rate or muscle activity could be used for optimization, providing noisier but more abundant data. These approaches could be used to enhance biomechanics research, and to improve assistive devices for people with a wide range of unique physiological needs, from individuals with chronic stroke to athletes.

References:

[1] Zhang, J., Fiers, P., Witte, K. A., Jackson, R. W., Poggensee, K. L., Atkeson, C. G., Collins, S. H. (2017) Human-in-the-loop optimization of exoskeleton assistance during walking. *Science*, **356**:1280-1284.