Continuous Energy Optimization Controls Preferred Step Width in Human Walking

Sabrina J. Abram[1], Jessica C. Selinger[2], and J. Maxwell Donelan[1,2]
[1]School of Engineering Science, Simon Fraser University, Burnaby, BC, Canada
[2]Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, BC, Canada
sabram@sfu.ca

Introduction

When we walk, we usually have the freedom to choose how narrow or wide we step while still getting to where we want to go. Despite this freedom, people tend to prefer a particular step width, and execute this preference with remarkably small variability [1]. In arriving at this preference, the nervous system may have to solve an objective function with multiple terms such as energy, stability, and maneuverability. As one example of an objective function, the nervous system may seek to simultaneously minimize energy expenditure, maximize stability and maximize maneuverability. Furthermore, these terms may have different weightings, may depend on walking context, or may be treated as constraints rather than objectives.

The purpose of our study was to understand how the nervous systems of able-bodied people weigh objectives when selecting the preferred step width. For example, if the nervous system weighs optimizing energy higher than other objectives, or perhaps treats them as constraints, we would expect that when the relationship between step width and energetic cost is changed, the nervous system would adapt to the new energy optimal step width. Our lab has recently demonstrated that people continuously optimize step frequency to minimize energy expenditure [2]. Here we hypothesize that preferred step width is also primarily determined through real-time energy optimization.

Methods

To test this hypothesis, we built a custom device that uses closed-loop control to apply energetic penalties as a function of step width to shift the energy optimal step width wider than that initially preferred (Figure 1a, 1b, and 2). We define the new relationship between energetic cost and step width as the 'new cost landscape'. Our custom device combines a constant energetic reward, achieved by applying a forward horizontal force to a hip-belt worn by the user, with a controllable energetic penalty, achieved by manipulating treadmill incline (Figure 1a).

We first established each subject's preferred step width and step width variability, and then designed a control function (Figure 2, red dashed) to shift the energy optimal step width 3 standard deviations away from that initially preferred. We define control function as the relationship between added energetic penalty and step width. We calculated preferred step width as the average step width during the final 3 minutes of a 12 minute walking period. We calculated each subject's step width variability as the standard deviation during the same averaging window. Subjects had an average preferred step width of 15±4cm (mean±SD) and step width variability of 1.5±0.2cm (mean±SD). We represent shifts in step width relative to each subject's originally preferred step width as multiples of their natural variability in step width, measured in number of standard deviations. This is a useful means of creating a new energy optimal step width that is distinct from that which subjects initially preferred, and allows us to distinguish between a shift in the preferred step width and that occurring by random chance.

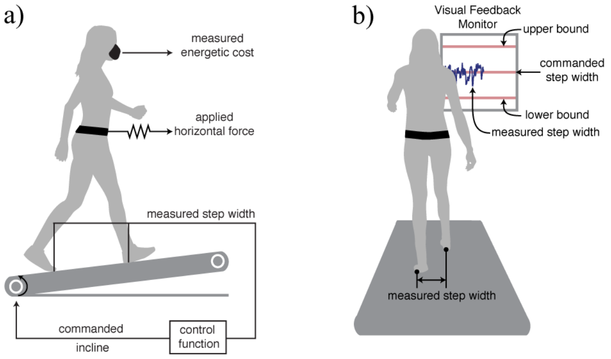

Figure 1: a) Our real-time controller uses forces and moments measured by the treadmill to trigger foot contact events, calculate step width, and then command the appropriate treadmill incline based on the desired energetic penalty for the measured step width. Load-cells mounted on a hip-belt (LCM201, Omega Engineering) are used to measure the actual forward force applied. b) Our real-time visual feedback system allows us to enforce specific step widths by instructing subjects to keep their measured step width signal within a particular bound.

We then turned the controller on and tested for adaptations toward the new energy optimal step width. First, we measured whether subjects would adapt their preferred width towards the energy optimal width spontaneously, calculated as the average step width during the final 3 minutes of the 6 minute pre-exploration period (Figure 3a and 3b, pre-exploration). Second, we measured whether subjects would adapt their preferred width to the cost optimal width when provided experience with higher (narrower widths) and lower (wider widths) costs (Figure 3a and 3b, post-exploration). Step widths were successfully enforced using real-time visual feedback—subjects matched the commanded width with an average error of 0.8±0.3cm (mean±SD). We guided subjects through 8 perturbations. Each perturbation was followed by a release, allowing subjects to self-select their step width. The perturbations and releases lasted 5 minutes each. We calculated the change in preferred step width after each perturbation as the average step width during the final 3 minutes of the subsequent release (Figure 3b). We calculated each subject's final preferred step width as the average step width during the 3 minute post-exploration period (Figure 3a and 3b, post-exploration).

We mapped each subject's new cost landscape to verify that we had indeed shifted the energy optimal step width to a width wider than that initially preferred. We measured energetic cost using respiratory gas analysis equipment (Viasys). We determined the energetic cost at specific points in the new cost landscape by instructing subjects to walk at each step width for 5 minutes—achieved by commanding step widths using visual feedback—and averaging over the final 3 minutes.

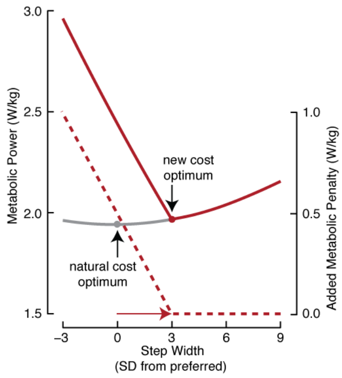

Figure 2: We used simulations to predict our new cost landscape by combining literature values for energetic costs of walking at different step widths, at different inclines, and with a forward horizontal force [1, 3-4]. We add the energetic cost of the control function (dashed red) to the natural cost landscape (gray) to produce the new cost landscape (red).

Results

Subjects adapted their preferred step width wider than that initially preferred after experience with the new cost landscape. We tested 8 able-bodied young adults, and found that, at the end of the experiment, subjects had shifted their preferred step width by 3.5 standard deviations ± 0.8 standard deviations ($p<0.05$; mean±SD) (Figure 3b, post-exploration). We first see a significant shift in preferred step width after a perturbation to a lower cost ($p<0.05$) (Figure 3b, release 2). Following this, with each perturbation, subjects gradually adapted their step width closer to the energy optimum (Figure 3b, releases 3-7). Self-selected steps between perturbations showed that subjects settled within 95% of their final preferred step width, on average, after 2227 self-selected steps. After these steps, perturbations to higher or lower costs did not influence the magnitude of adaptation (Figure 3b).

We found that the preferred step width in a new cost landscape is determined by continuous energy optimization. The energetic cost measured in the new cost landscape at step widths both narrow and wide relative to the cost at final preferred step width suggested that subjects converged on the energetic minimum (Figure 3c). The final preferred step width reduced energetic cost, on average, by 14.2±6.1% (mean±SD) relative to the cost at the initial preferred step width in the new cost landscape.

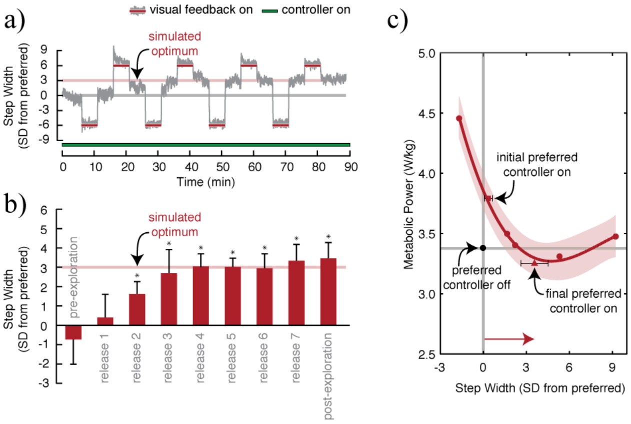

Figure 3: Averaged across all subjects: a) Experimental protocol with perturbations to discrete step widths in the new cost landscape. b) Average step width at each release. Error bars represent 1 SD. Asterisks indicate statistically significant differences in step width when compared to initial preferred step width. c) New cost landscape. The curve is a second-order polynomial fit, and the shading shows the 95% confidence interval.

Conclusions

The nervous systems of able-bodied people highly weight energetic cost and continuously optimize it to determine preferred step width. Our lab has recently demonstrated continuous energy optimization for step frequency [2]. However, this is one out of many possible gait parameters that the nervous system has to select for walking. Here, we demonstrated that continuous energy optimization also controls preferred step width. Furthermore, these two findings use two different methods of applying energetic penalties and study two different gait parameters. This suggests that continuous energy optimization is a dominant and general objective in able-bodied gait.

References

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