The metabolic cost of changing speeds is significant and may affect preferred walking speeds

Nidhi Seethapathi and Manoj Srinivasan
Mechanical and Aerospace Engineering, The Ohio State University, Columbus, OH, USA
seethapathi.1@osu.edu and *srinivasan.88@osu.edu*

1 Introduction

In daily life, people seldom walk at exactly constant speeds. Most walking over a day is performed in short bouts [1]. Thus, it is of interest to measure the cost of changing speed. Minetti and co-workers [3] measured the cost of changing speeds but with non-inertial treadmill speed changes or step-frequency control. Here, we measure the metabolic cost of changing speeds to better quantify the relative contribution of changing-speed versus constant-speed walking costs. Human preferring walking speeds are found to be close to energetically optimal speeds [4]. The cost of changing speeds may cause a change in preferred walking behavior, in some situations. We test this by measuring the walking speed for a range of short-distance bouts, for which acceleration-deceleration constitutes a significant fraction of the total bout.

2 Methods

Experiment 1: Metabolic cost of oscillating speed walking. Subjects ($N = 16$) performed both "constant-speed" and "oscillating-speed" walking trials. Oscillating walking speeds were achieved on a constant-speed treadmill by having the subjects alternate between walking faster and slower than the belt indicated by two audible tones alternated on a loop, of three combinations of durations $T_{\rm fwd}$ and $T_{\rm bck}$. A portable system (Oxycon Mobile) measured respiratory oxygen and carbon dioxide flux during resting and walking to later approximate metabolic rate per unit mass$\dot{E}$ (W/kg). Hip motion during walking was measured with a marker-based motion capture system (Vicon).

Experiment 2: Preferred walking speed for short distances. Subjects ($N = 10$) were asked to walk a specified at a comfortable walking speed, starting and ending at rest without overshooting; distances used were 2, 4, 6, 8, 10, 12, 14 and 89 m, each three times, in random order. Camera-based videos of the trials were recorded to later analyze the average walking speed over the whole distance and the steady-state speed defined as the average speed for the middle one meter portion of the walking distance.

Simple Model based on kinetic energy. In this model, the metabolic cost increase for oscillating-speed walking over steady walking is attributed to positive and negative leg work needed to accomplish the forward kinetic energy fluctuations of the body, over and above what naturally happens within a step in steady walking (that is, after smoothing out the within-step speed fluctuations). Positive and negative work are assumed to have different positive costs, with proportionality constants of $\eta_{\rm pos}^{-1} = 4$ and $\eta_{\rm neg}^{-1} = 0.83$ respectively.

Model-predictions of speed-dependent optimal walking speeds. The slope of a linear regression $m_{\rm ke}$ of the above kinetic energy model to the the data was used to predict the measured preferred speed for short walking distances. Firstly, the total cost $\dot{E}_{\rm bout}$ for a short walking bout of distance d was defined as the cost of instantaneously increasing walking speed from zero to some constant speed v, walking at that speed for the whole distance and then instantaneously decreasing the walking speed to zero. The optimal speed $v_{\rm opt}$ that minimizes $\dot{E}_{\rm bout}(d, v)$ for a given distance was given by $d = m_{\rm ke} {v_{\rm opt}}^3 \left(\eta_{\rm neg}^{-1} + \eta_{\rm pos}^{-1}\right)/(a - b v_{\rm opt}^2)$ where a and b are obtained from the parabolic regression between metabolic energy and constant walking speed given in [2].

3 Results

The metabolic rate of walking for any of our six oscillating-speed trials was significantly higher than the corresponding steady state cost, using a significance level $p = 0.05$. A scatter-plot with data from 78 oscillating speed trials, shown in Figure 5A relates the values predicted by the kinetic energy fluctuation model to the experimentally measured change in metabolic energy. A linear fit between the model and the experimental data was found to be $\Delta \dot{E}_e = 0.67\,\Delta \dot{E}_m - 0.04$, with $R^2 = 0.24$ and 95% confidence interval for the slope = 0.39 to 0.94.

The cost of changing speeds obtained from the above regression was applied to daily ambulatory data collected by [1] to show that changing speeds contributes to upto 9% of daily walking metabolic cost.

Figure 5B shows that the bout-based model, described in the methods section, correctly predicts the experimentally-observed trend in the preferred speed of walking as it varies with distance. In particular, the preferred speed for short distances is significantly lower than and asymptotically approaches the preferred speed for long distances.

4 Discussion

While it may superficially be thought that the cost of changing speeds may be too small during walking, we have found that it may be a big part of daily life. Similarly, while it may superficially be thought it may to too small to have a behavioral effect, we have shown that it has a significant effect on optimal walking speeds as a function of distance, reflected in our measurements of preferred walking speeds.

Finally, the cost of changing speeds was found to be statistically significantly different from zero here, contrary to what was found by Minetti and co-workers. Perhaps this is due to methodological differences.

5 5. Acknowledgments

This work was supported by National Science Foundation grant 1254842.

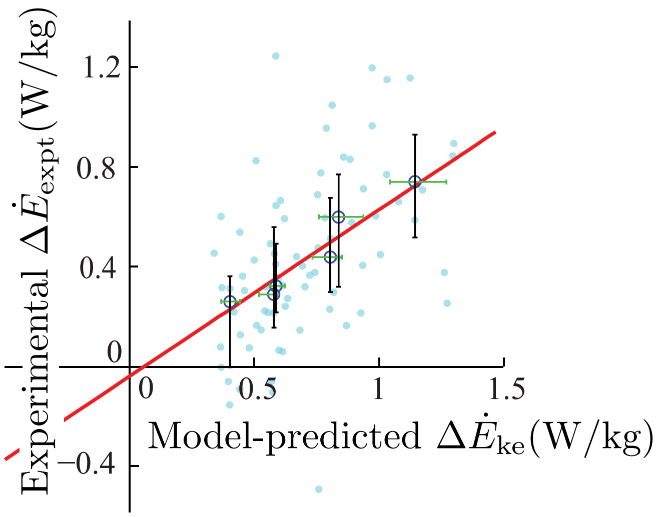

Figure 1: The model based on change in kinetic energy correlates with the increase in metabolic energy for walking at changing speeds. The slope of the regression line is about 0.67.

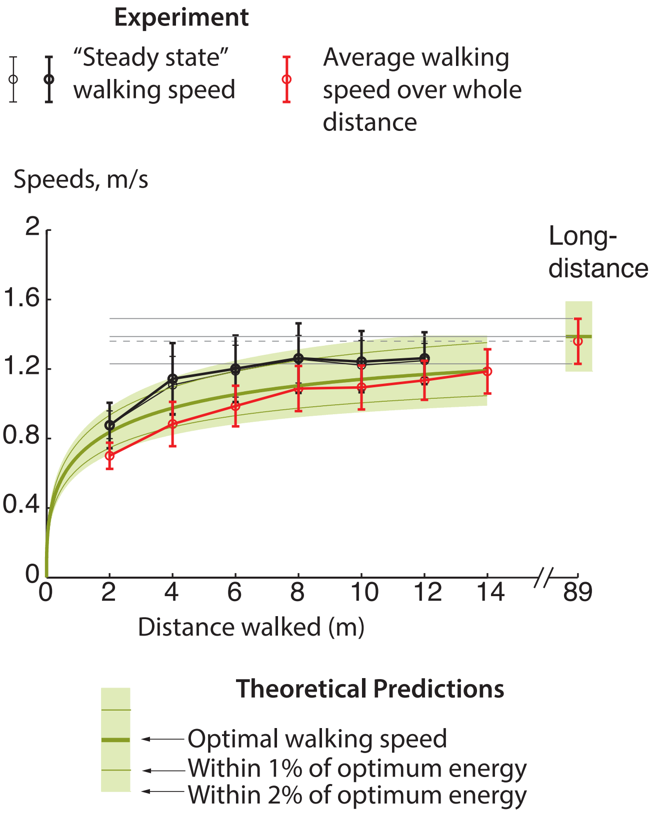

Figure 2: The prediction for preferred walking speed v/s distance walked agrees with the experimentally observed values.

References

[1] M. S. Orendurff, J. A. Schoen, G. C. Bernatz, A. D. Segal, and G. K. Klute. How humans walk: bout duration, steps per bout, and rest duration. *J. Rehabil. Res. Dev.*, 45(7), 2008.

[2] A. C. Bobbert. Energy expenditure in level and grade walking. *J. Appl. Physiol.*, 15(6):1015–1021, 1960.

[3] A. E. Minetti, L. P. Ardigò, E. M. Capodaglio, and F. Saibene. Energetics and mechanics of human walking at oscillating speeds. *Amer. Zool.*, 41(2):205–210, 2001.

[4] M. Srinivasan. Optimal speeds for walking and running, and walking on a moving walkway. *CHAOS*, 19:026112, 2009.