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ASSISTED PLANTARFLEXION INFLUENCES MUSCULAR ACTIVITY IN ALL LEG MUSCLES DURING UPHILL WALKING

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SUMMARY

Recent findings suggest that pneumatic ankle-foot exoskeletons have an optimal actuation onset when exoskeleton push-off initiates just before opposite leg heel strike. For a better understanding of the human-exoskeleton interaction, we wanted to study uphill walking with an ankle-foot exoskeleton and search for the optimal actuation timing.

Seven subjects walked on an inclined treadmill (15%) with an unpowered and a powered exoskeleton. When powered, the pneumatic muscles were actuated with 4 different actuation timings from early to late in the stance phase.

While the latest actuation timing was not metabolically optimal, no clear distinction could be made for earlier actuation timings. We found reductions in metabolic cost of 12.4, 13.2 and 13.0% compared to unpowered walking when actuation timing of the pneumatic muscles started at 20, 28 and 35% of stride. As the ankle-foot exoskeleton assists plantarflexion during push-off, we found a reduction in *m. soleus* activity during push-off and an increase in *m. tibialis anterior* activity during swing. Surprisingly, the biggest reductions in muscular activity were found in the *m. vastus lateralis* and *m. biceps femoris* in the period when the opposite leg was actuated. While the ankle-foot exoskeleton affects the ankle joint during push-off, there seems a mechanism that causes reduced thigh muscle activity in the opposite leg during initial stance and thereby contribute to a reduction in metabolic cost. Further data analysis will give more insight into this mechanism, which is a necessary step in the evolution towards ankle-foot exoskeletons in daily life.

INTRODUCTION

Robotic exoskeletons that assist human movement are suggested to be implemented in daily life in about 10 years [1]. Although this seems farfetched, sophisticated designs like the HAL exoskeleton suit or the Berkeley Bionics HULC exoskeleton [2] are auspicious. In addition, also simple exoskeletons that affect a single joint like pneumatic ankle-foot exoskeletons have promising outcomes.

Pneumatic ankle-foot exoskeletons with EMG based control algorithms can lower the metabolic cost of walking, with reported reductions of 10 to 15% [3-5] compared to unpowered walking. Although these ankle-foot exoskeletons with EMG based control algorithms were favored in previous studies [6], recently even larger reductions in metabolic cost were found using kinematic control. Malcolm *et al.* [7] showed that the metabolic cost of walking with a powered ankle-foot exoskeleton can be lower than that of walking with normal shoes if actuation onset of the pneumatic muscles initiates just before the opposite leg touches the ground and Galle *et al.* [8] showed that metabolic adaptation occurs within 18 min with this control algorithm. Because of the fast adaptation and the large reductions in metabolic cost, it was suggested that this actuation timing could be used for steering exoskeletons in the future [7].

Prior to an implementation of exoskeletons in daily life, it is necessary to study exoskeletons in a broader context. While more strenuous physical activities seems relevant for practical applications, *e.g.* for soldier or rescue workers, only one study investigated uphill walking with ankle-foot exoskeletons [5]. For a better understanding of the human-exoskeleton interaction we wanted to search for the optimal actuation timing during uphill walking with pneumatic ankle-foot exoskeletons.

METHODS

Seven female subjects (age=20.8±0.4y; weight =61.1±5.1kg; leg length=86.7±4.6cm) were equipped with bilateral powered ankle-foot exoskeletons with pneumatic muscles that assisted push-off [7,8]. Based on footswitch signals, a computer program (Labview, National Instruments) triggered onset and offset of the pneumatic muscles.

After a habituation period of 24 min on a level treadmill, subjects performed 5 randomized uphill walking conditions of 4 min each on a treadmill with an inclination of 15%. In the unpowered condition subjects walked with the exoskeleton without actuation of the pneumatic muscles. In the 4 powered conditions subjects walked with actuation of the pneumatic muscles with 4 different actuation timings from an actuation early in the stance phase to an actuation late in the stance phase. Onset was set at 20, 28, 35 and 42% of stride for respectively condition 1 to 4 and offset was set at toe-off (~65%). During the entire experiment O_2 consumption and CO_2 production were recorded (Oxycon Pro, Jaeger GMBH) to calculate net metabolic cost [9]. Lower limb kinematics were recorded with reflective markers and infrared camera's (Pro Reflex, Qualisys AB). Surface EMG was measured (Zerowire, Noraxon) for the *m. vastus lateralis*, the *m. biceps femoris*, the *m. tibialis anterior*, the *m. soleus* and the *m. gastrocnemius*. Raw EMG signals were band pass filtered (20-500Hz), rectified and RMS was used to create linear envelops.

RESULTS AND DISCUSSION

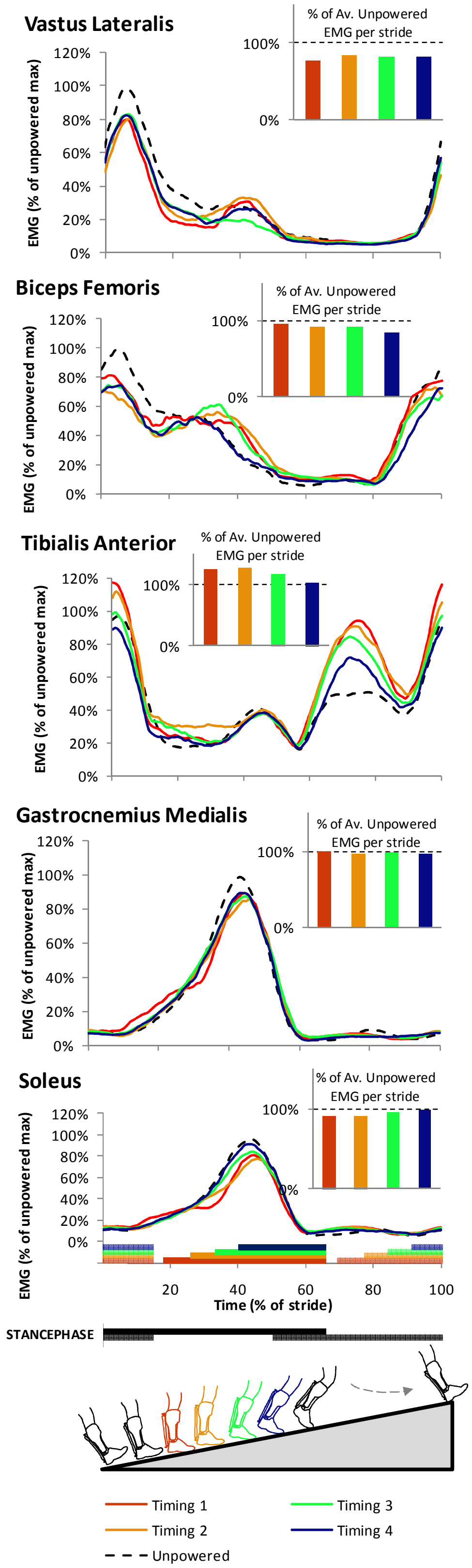

Figure 1: EMG RMS during an unpowered and 4 powered walking conditions. Horizontal colored bars represent actuation duration of 4 powered conditions (bold), and the actuation of the opposite leg (transparent). Linear envelops are normalized from heel contact to heel contact and expressed as a percentage of the max. value in the unpowered condition. Graphs with vertical bars are the averaged values of the linear envelops per stride, expressed as a percentage of the unpowered condition.

The metabolic cost (n=7) was significantly lower ($p \leq 0.05$) in all powered conditions, compared to the unpowered condition (11,0±0,9 Wkg^{-1}). While the latest actuation timing was not metabolically optimal for any subject, no clear distinction could be made for earlier actuation timings. We found a reduction in metabolic cost of 12.4±2.8%, 13.2±2.3% and 13.0±2.8% compared to unpowered uphill walking for the first 3 actuation timings.

EMG results (provisionary in 4 subjects) suggest that the powered exoskeleton, which assists plantarflexion during push-off, reduces *m. soleus* activity during push-off with a trend for a larger reduction the earlier the pneumatic muscles start (Figure 1). While there is a reduction in peak activity of the *gastrocnemius* muscles during push-off, stride averages do not seem to suggest reduced muscular activity. Earlier actuation timings have a negative effect on the *m. tibialis* activity during swing, in an attempt to restore normal joint angles at heel contact. The biggest reductions in muscular activity in the powered conditions are found in the *m. vastus lateralis* and the *m. biceps femoris*. These reductions are mainly found during the beginning of the stance phase, when the exoskeleton was not actuated in the assisted leg but in the opposite leg (Figure 1).

CONCLUSIONS

We found reductions in metabolic cost up to 13% for uphill walking with a powered exoskeleton compared to an unpowered exoskeleton with only small influence of actuation timing. The assistance of the powered exoskeleton during push-off caused an expected reduction in m. soleus activity and an increase in *m. tibialis anterior* activity. Surprisingly, the biggest reductions in muscular activity were found in the *m. vastus lateralis* and *m. biceps femoris* when the opposite leg was actuated. While the pneumatic ankle-foot exoskeleton affects the ankle joint, there seems a mechanism that causes reduced thigh muscle activity in the opposite leg during initial stance and thereby contribute to a reduction in metabolic cost. Further analysis of the kinematics will give more insight into the mechanism.

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