Optimization of soft exosuit peak force with ramp and step sweep protocol

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Summary

Parameter sweeps allow for optimization of control parameters in assistive devices, but collecting data from a series of parameters at metabolic steady state is prohibitively time consuming. We implement a pair of *continuous* parameter sweeps, varying assistive force delivered by a soft exosuit in parallel with ankle plantarflexors and hip flexors from 0 to 75% body weight, with on average a 10.1-cm moment arm at the ankle and an 11.1-cm moment arm at the hip. We conducted continuous sweeps that included both increasing and decreasing peak assistance, each in 40% less time than a sweep at four discrete steady-state force intervals over the same range. Furthermore, the continuous sweeps explored the effects of more parameter values. Continuously increasing force showed less metabolic reduction relative to an unpowered condition compared to steady-state forces, suggesting that additional adjustments for delay are still needed. Methods such as these may help improve tuning procedures for wearable robots.

Introduction

Parameter sweeps can help explain how people adapt their gait to varying assistance from wearable robots. In the past, there have been differing results when relating assistance magnitude to metabolic reduction, showing that both maximal (Jackson and Collins, 2015) and intermediate (Galle et al., 2015, Collins et al., 2015) assistance levels produce the largest metabolic reduction in exoskeletons.

Promising results of metabolic reduction have also been demonstrated with soft exosuits, which apply assistive forces at the joint level through a textile-based structure acting in parallel with the wearer's muscles. Modulating assistance at discrete levels, a previous study showed metabolic reductions with a tethered system up to 15%, compared to an unpowered condition (Lee et al., 2016).

In unassisted walking, continuous sweeps have been similarly accurate, less time consuming, and investigated more parameter settings than steady-state sweeps (Felt et al., 2015), and such methods are now being explored with exoskeletons by a number of groups. Accordingly, a continuously changing peak force delivered by the exosuit to the body could facilitate faster selection of energetically optimal assistance magnitude. However, measuring metabolic response in non-steady-state conditions is challenging (Boone and Bourgois, 2012). This study's aim is to compare the relationship between metabolic response and peak assistive force from a soft exosuit in a continuous sweep to the same relationship in a step sweep.

Methods

Seven trained participants (27±5 yrs; 68±10 kg; 1.7±0.1 m; mean ± SD) walked on a treadmill at 1.50 m s^{-1} wearing a soft exosuit that assists plantarflexion and hip flexion under three classes of parameter sweep. Though the exosuit did assist hip flexion, its primary mechanism acted through the ankle, so this is the main focus on this abstract. In *ramp-up*, assistance ranged from powered off (PO) at 0% body weight (BW) to 75% BW over 10 minutes; *ramp-down* was the opposite. In *step,* participants also underwent a series of five five-minute steady-state conditions with peak forces at 0 (PO), 18.7 (LOW), 37.5 (MED), 56.2 (HIGH), and 75.0% BW (MAX). Energy cost was measured by indirect calorimetry.

Percent change was calculated relative to the PO condition in each of *ramp-up*, *ramp-down*, and *step*, as illustrated in Fig. 1B. In *ramp-up* and *-down*, we fit change in metabolic cost to peak delivered force using linear regression, as shown in Fig. 1A. To compensate for metabolic delay, we averaged *ramp-up* and *ramp-down*. In *step*, we calculated two-minute steady-state averages of metabolic rate and peak force in each condition, then calculated a linear fit through these points. Linear fits for *ramp-up*, *ramp-down*, and *step* were evaluated at average force levels from each *step* condition, a metric here referred to as *equivalent* metabolic reduction (EMR). Because *measured* metabolic reductions in *ramp-up*, *ramp-down*, and *step* were not necessarily at the exact same force levels, this metric allowed comparison among the three. Moment arms were measured in *step* by motion capture.

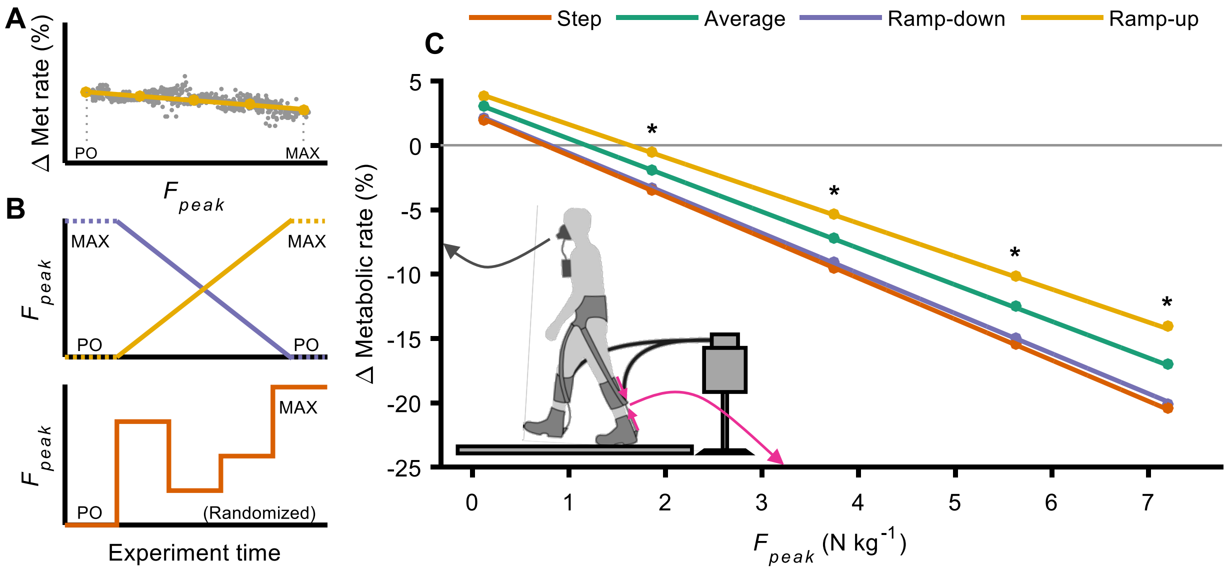

Figure 1. (A) Representative linear fit for one participant in *ramp-up* only. Small grey points are raw percent change in metabolic rate, and large yellow dots are EMR. (B) Schematic of experimental procedure. (C) Average linear fits for ramp-up, ramp-down, average, and step, along with equivalent metabolic reduction (EMR, represented by points) for all sweeps. The largest EMR for all sweeps occurred at the MAX force level and was -14.0% in ramp-up, -20.9% in ramp-down, -20.4% in step, and -17.1% in the average between ramp-up and ramp-down. Though it may be expected that the PO EMRs meet at 0% for all sweep versions, our method of using linear regression produces slightly positive values at PO force levels. Asterisks (*) indicate $p<0.011$ for ramp-up EMR smaller than ramp-down and step (repeated measures ANOVA with Tukey-HSD post-hoc correction). F_{peak} is the peak force (N kg^{-1}) in every stride.

Results and Discussion

Fig. 1C presents the average linear fits across all participants, as well as the group-average EMR at all conditions. Average peak ankle forces (and torques), increasing from LOW to MAX, were: 1.86 N kg^{-1} (0.181 N m kg^{-1}), 3.75 N kg^{-1} (0.357 N m kg^{-1}), 5.62 N kg^{-1} (0.540 N m kg^{-1}), and 7.20 N kg^{-1} (0.707 N m kg^{-1}). *Ramp-up* EMR was significantly smaller than *step* and *ramp-down* in all conditions ($p<0.011$) except PO, which may be attributable to a time delay between delivered assistance and measured metabolic rate during the continuous ramp. At any point during *ramp-down*, the current metabolic rate is due to a previous (slightly higher) delivered force level, inflating the metabolic reduction. The converse is true in *ramp-up*. If this delay alone influenced metabolic response, it could be expected that taking the average would yield results similar to *step* and different than both *ramp-down* and *ramp-up*. However, *step* EMRs are not significantly different from *ramp-down* EMRs (though they are significantly different than *ramp-up*), suggesting the influence of additional adaptation effects. Additional adjustments for delay outlined by Selinger and Donelan (2014) may be more effective at uncovering the relationship between force and metabolic rate at any given point in time. In *ramp-up*, *ramp-down*, and *step*, the largest EMR was in the MAX condition. Mechanical limitations required our MAX condition to peak at 75% BW, but it would be interesting to explore even higher forces that produce non-monotonic responses in metabolic reduction.

This preliminary study highlights that continuous parameter sweeps may help tuning procedures for wearable robots, providing the ability to explore more parameter settings over a shorter period of time.

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