The high cost of swing leg circumduction during human walking

Authors:

K. Alex Shorter^a (Corresponding Author)

Email: kshorter@umich.edu

Amy Wu^a

Email: amyrwu@umich.edu

Arthur D. Kuo^{a,b}

Email: artkuo@umich.edu

Affiliations:

^aDepartment of Mechanical Engineering
University of Michigan
G.G. Brown Laboratory
2350 Hayward
Ann Arbor, MI 48109
USA

^bFaculty of Kinesiology
University of Calgary
Calgary, AB T2N 1N4 CANADA

Acknowledgments:

The authors would like to thank Genevieve Flaspohler, Meghna Menon and Sara Rusignuolo for their help with the work. This work was supported in part by the Office of Naval Research (ETOWL program), National Institutes of Health (AG030815), and Department of Defense (W81XWH-09-2-0142, National Defense Science & Engineering Graduate Fellowship Program).

ABSTRACT

Humans tend to walk economically, with preferred step width and length corresponding to an energetic optimum. In the case of step width, it is costlier to walk with either wider or narrower steps than normally preferred. Wider steps require more mechanical work to redirect the body's motion laterally with each step, but the cost for narrower steps remains unexplained. Here we show that narrow steps are costly because they require the swing leg to be circumducted around the stance leg. Healthy adults (N=8) were tested walking with varying levels of circumduction, induced through lightweight, physical obstructions ("Fins") attached medially to the lower legs, during treadmill walking at fixed speed ($1.25 \text{ m}\cdot\text{s}^{-1}$) and step width. The net rate of metabolic energy expenditure increased approximately with the square of circumduction amplitude, by about 50% for an amplitude (measured at mid-swing) of about 18 cm. Subjects also generated greater stance leg torque and more arm motion to counter the circumduction, among other compensatory motions that may contribute to energy expenditure. The costs of producing and countering lateral leg motion partially explains the poorer economy of some gait pathologies where circumduction may occur, for example stiff-knee gait. And for healthy individuals, it explains how the energetically optimal average step width, along with the additional variability inherent with multiple steps, should be narrow enough to avoid excessive redirection of the body, yet wide enough to avoid costly circumduction. Humans appear to prefer a step width that compromises between the competing energetic costs for either wider or narrower steps.

Key Words: Biomechanics, Gait, Circumduction, Energetics, Locomotion

1 INTRODUCTION

2 The swing foot's motion during walking follows a fairly straight path when viewed from above.
3 Mirroring paths of the opposing feet seem to be separated by just enough distance to allow
4 movement past each other without colliding. A narrower step width would require lateral
5 circumduction of the swing leg to avoid the stance foot. However, such circumduction might
6 require additional effort, as any healthy person can experience with a few minutes' practice. Gait
7 pathologies such as foot drop or stiff-knee gait often lead to circumduction and other
8 compensations that gain better swing leg ground clearance, but at considerably greater energy
9 expenditure (Waters and Mulroy, 1999). Part of the added cost is likely attributable to
10 circumduction itself, in amount both unknown and difficult to isolate from other contributions.
11 Even for the healthy, it remains unproven whether the normal swing foot path is chosen to avoid
12 circumduction. Quantification of the energetic cost of circumduction might lend insight
13 regarding the swing leg motion in both healthy and pathological gait.

14 Normal step width may be determined by two opposing trade-offs: a cost for wider steps and a
15 cost for circumduction (Donelan et al., 2001). Wider steps entail more side-to-side motion of the
16 body center of mass (COM). Simple models show that redirecting motion requires mechanical
17 work—termed step-to-step transition work—increasing with the square of step width (Kuo,
18 1999), as supported by experimental data for both work and a proportional metabolic cost
19 (Donelan et al., 2001). But step-to-step transition costs are minimized at zero step width, whereas
20 the observed minimum for humans is at the preferred width of about 14 cm (midline-to-midline
21 of the feet), just wide enough for the feet to pass each other without circumduction. This suggests
22 an additional cost for narrower steps, explained not by step-to-step transitions, but perhaps by the
23 need to circumduct the swing leg around the stance leg.

24 There are several reasons why swing leg circumduction might be costly. There may be a cost
25 directly attributable to muscular effort needed to deviate the leg laterally during swing. The
26 passive dynamics of the thigh and shank act like coupled pendulums (Dean and Kuo, 2009;
27 McGeer, 1990; Mochon and McMahon, 1980), with natural motion that is largely planar.
28 Muscular force and work would presumably be needed to deviate from the sagittal plane. But
29 there may also be other, more indirect costs. To produce circumduction, the body must also
30 create opposing reaction forces, which must be transmitted either to the ground or to opposing

1 motions of other limbs. This is similar to how the arm swing of normal walking appears to react
2 against the vertical twisting induced by the legs (Elftman, 1939), resulting in higher energy cost
3 when walking without arm swing (Collins et al., 2009).

4 The purpose of this study is to quantify the mechanical and metabolic costs of swing leg
5 circumduction. We hypothesize that increased circumduction will result in greater metabolic
6 energy expenditure. That cost should be associated with the direct actions producing
7 circumduction and indirect reactions in the stance leg and arms. We performed an experiment
8 using physical constraints to induce varying amounts of circumduction in healthy adults, similar
9 to a preliminary experiment reported previously (Shipman et al., 2002). We expected energy cost
10 to increase with greater swing leg circumduction and lead to compensatory actions throughout
11 the arms, and stance leg, with these added indirect costs contributing to greater metabolic cost
12 during walking.

13 **EXPERIMENTAL METHODS**

14 We measured energetic and mechanical effects of walking with artificially induced swing leg
15 circumduction in healthy adults. The amount of circumduction was modulated using lightweight
16 foam obstacles—“Fins”—on the medial aspect of each leg to interfere with normal swing
17 (Figure 1). Subjects were asked to walk with circumduction to avoid collisions between the Fins,
18 while being constrained to their preferred step width. For comparison, subjects were also asked
19 to walk with zero step width. Measurements included swing foot trajectories as an indicator of
20 circumduction, the associated energy expenditure, and the amount of arm swing and ground
21 reaction moments as indicators of indirect reactions to circumduction.

22 Eight healthy young adults (5 males and 3 females; body mass M of 73 ± 13 kg, mean $\pm$ s.d; leg
23 length L of 0.89 ± 0.08 m) participated in the study, walking on an instrumented treadmill at 1.25
24 $\text{m} \cdot \text{s}^{-1}$ in six experimental conditions. Fins were strapped medially to the shank of each leg,
25 with different horizontal widths requiring greater circumduction (Figure 2). The Fins were in five
26 widths ranging 0–127 mm (labeled Fin0, Fin2, Fin3, Fin4, and Fin5, numbered according to the
27 width in inches) and approximately weight-matched (about 15 g, closed-cell foam 13 mm thick).
28 The sixth experimental condition required the subject to walk with zero step width (with Fin0 for

weight matching). All subjects provided written informed consent prior to the study in accordance with Institutional Review Board procedures.

Step width was controlled in each condition. The subject's preferred step width was determined during 6 minutes of normal, unconstrained treadmill walking at 1.25 m/s. That same width (about 0.18 ± 0.02 m, mean $\pm$ s.d.) was used for the subject's five Fin trials, displayed as a pair of laser lines projected longitudinally onto the treadmill. Subjects were instructed to step on the laser lines, aided by a real-time video projection of their feet and the lines, displayed in front of them. For the zero step width condition, subjects were asked to step on a single laser line.

Data collection was performed as follows. Oxygen consumption and carbon dioxide production were measured using a respirometry system (CareFusion, Vernon Hills, IL, USA). Steady state energy expenditure was calculated from the final 3 minutes of each 6 minute trial. Gross metabolic energy expenditure (in W) was calculated using standard conversion factors (Brockway, 1987), and the rate for quiet standing (112 ± 19 W) subtracted to yield net metabolic rate. Also measured were ground reaction forces (instrumented treadmill, Bertec, Columbus, OH, USA) and lower extremity kinematics (motion capture, Phasespace, San Leandro, CA, USA), for one minute of each trial, and used for standard inverse dynamics analysis (Visual3D, C-Motion, Germantown, MD, USA). Additional kinematics were recorded throughout the entire trial from inertial measurement units (APDM Inc, OR, USA), secured to the insteps of both shoes, and to both wrists. The IMUs recorded acceleration and angular velocity of each foot, which were then used to compute estimate of foot trajectories, using previously validated integration methods (Ojeda and Borenstein, 2007; Rebula et al., 2013).

These data were processed to yield measures of circumduction and associated gait compensations. Heel strike events were identified from ground reaction forces (Fin trials) and kinematic data (zero step width trial). Circumduction was measured laterally from the straight line connecting consecutive heel strikes, sampled at mid-swing (a consistent gait event defined at 80% of a stride cycle), near the time of maximum lateral excursion. Energetic cost was quantified with net metabolic rate, and indirect compensations with the peak stance leg moment (free vertical ground reaction moment) and the peak arm acceleration (from translational accelerations of wrist IMUs). Effects on gait parameters were quantified with step length and

width from heel marker positions sampled at mid-stance, and step period and double support duration (from ground reaction forces). To account for differences in body size, measurements were non-dimensionalized using base units of body mass M , standing leg length L (ground to greater trochanter), and gravitational acceleration g . The mean normalization constant for step length and step width was L (average 0.89 m), step time $\sqrt{L/g}$ (0.30 s), force Mg (741 N) moment MgL (642 N-m), and power $Mg^{1.5}L^{0.5}$ (2121 W).

We performed statistical tests for differences in circumduction, energy cost, and other variables. Paired t-tests were used to test discrete fin conditions against the Fin0 condition, and linear regression for dependence on mid-swing circumduction (significance level $\alpha = 0.05$). For metabolic rate, we tested for a dependence on the square of the circumduction amplitude, expected because the mechanical work required to move the leg from side to side should increase thus (similar to back-and-forth; Doke et al., 2005).

RESULTS

The fin obstacles induced significant changes in circumduction (see Figure 2, Table 1), resulting in a controlled, graded effect on limb circumduction ($P < 10^{-4}$ paired post-hoc t-test with Holm-Sidak correction), with an amplitude of about 16 cm with the largest fins. Metabolic cost increased with greater circumduction (Figure 3a), about 60% greater for Fin5 than Fin0, and changing approximately with the square of mid-swing circumduction. There were also indirect biomechanical changes, such as greater torque applied by the stance leg to the ground (i.e., free vertical moment, Figure 3b). Arm swing also increased, indicated by increasing peak translational acceleration of the swinging wrist (Figure 3c).

There were also small but significant effects on average step period, step length, and step width both in terms of discrete conditions ($P < 10^{-4}$, $P = 1.1e-3$, $P = 4.2e-3$, respectively; paired t-test, Table 1) and with circumduction as a continuous regression variable. Contrary to both instruction and the step width constraint, the subjects slightly increased their step width as the fins grew larger (Figure 4A). Step length and step period also increased while double support duration decreased, all linearly with circumduction (Figure 4).

The Zero step width condition also had effects on gait (Table 1). Most notably, this condition resulted in significantly more circumduction than the Fin0 condition ($P < 10^{-4}$, paired t-test), and

roughly comparable to the Fin4 and Fin5 conditions (Figures 5a and b). Metabolic rate also increased by about 28% compared to Fin0, similar to the Fin4 condition.

DISCUSSION

We had sought to systematically investigate the energetic cost of swing leg circumduction. We found increasing cost with greater circumduction, attributable in part to direct costs for moving the swing leg. However, we also observed increasing indirect effects associated with compensatory strategies such as stance leg ground reaction moment and arm acceleration, which may also contribute to the cost of walking with narrow steps. We propose that swing leg circumduction may play a role in the selection of preferred step width, particularly in relation to lateral balance control.

Energy cost and biomechanical variables were minimized for unobstructed walking (Figure 3). The greater metabolic rate could potentially be explained by the work needed to circumduct the leg. Mechanical work increases with the square of amplitude for periodic leg swinging (Doke *et al.*, 2005). Applying similar pendulum-like mechanics to lateral motion, work should increase with the square of circumduction amplitude (with step length and period remaining relatively unchanged, Table 1). However, the present study cannot exclude alternative explanations for the cost of greater circumduction.

We also observed indirect effects from circumduction. Circumduction of the swing leg requires an equal and opposite reaction forces and moments, which were transmitted to the ground (e.g., free vertical moment, Figure 3b) or into accelerations of other body segments such as the arms (e.g., Figure 3c), consistent with previous observations that walking while preventing arm swinging results greater free vertical moment and about 7% greater energetic cost (Collins *et al.*, 2009). Here, subjects tended to swing their arms more, and these and other compensations throughout the body may have required greater muscle effort and therefore contributed to energetic cost.

Walking with narrow steps requires circumduction of the swing leg to avoid collision with the stance leg. This is illustrated by the zero step width condition, where circumduction (0.12 ± 0.02 m) exceeded that for Fin0, and was comparable to the Fin4 and Fin5 conditions (Table 1 and

Figures 5 A & B). Thus, costs observed from experimentally-induced circumduction suggest a substantial contribution to the cost of walking with narrow steps.

We next return to the original hypothesis that the preferred step width may result from the trade-off between the costs for circumduction and for redirecting the COM during step-to-step transitions (Donelan *et al.*, 2001; see Fig. 5C). The step-to-step transition cost P_{s-s} increases with the square of step width (Kuo, 1999), thus favoring zero width if not for P_{circ} , the hypothesized cost for circumduction. Indeed, the preferred step width observed here appears to be just wide enough to afford nearly zero circumduction (0.01 ± 0.02 m for Fin0 condition, Figure 5a). Here we also refine the circumduction hypothesis to factor in the role of foot placement variability (Fig. 5C inset), which should also affect the average cost of a given step width. This is because some steps will vary medially and require more circumduction, while others will vary laterally and exact a higher step-to-step transition cost. The overall effect is summarized by the expected value function $E[\cdot]$,

$$E[P_{net}(w)] = \int_{-\infty}^{\infty} (P_{circ}(w + \tau) + P_{s-s}(w + \tau))p(\tau)d\tau$$

where w denotes mean step width, p the associated variability about the mean (as a probability distribution), and P_{circ} , P_{s-s} , and P_{net} respectively denote circumduction, step-to-step transition, and net contributions to the metabolic power associated with step width. If circumduction is relatively costly compared to the cost of taking a wider and variable steps, it may be economically favorable overall to take slightly wider steps on average, despite their greater step-to-step transition cost.

This statistical approach can help explain some observed effects of external lateral stabilization. Humans walking (on a treadmill) with their bodies laterally stabilized by elastic cords, decrease their lateral foot placement variability as well their preferred step width (Donelan *et al.*, 2004). External stabilization decreases the need for active foot placement for balance, and therefore explains the decreased variability, but not (directly) the preferred step width. The expected cost above explains how decreased variability should favor a narrower mean step width due to less likelihood for the swing leg to collide with the stance leg. An additional observation is that older adults have greater step variability, prefer wider steps than young, and have less of a difference

1 with external stabilization (Dean et al., 2007). If circumduction is relatively costly compared to
2 taking a wider step, older adults might again be expected to compensate for the greater
3 probability of experiencing a costly narrow step (higher step variability) by increasing their step
4 width accordingly.

5 Our findings may have implications for impaired gait. Patients with stiff-kneed gait (e.g., from
6 stroke or cerebral palsy, Sutherland et al., 1990) or other pathologies restricting knee flexion may
7 employ circumduction, among other compensations, to improve ground clearance (Kerrigan et
8 al., 1991; Wren et al., 2005). Our results show that such compensations are energetically costly
9 even for healthy individuals, as also observed with constrained knee flexion (Lewek et al., 2012).
10 Of course, impaired gait occurs at slower speeds and poses many other limitations that may
11 outweigh the effects seen here. There should nevertheless be mechanical consequences to
12 circumduction, whatever the origin.

13 The findings here are subject to a number of limitations. We imposed circumduction as part of a
14 controlled experiment, but this may not replicate other causes for circumduction, such as walking
15 with narrow steps. It was also possible for subjects to elect other compensation strategies, not
16 measured here. Additionally, other issues such as cognitive effort of visual feedback, or explicit
17 changes in step variability were not considered here. Although many complexities were not
18 considered, their effects do not appear large enough to negate the high cost of circumduction
19 observed in this simple experiment.

20 Walking with narrow steps typically entails circumduction of the swing leg. That circumduction
21 comes at an increased metabolic cost, not only to move the leg itself, but also for compensatory
22 motions elsewhere in the body. Circumduction appears to trade off against the separate cost for
23 taking wider steps. Together, the two contributions appear to determine the metabolically
24 optimal (and normally preferred) step width, and may explain why it is most economical to walk
25 with the feet just passing by each other, with little circumduction.

26 **Conflict of Interest Statement**

27 Conflicts of interest: none

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TABLES

Table 1 Experimental result by circumduction condition, Fin0 – Fin5, as well as Zero step width condition. Results as presented in SI units, as well as dimensionless (d'less) form.

Measure	Fin0	Fin2	Fin3	Fin4	Fin5	Zero
Mid-swing						
Circumduction (m)	0.01 ± 0.02	0.03 ± 0.02	0.08 ± 0.02	0.09 ± 0.02	0.16 ± 0.04	0.12 ± 0.02
Mid-swing						
Circumduction (d'less)	0.01 ± 0.02	0.04 ± 0.02	0.09 ± 0.03	0.10 ± 0.03	0.18 ± 0.05	0.13 ± 0.02
Step Length (m)	0.69 ± 0.04	0.68 ± 0.04	0.69 ± 0.04	0.70 ± 0.04	0.74 ± 0.05	0.71 ± 0.02
Step Length (d'less)	0.78 ± 0.04	0.76 ± 0.04	0.77 ± 0.04	0.78 ± 0.04	0.83 ± 0.06	0.80 ± 0.06
Step Width (m)	0.21 ± 0.02	0.24 ± 0.03	0.24 ± 0.04	0.26 ± 0.04	0.28 ± 0.05	0.00 ± 0.02
Step Width (d'less)	0.24 ± 0.03	0.27 ± 0.03	0.28 ± 0.04	0.29 ± 0.03	0.32 ± 0.05	0.00 ± 0.02
Step Period (s)	0.55 ± 0.03	0.55 ± 0.03	0.55 ± 0.04	0.56 ± 0.03	0.60 ± 0.05	0.57 ± 0.02
Step Period (d'less)	1.84 ± 0.06	1.81 ± 0.05	1.83 ± 0.07	1.86 ± 0.07	1.98 ± 0.12	1.90 ± 0.05
Net metabolic rate (W)	203 ± 44.6	220 ± 41.9	240 ± 55.7	247 ± 45.7	324 ± 77.0	259 ± 61.2
Net metabolic rate (d'less)	0.10 ± 0.02	0.10 ± 0.02	0.11 ± 0.02	0.12 ± 0.02	0.15 ± 0.03	0.12 ± 0.02

FIGURES

Figure 1 Setup for experimentally-induced swing leg circumduction. Circumduction was modulated using foam obstacles (“Fins”) of various widths, secured medially to each shank. Step width was constrained using laser lines projected onto treadmill that subjects were asked to step on, with a projected video image as aid.

Figure 2 Effect of Fin constraints on swing foot trajectories. **(A)** Average foot trajectories (forward vs. lateral displacement of toe marker, in laboratory frame) for five Fin conditions. Mid-swing circumduction is measured as lateral deviation middle of swing (shaded symbols) for each trajectory at mid-swing. **(B)** Mid-Swing Circumduction (mean $\pm$ s. d. across subjects) vs. Fin condition. Asterisk * denotes significant difference from Fin0 condition.

Figure 3 Energy expenditure and compensatory motions vs. mid-swing circumduction. **(A)** Net metabolic rate data, with square fit ($1.36x^2 + 0.1$ where x denotes circumduction; $R^2 = 0.81$). **(B)** Stance leg moment (peak of vertical free ground reaction moment) data, with linear fit ($0.2x + 0.01$, $R^2 = 0.32$). **(C)** Arm acceleration (peak) data, with linear fit ($0.89x + 1.09$, $R^2 = 0.66$). Both dimensionless (left and bottom axes) and SI units (right and top) are shown. Asterisk (*) indicates significant regression.

Figure 4 Step parameters as function of mid-swing circumduction, with linear fits. **(A)** Step length ($0.33x + 0.76$, $R^2 = 0.55$) and width data ($0.35x + 0.25$, $R^2 = 0.45$) for all subjects. **(B)** Step period ($0.76x + 1.80$, $R^2 = 0.51$) and double support times ($-0.32x + 0.56$, $R^2 = 0.67$) for all subjects. Both dimensionless (left and bottom axes, using base units of body mass, leg length and gravitational acceleration) and SI units (right and top) are shown. Asterisk (*) indicates significant regression.

Figure 5 Interaction between swing leg circumduction and step width. **(A)** Foot trajectories for the Fin0 and Fin5 conditions (at fixed step width) and the zero step width condition. **(B)** Mid-Swing Circumduction (mean $\pm$ s. d. across subjects) vs. condition. Asterisk (*) denotes significant difference from Fin0 condition. **(C)** Conceptual illustration of how both wide and narrow step widths contribute to metabolic cost. Wider steps entail step-to-step transition costs, P_{s-s} , increasing with step width squared. Narrower steps require increasing swing leg circumduction costs, P_{circ} . The expected value of the sum of these two costs, P_{net} , incorporating step width variability (Inset), explains why an intermediate step width may be optimal.