Effect of push-off timing on metabolic cost during walking with a universal ankle-foot prosthesis emulator

Philippe Malcolm*, Roberto E. Quesada**, Joshua M. Caputo**, Dirk De Clercq*, Steven H. Collins**
* Department of Movement and Sports Science, Ghent University, Belgium
philippe.malcolm@ugent.be
** Department of Mechanical Engineering, Carnegie Mellon University, Pittsburgh, PA, USA
stevecollins@cmu.edu, biomechatronics.cit.cmu.edu

1 Introduction

The ankle delivers about half of the total mechanical work during walking. Lower-limb amputees using conventional passive-elastic prostheses experience 20 to 30% higher metabolic cost than able-bodied individuals, perhaps because these prostheses do not provide net positive work during the course of a step [1]. To address this problem, companies are developing battery-powered prostheses (*e.g.,* [2]) that provide net positive push-off work.

Simulations of normal walking predict that trailing leg push-off just before collision of the leading leg reduces energy dissipation, thereby reducing overall mechanical work requirements [3]. This is consistent with reductions in metabolic cost observed in an experiment with powered bilateral ankle exoskeletons [4]. In this experiment, however, timing was varied together with push-off work, which also affects metabolic cost [5]. Subjects wearing an exoskeleton in parallel with their ankle could also independently affect total push-off timing and work.

Therefore, our goal was to study the isolated effects of varying the timing of total ankle push-off on the energetics and kinetics of human walking. We used a universal ankle-foot prosthesis emulator, which allowed precise control of push-off mechanics.

2 Methods

10 able-bodied subjects (60±6kg, 1.68±0.9m, 23±2yr, 6♀4♂) walked with the universal ankle-foot prosthesis emulator [5] mounted below a rigid boot on their right leg and a lift shoe on their left leg. This tethered prosthesis allowed high-bandwidth ankle-torque control.

In a reference condition, prosthesis torque was controlled as a function of ankle flexion angle in order to mimic the behavior of a conventional passive elastic prosthesis. In the experimental conditions, commanded torque was the sum of this angle-dependent torque and an additional time-dependent square wave, referred to here as Time-torque. The amplitude of this Time-torque was recursively adjusted via an iterative learning controller such that subjects would receive a consistent net positive work rate of 14W on average in each of the timing conditions. The Time-torque component was programmed to last 10% of the stride period and to start at a chosen delay after initial contact, with both based on a low-pass filter of stride period calculated from previous strides.

Subjects completed two habituation sessions (20 and 49 minutes of prosthesis walking) before the actual measurements. (In one subject who showed fast habituation, measurements were used from the second session due to prosthesis malfunction in the third session). For each subject, we applied 5 to 6 Time-torque onsets between 44 and 60% of the stride. Ranges were selected individually for each subject because limitations in prosthesis strength and stability prevented maintaining consistent work rate in some timing conditions for some subjects. Conditions were randomized.

We measured metabolic cost via indirect calorimetry (Jaeger) during 7-minute walking bouts. Trials were grouped in onset timing bins of 2.5% of the stride period, which were compared with repeated measures and Tukey’s honestly significant difference test.

3 Results

The effect of timing varied across subjects and some subjects did not show a clear trend (Figure 1). However, when conditions were binned (Figure 2), we found that in the last 3 bins (50.5 to 58% of stride) metabolic cost was significantly reduced versus the reference condition (~10±7% lower, $p < 0.02$). In the first bin, metabolic cost was on average 1±6% higher (not significant) than the reference condition. This was significantly higher than the last bin ($p = 0.03$) and showed a trend towards a higher metabolic cost than the middle bin ($p = 0.06$).

On average, metabolic rate was lower than the reference condition only when push-off started at or after opposite heel contact, as can be seen from the relative phasing of Time-torque and double stance (Figure 2).

4 Discussion

Our results confirm the main finding from simulations and experiments with wearable devices that the relative timing of trailing leg push-off and leading leg contact is important. In the timing bins where push-off started at or after leading leg heel contact, there was a ~10% reduction in metabolic rate on average, whereas in the earliest timing bin added push-off work had no effect.

Simple models of walking predict that push-off just before leading leg contact will minimize mechanical work requirements [3]. Compared to such models, we found optimal push-off to occur later in the stride. Simple models inevitably involve simplifications such as impulsive push-off, rigid mass-less legs and the absence of double stance which could partially explain this discrepancy.

The onset of positive ankle power during normal walking has typically been reported to occur prior to opposite-limb heel strike [6], while experiments with exoskeletons powered via pneumatic artificial muscles have found the optimal timing of pneumatic pressure onset to be about 30% [7] to 45% [4] of stride. The later optimum observed in the present study might be due to changes in gait symmetry with unilateral prostheses. For example, heel strike and toe off in normal walking typically occur at 50% and 60% of stride, respectively, whereas here opposite-limb heel strike occurred at 52% and prosthesis toe off ranged from ~59% to 64% of stride, with later toe off in later Time-torque conditions. The observed optimum is consistent with the anecdote from one user in another robotic prosthesis study that ‘the best timing for adding power was when the heel of the adjacent foot had initial contact’ [8]. Alternatively, added mass from the simulator boot and prosthesis could increase the importance of leg swing initiation by means of a late push-off [9]. The increased leg length caused by the lift shoe might also reduce energy dissipation at leading leg collision [10]. Such factors would not, however, explain the lack of benefit from pre-emptive push-off through work provided beginning at around 46% of stride.

5 Conclusions

Prosthesis push-off timing, isolated from push-off work, had a strong effect on metabolic cost, with optimal push-off occurring at or after opposite leg heel contact. This result roughly concurs with findings from simulations, exoskeleton experiments, and normal walking, although the optimal timing was slightly later. It is possible that a different result would be found if the prosthesis were worn by amputees, as they would not have the additional weight and leg length and are more acclimated to walking with prostheses [11]. These results confirm that the prosthesis emulator used here allows experimental tests of the influence of push-off parameters on metabolic cost. In the future a similar experimental approach could be used to optimize the assistance that amputees can get from a constrained amount of battery energy.

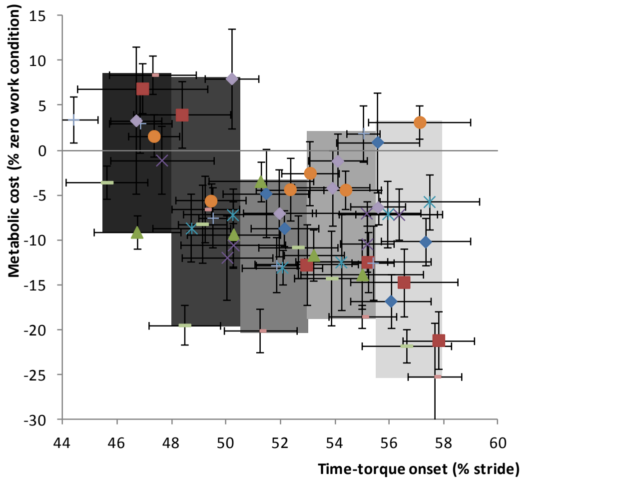

Figure 1: Metabolic cost vs. Time-torque onset. Different colored symbols = subjects, T-bars = standard deviation. Shaded areas = 2.5% Time-torque onset bins.

6 Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. CMMI-1300804. P. Malcolm received a travel grant from Ghent University to collect data at Carnegie Mellon University.

7 References

[1] G. Colborne et al., “Analysis of Mechanical and Metabolic Factors in the Gait of Congenital Below Knee Amputees,” Amer J Phys Med Rehabil, 1992.
[2] A. Ferris and J Aldridge, “Evaluation of a Powered Ankle-foot Prosthetic System during Walking,” Arch Phys Med Rehabil, 2012.
[3] A. Kuo, “Energetics of Actively Powered Locomtion using the Simplest Walking Model,” J Biomech Eng, 2002.
[4] P. Malcolm et al, “A Simple Exoskeleton that Assists Plantarflexion Can Reduce the Metabolic Cost of Human Walking,” PLoS One, 2013.
[5] J. Caputo and S. Collins, “Quantifying the Relationship Between Prosthesis Work and Metabolic Rate,” Dynamic Walking, 2013.
[6] M. Schwartz, et al. “The effect of walking speed on the gait of typically developing children,” J Biomech, 2008.
[7] M. Wehner et al, “A lightweight soft exosuit for gait assistance,” ICRA, 2013.
[8] S. Au et al. “An Ankle-Foot Emulation System for the Study of Human Walking Biomechanics,” ICRA, 2006.
[9] S. Lipfert et al., “Impulsive Ankle Push-Off powers Leg Swing in Human Walking,” J Exp Biol, 2013.
[10] P. Adamczyk, S. Collins, A. Kuo, “The Advantages of a Rolling Foot in Human Walking,” J Exp Biol, 2006.
[11] K. Zelik, S. Collins, et al., “Systematic Variation of Prosthetic Foot Spring Affects Center-of-Mass Mechanics and Metabolic Cost During Walking,” IEEE Trans Neural Syst Rehabil Eng, 2011.

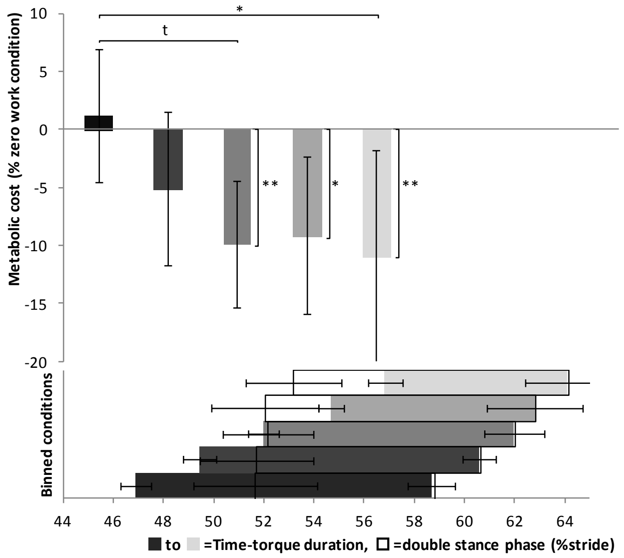

Figure 2: a) Metabolic cost vs. Time-torque condition bins with corresponding grayscale. ** =p <0.01, * = p<0.05, t = p<0.10). **b)** Time-torque duration (shaded bars) and double stance (non-filled rectangles).