2D Parameter sweep of bilateral exoskeleton actuation: push off timing and work

Galle Samuel, Malcolm Philippe and De Clercq Dirk
Ghent University, Department of Movement and Sport Sciences, Ghent, Belgium
samuel.galle@ugent.be
philippe.malcolm@ugent.be, dirk.declercq@ugent.be

1 Introduction

Exoskeletons that assist human movement are constantly evolving and will play an important role in future military devices, healthcare- and daily life applications. While technological improvements are exponentially increasing, the challenge remains in the interaction between the human body and the exoskeleton device.

Simple powered ankle-foot exoskeletons that assist plantarflexion by means of pneumatic muscles are known to allow the user to adapt to the new walking pattern in less than 20 minutes [1] and result in reductions in net metabolic cost up to 17% compared to walking with an unpowered exoskeleton [2]. Malcolm et al. showed that actuation timing of the pneumatic muscles is a crucial element for a maximal reduction in metabolic cost and that optimal actuation timing of the exoskeleton is just before opposite leg heel contact.

While the study of Malcolm et al. [2] suggests general actuation timing guidelines for exoskeletons, there is no consensus on the optimal amount of additional ankle push-off work. It is unclear if subjects can still adapt to, and efficiently use more ankle push-off work. Therefore, we wanted to search for the optimal combination of actuation timing and push-off work during walking with a powered ankle-foot exoskeleton as this is a necessary step in the development of optimal exoskeleton devices and to gain more insight into human-exoskeleton interaction in general.

2 Methods

As a pilot study, we let 1 female subject (age 20y; length 1.7m, weight 60.1kg) walk with a powered ankle-foot exoskeleton [2] on a treadmill at 5 km·h^{-1}. The subject walked during 4 min. with 4 different actuation timings of the pneumatic muscles: onset was set at 31, 36, 41 and 46% of stride and actuation ending at 60% of stride. Actuation timing was controlled with a feed forward algorithm based on heelcontact detected by footswitches. Pneumatic muscles were inflated with air pressure, which was set at 2, 3 and 4 bar, resulting in varying pneumatic muscle tension force. This resulted in 12 powered conditions (4 actuation timings x 3 pneumatic muscle air pressures) from which 2 were excluded in the results section because of technical failure. Also an unpowered condition (with exoskeleton without pneumatic muscle actuation) and a standard shoe condition were done.

Metabolic power was measured during the entire protocol, averaged for the last 2 min of each condition and diminished with standing rest metabolic power to calculate net metabolic power based on the formulae of Brockway [3]. Δ Net metabolic power was the reduction in metabolic power compared to unpowered walking.

Ankle angle and moment arm of the right leg were recorded with infrared cameras and reflective markers, and a tension load cell allowed to measure pneumatic muscle force. We calculated exoskeleton torque by multiplying pneumatic muscle force with moment arm of the pneumatic muscle. Exoskeleton power was calculated by multiplying exoskeleton torque with ankle angular velocity and divided by body mass. Positive exoskeleton work rate was calculated by averaging the positive power per stride and multiplied by two in order to represent the assistance from both legs. This allowed to compare the added exoskeleton power with the resulting alterations in metabolic power during walking with the exoskeleton.

3 Results

Net metabolic power was reduced with up to 26% for the metabolically best condition (actuation timing 41% and air pressure 4bar) when compared with unpowered walking. When compared to walking with standard shoes there was still a reduction of 10% in net metabolic power for this optimal condition.

Exoskeleton power was effectively altered by actuation timing and pneumatic muscle air pressure. A later actuation timing of the pneumatic muscles resulted in a delayed onset of exoskeleton power and increased air pressure led to increased peak power (Fig. 1) and resulting increased positive exoskeleton work rate (Fig. 2).

When the reduction in net metabolic power was plotted against the positive exoskeleton work rate (Fig. 2) a linear relationship was found. For all actuation timings, more exoskeleton power resulted in bigger reductions in metabolic cost. Depending on actuation timing the slope of the linear regression varied between -2.09 (R^2=0.99) and -3.47 (R^2=0.98).

4 Discussion

Following this pilot study, we will collect data of 10 subjects that perform a similar protocol. Full body 3D kinematics, surface EMG, perception and metabolic cost will be measured. These data will be collected during February 2014 and will be presented at the Dynamic Walking conference 2014. The protocol will be similar to this pilot but exoskeleton power will be held constant across conditions, which allows to study the influence of actuation timing, exoskeleton work rate and the interaction between both. This complete data set will allow to get a better understanding of the driving mechanism behind the metabolically optimal condition.

Results in this one subject show that the amount of additional ankle push-off work is an important parameter for exoskeleton actuation.

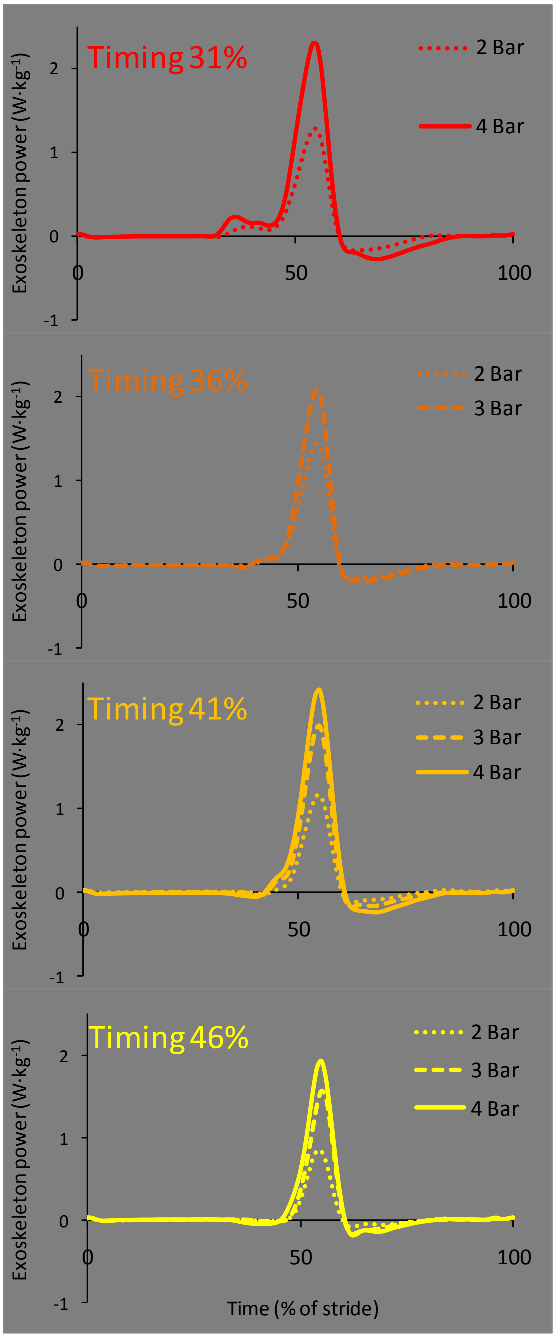

Figure 1: Exoskeleton power per stride for 4 actuation timings and different pneumatic muscles air pressures.

Our data suggest that increased ankle push-off power can result in bigger reductions in metabolic cost than used in most exoskeleton studies. This also shows the possibilities of the body to adapt to new walking configurations and to efficiently use additional ankle push-off power.
The linear coefficient for the optimal actuation timing (3.45) is close to the results of a prosthesis study by Caputo and Collins [5] who studied the influence of prosthesis work on metabolic rate. As our coefficient is also close to the estimated efficiency of human muscles [4], this suggests that humans use the additional push-off power at the ankle in a very efficient way and/or that the altered walking pattern, because of the additional push-off power at the ankle, is more efficient than the normal walking

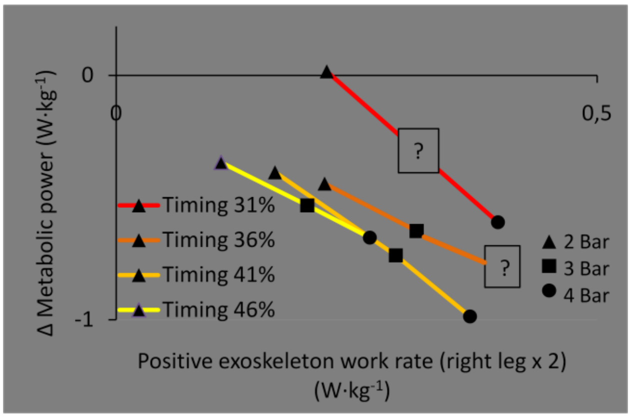

Figure 2: Reduction in net metabolic power compared to unpowered walking versus positive exoskeleton work rate. Question marks refer to missing data points.

pattern. More insight into this matter will be available after our complete data analysis.
Collins et al.[5] showed that net metabolic cost decreased during walking with an ankle-foot prosthesis testbed when net prosthesis power increased until 4 times the net work performed by the biological ankle. The exoskeleton positive work rate during our test was around half of normal ankle power [2] and is thereby much lower compared to the used ankle push-off work in this prosthesis study.
In our complete data analysis of 10 subjects, we will search for the maximal positive exoskeleton work rate that can be efficiently used by humans. This will result into specific guidelines for optimal exoskeleton actuation.

In conclusion, our pilot study shows that ankle push-off power is an important parameter for exoskeleton actuation. Increasing ankle push-off work during an optimal actuation timing results in bigger reductions in net metabolic cost compared to previous studies [2]. Additional data collection and data analysis will give more insight into ankle push-off work as an optimization parameter for powered ankle-foot exoskeletons.

References

[1] S. Galle, P. Malcolm, W. Derave, and D. De Clercq, "Adaptation to walking with an exoskeleton that assists ankle extension," Gait Posture, 2013.

[2] P. Malcolm, W. Derave, S. Galle, and D. De Clercq, "A simple exoskeleton that assists plantarflexion can reduce the metabolic cost of human walking," PLoS One, 2013.

[3] J. Brockway, "Derivation of formulas used to calculate energy-expenditure in man," Hum. Nutr. Clin. Nutr.,1987.

[4] G. Sawicki and D. Ferris, "Mechanics and energetics of level walking with powered ankle exoskeletons," J. Exp. Biol, 2008.

[5] J. Caputo and S. Collins, "Quantifying the relationship between prosthesis work and metabolic rate." [Conference abstract] Dynamic Walking Conference 2013