

Optimizing Robotic Exoskeletons Actuation based on Human Neuromechanics Experiments: Interaction of Push-off Timing and Work

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1 Motivation

Different labs are building robotic exoskeletons for assisting walking [1]–[5] in able bodied or impaired subjects [6]. Until recently, such devices were controlled based on some hypothesis of how walking should be assisted in combination with reference data of kinetics of normal biological walking (e.g. [5]). These early exoskeletons could not reduce metabolic rate below normal walking. This indicates that normal walking data is not always a good basis for choosing exoskeleton actuation. This could be expected because normal walking is optimized through evolution [7] for the limitations of our biological locomotor system (e.g. skeletal muscle properties) whereas in exoskeleton assisted walking different limitations apply.

A new approach consists in optimization of the reduction in metabolic rate (or any criterion of choice) by systematically exploring the human response to changes in different parameters of the actuation pattern [1], [4], [8] (Figure 1).

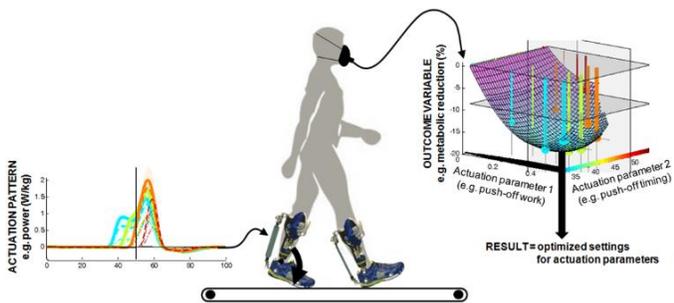


Figure 1: Optimization of exoskeleton actuation based on systematic exploration of the effect of actuation parameters on a chosen optimization criterion (e.g. metabolic rate).

2 State-of-the-art

A parameter sweep study with a unilateral exoskeleton [8] shows that increasing net work assistance leads to linearly increasing reductions in metabolic rate. It was unsure, however, how this result would be in bilateral exoskeletons [9].

Concerning push-off timing, simple walking models predict that ankle-push before leading leg contact reduces energy loss from collision dissipation [10]. In a previous study with our bilateral pneumatic exoskeleton we found that timing was optimal when push-off started just before leading leg contact [1]. However, push-off work was not maintained, which could have confounded the results [8]. Indeed, in a prosthesis study we kept push-off work constant, we found that timing was optimal when push-off started at or after leading leg contact [11], possibly because this causes less balance perturbation as was found in powered bipedal robots [12]. Again, it is unsure if the finding from the study with a unilateral prosthesis is relevant for bilateral exoskeleton walking.

The aim of the present experiment was to study isolated effects and potential interaction of push-off timing and positive work of a bilateral exoskeleton on the energetics and neuromechanics of walking.

3 Own approach

We tested 12 subjects during treadmill walking at $1.25 \text{ m}\cdot\text{s}^{-1}$ wearing bilateral ankle exoskeletons powered by pneumatic muscles [1].

Average positive power assistance was measured in real time and could be set to desired values, referred to here as Low, Medium and High Work by using the same iterative learning controller as in [11]. Push-off timing could be set to desired values, referred to here as Earliest, Early, Late and Latest Timing, based on footswitch control as in [1].

We tested 12 timing and work combinations (Figure 2). In one reference condition the subjects walked with the exoskeleton without work assistance (Zero-Work). In another reference condition the subjects walked without exoskeleton (Normal Walking). We analyzed metabolic rate, EMG, kinematics, total body center-of-mass power and swing leg joint kinetics. In this abstract we highlight the results of metabolic rate and EMG during certain phases of interest.

4 Results and Discussion

We found the highest reduction in metabolic rate ($-0.87 \text{ W}\cdot\text{kg}^{-1}$ versus Zero-Work) in the condition with Early timing and Medium work (Figure 2). In contrast to the earlier work sweep experiments with a unilateral prosthesis [13] and unilateral exoskeleton [8] metabolic rate did not show further decrease with further increases in work assistance.

In the peak EMG values of soleus and gastrocnemius the highest reductions were found in the High Work conditions (Figure 3A and B). The maximal reduction in soleus EMG was larger than in gastrocnemius EMG, possibly because the exoskeleton acts in parallel with the uni-articular soleus.

The highest reduction in vastus lateralis EMG during the collision phase occurred with Low Work and Early Timing (Figure 3C). Considering that part of the collision absorption [14] takes place at the knee joint this result seems in accordance with the prediction that pre-emptive push-off reduces collision [10].

The highest reduction in rectus femoris EMG occurred in the Latest Timing condition. This seems related to the hypothesis from Lipfert et al. [15] that push-off after leading leg contact powers leg swing initiation.

5 Conclusions

Arising from the interaction between the biological locomotor system of the participants and the mechanics of our robotic exoskeleton, we found optimal reduction in metabolic rate with Medium Work and Early Timing. From the EMG results it appears that maximum exoskeleton work is beneficial for the plantarflexor muscles that are assisted directly by the exoskeleton but detrimental to larger proximal muscles. This could explain part of why on average metabolic rate did not keep decreasing with higher exoskeleton work but reached a local minimum at Medium Work and Early Timing.

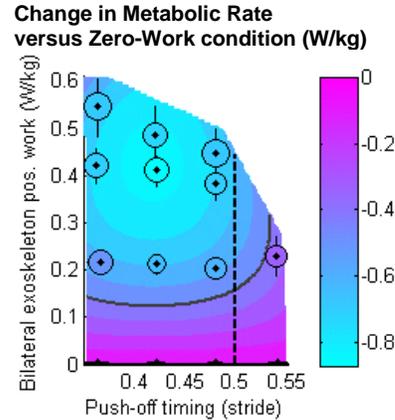


Figure 2: Change in metabolic rate versus Zero-Work condition (color scale) plotted versus push-off timing (horizontal axis) and total positive work of bilateral exoskeleton (vertical axis). Circles are actual conditions. Contour plot is interpolated surface. Grey line is intersection with metabolic rate of normal walking. Dashed line indicates timing of leading leg contact.

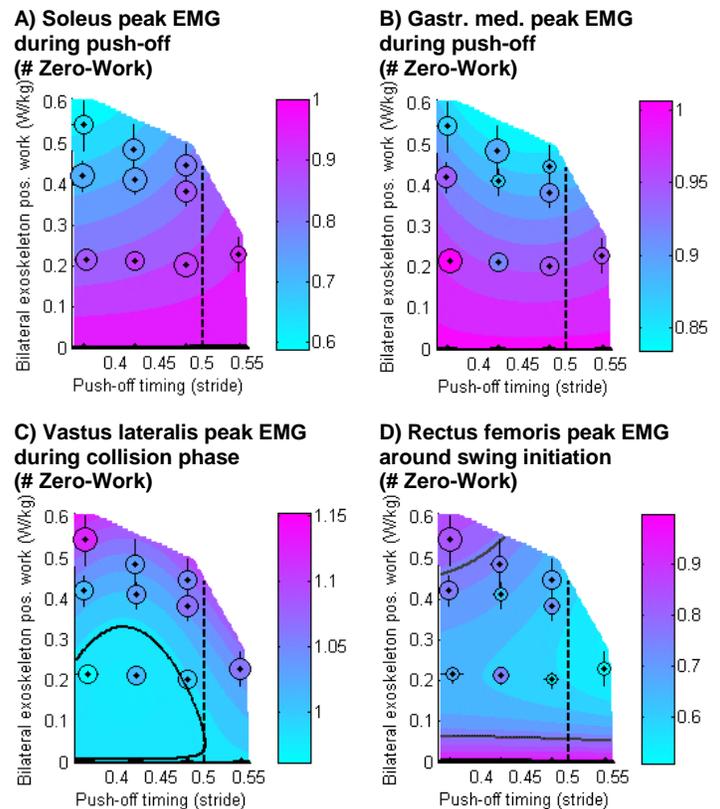


Figure 3: Peak EMG during phases of interest

A) soleus, B) gastrocnemius medialis, C) vastus lateralis, D) rectus femoris.

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