Analysis of walking with unilateral exoskeleton assistance compared to bilateral assistance with matched work.

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1 Introduction

For exoskeletons intended for partial gait assistance, unilateral plantarflexion assistance in patients with hemiparesis (e.g. stroke) is an important potential application (e.g. [1,2]). The underlying rationale is that unilateral assistance to the paretic limb could reduce propulsion asymmetry and thus reduce the metabolic cost of walking.
Most of the studies with ankle exoskeletons used bilateral exoskeletons, whereas only a limited number of studies used unilateral exoskeletons (e.g. [1,3,4]). It is unknown to what extent the findings from studies with bilateral exoskeletons apply to unilateral exoskeletons.

A study with unilateral ankle fixation shows increased metabolic cost due to work redistribution from the ankle towards the less efficient hip [5]. From the simplest model one could predict higher collision dissipation for each one out of two steps without augmented ankle push-off [6]. It is uncertain, however, to what extent results from simple models or perturbation experiments [7] can be extrapolated towards unilateral push-off assistance experiments. A recent parameter-sweep study with unilateral exoskeleton assistance did find reductions in metabolic cost and biomechanical parameters versus zero-walk assistance [4] but no direct comparisons versus bilateral assistance was done as this was not part of that study.

The aim of the present study is to compare unilateral versus bilateral exoskeleton assistance.
First, we hypothesize that asymmetric (i.e. unilateral) push-off assistance leads to lower metabolic reduction than bilateral assistance with the same amount of work assistance.
Second, we hypothesize that unilateral assistance will cause asymmetry that will lead to compensation(?) effects in the unassisted leg compared to zero work assistance.
Third, we will analyze if there are differences in adaptation in the assisted limb during unilateral versus bilateral assistance.

Methods

We tested 12 healthy subjects during treadmill walking with a tethered pneumatic ankle exoskeleton [8].
The delivered positive work was monitored via force and displacement sensors on the exoskeletons. We were able to set positive work assistance to fixed desired values via an iterative learning controller as in [9].

In the 'Unilateral' conditions the subjects wore both exoskeletons but only one leg was assisted (this was done for the left and right leg alternatively).
In the 'Bilateral Matched Total Work' condition, half of the total work from the Unilateral condition was applied to both legs such that the total positive work assistance was equal to the Unilateral condition.
In a second bilateral condition, the 'Bilateral Matched Leg Work' condition, the same work per leg as in the assisted leg of the Unilateral condition was provided to both legs such that the total work assistance was double of the Unilateral condition (Figure 1A).
In the 'Zero-Work' condition subjects walked wearing the exoskeleton with the assistance turned off.

Paired t-tests were done for specific comparisons of interest:
The total effect of the Unilateral conditions versus Bilateral Matched Total work
The unassisted leg in Unilateral versus the same leg in Zero-Work.
The assisted leg in Unilateral versus the same leg in Bilateral Matched Leg Work.
We analyzed metabolic rate, EMG, kinematics, total body center-of-mass power and swing leg joint kinetics. In this abstract we highlight metabolic rate and one EMG result.

3 Results and Discussion

The reduction in metabolic rate in the Unilateral conditions trended to be smaller than in the Bilateral Matched Total Work condition and was about half of the Bilateral Matched Leg Work condition (Figure 1B).
When the reductions in metabolic rate are normalized versus total positive work assistance, the Bilateral Matched Total Work condition had the best metabolic rate versus mechanical work ratio approaching minus 4 J metabolic rate per J positive exoskeleton work. The other three conditions all had the same ratio of about 2.

Analysis of EMG indicates that Unilateral conditions cause reductions in the assisted leg as well as in the unassisted leg (Figure 2A). Reductions in EMG in the unassisted leg could be caused by collision and/or rebound reduction from the contralateral assisted leg during the step-to-step transition (Figure 2B). These could also be caused by assistance in the ipsilateral leg during the previous step leading to reduced required propulsion in the next step. Or they could be caused by a tradeoff with another joint in the unassisted leg where the subject actively tries to match the assisted leg push-off.

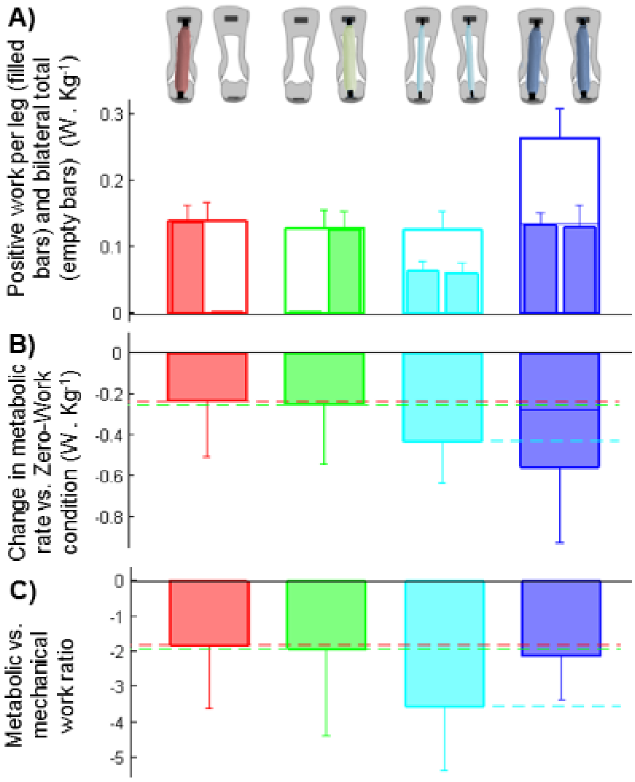

Figure 1: A) Positive work per leg and bilateral sum in the different exoskeleton conditions. **B)** Change in metabolic rate. **C)** Metabolic rate vs. mechanical work ratio.

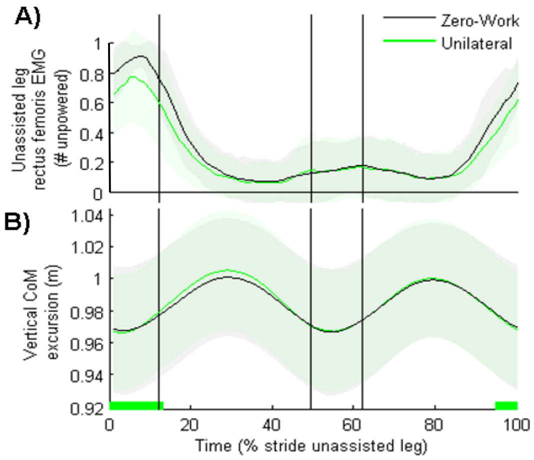

Figure 2: A) Unassisted leg rectus femoris EMG.
B) CoM excursion. Horizontal green bar represents actuation period in contralateral leg.

4 Conclusion

The finding of the highest negative metabolic rate versus mechanical work ratio in the Bilateral Matched Total Work condition means that if a constrained amount of mechanical work is available (e.g. from a battery) it is more advantageous to distribute this work evenly over both legs.
The EMG reductions in the unassisted leg also suggest that if the goal is to maximize assistance to one (impaired) leg it might still be advantageous to use a bilateral exoskeleton, perhaps with a different actuation pattern for each leg that is specifically optimized such that each exoskeleton side assists specific phases in the impaired leg.

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6 References

[1] K. Z. Takahashi, M. D. Lewek, and G. S. Sawicki, “A neuromechanics-based powered ankle exoskeleton to assist walking post-stroke: a feasibility study,” *J. Neuroeng. Rehabil.*, vol. 12, no. 1, p. 23, Feb. 2015.

[2] S. De Rossi, J. Bae, K. O’Donnel, K. Hendron, K. Holt, T. Ellis, and C. Walsh, “Gait improvements in stroke patients with a soft exosuit,” in *GCMAS*, 2015.

[3] R. Jackson and S. Collins, “Targeting specific muscles for rehabilitation with an EMG-controlled ankle-foot orthosis,” in *Dynamic Walking*, 2012.

[4] R. W. Jackson and S. H. Collins, “The Relative Benefits of Work Assistance and Torque Assistance in Ankle Exoskeletons.,” in *7th World Congress of Biomechanics*, 2014.

[5] C. Wutzke, G. Sawicki, and M. Lewek, “The influence of a unilateral fixed ankle on metabolic and mechanical demands during walking in unimpaired young adults,” *J Biomech*, vol. 45, no. 14, pp. 2405–2410, Sep. 2012.

[6] A. D. Kuo, “Energetics of actively powered locomotion using the simplest walking model,” *J Biomech Eng*, vol. 124, pp. 113–120, 2002.

[7] P. Malcolm, P. Fiers, V. Segers, I. Van Caekenberghe, M. Lenoir, and D. De Clercq, “Experimental study on the role of the ankle push off in the walk-to-run transition by means of a powered ankle-foot-exoskeleton,” *Gait Posture*, vol. 30, no. 3, pp. 322–327, 2009.

[8] 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*, vol. 8, no. 2, p. e56137, 2013.

[9] P. Malcolm, R. E. Quesada, J. M. Caputo, and S. H. Collins, “The influence of push-off timing in a robotic ankle-foot prosthesis on the energetics and mechanics of walking,” *J Neuroeng Rehabil*, vol. 12, no. 21, 2015.