Shod vs. barefoot walking: why do humans change their step frequency?

Matthew B. Yandell, Karl E. Zelik
Vanderbilt University, Nashville, TN USA
matthew.yandell@vanderbilt.edu, karl.zelik@vanderbilt.edu

1 Introduction

Humans value economy of locomotion and seem to adopt a step frequency that minimizes metabolic cost at a given walking speed [1]. However, this observation is based on the study of shod walking. It has also been observed that humans increase their step frequency when walking barefoot (as compared to shod) [2,3], although the reason for this increase has not been explained.

Taken together, these empirical observations indicate that either: (1) removing the shoes changes gait dynamics sufficiently such that it shifts the metabolic minimum step frequency for a given walking speed, or (2) humans adopt a new step frequency when walking barefoot that does not minimize metabolic cost (i.e., people choose to walk less economically barefoot than is possible).

The goal of this study was to determine which of these two possibilities better explains the shift in step frequency when walking barefoot versus shod. To differentiate these potential explanations we performed an experiment that compared shod versus barefoot walking, and estimated metabolic cost as well as the relative effects of shoe-specific properties (e.g., mass, height) on step frequency. A secondary goal was to investigate changes in center of mass (COM) mechanics for shod vs. barefoot gait.

2 Methods

We studied 5 subjects (mean ± SD, 23 ± 4.3 years old, 72.3 ± 16.0 kg, 177.4 ± 11.0 cm height) during level walking on an instrumented split-belt treadmill (Bertec, Columbus, USA). All subjects gave informed written consent prior to participation. Three footwear variants were tested: shod (using each subject's personal athletic shoes), barefoot, and weight-matched (WM) barefoot (ankle mass was added to match shoe mass). At the beginning of each experiment subjects performed treadmill acclimation/training trials for each of the three footwear variants at the testing speed (1.25 m/s). These trials were used to determine each subject's baseline self-selected (SS) step frequency for each footwear variant.

Next, each subject was asked to walk at 1.25 m/s while matching the frequency of a metronome for the five testing conditions in Table 1. A Cosmed K4b^2 (Rome, Italy) metabolic system was used to measure the subject's oxygen uptake and carbon dioxide production rates for six minutes, and ground reaction force (GRF) data was collected during the last minute of each trial. Metabolic data was averaged over the last 2.5 minutes of the trial, with metabolic power being calculated from the equation given by Brockway [4]. GRF data was low-pass filtered at 25 Hz (Butterworth, 3rd order, zero lag) and used to compute individual limb COM power [5] for each limb. The metabolic results were used to determine if the energy consumed during barefoot walking was minimum at the barefoot self-selected frequency. COM power calculations were examined for differences in whole-body dynamics.

Table 1: Testing conditions for each footwear variant

	Footwear Variant		
Step Frequency	**Shod**	**Barefoot**	**Barefoot WM**
Shod SS	X	X	X
Barefoot SS		X	
Barefoot WM SS			X

The effect of leg length difference (barefoot vs. shod, due to shoe height) was analyzed using regression equations reported in literature [2,6]. We estimated the change in step frequency due to the height of the shoes worn. Statistical analysis was performed using analysis of variance with Holm-Sidak step down correction (alpha = 0.05).

3 Results

For all subjects, we found that the barefoot and barefoot WM self-selected step frequencies were significantly higher than the shod self-selected frequency ($P < 0.01$, Table 2). No significant difference in step frequency was observed between barefoot and barefoot WM ($P = 0.62$). Average shoe mass in this study was 296 g.

Table 2: Self-selected (SS) step frequency for each footwear variant

	Subject SS Step Frequency (steps/min)					
Variant	**1**	**2**	**3**	**4**	**5**	**AVG**
Shod	112	123	103	112	111	**112.2**
Barefoot	118	130	118	119	118	**120.6**
Barefoot WM	117	130	118	120	117	**120.4**

We observed from metabolic data that 4 out of 5 subjects exhibited a lower gross metabolic cost when walking barefoot at the shod self-selected step frequency (~112 steps/min) than barefoot at the barefoot self-selected frequency (~121 steps/min). This difference did not reach statistical significance, likely due to the low number of subjects. However, through ongoing testing of additional subjects we will attempt to distinguish if statistically significant differences exist. Qualitative differences were observed in COM power for barefoot vs. shod gait, specifically in terms of a reduced transient immediately following heelstrike.

The height of the shoe sole added 20 ± 6 mm to each participant's leg length, as compared to walking barefoot. Based on the published speed-step length relationship [2,6], we estimated this 20 mm decrease in leg length when walking barefoot would result in a 1.9 step/min increase in step frequency (Table 3). The predicted increase in step frequency due to the decrease in leg length was substantially smaller than the empirical increases observed in this study.

Table 3: Modeled vs. observed step frequency change due to differences in leg length, barefoot vs. shod

	Subject					
	1	**2**	**3**	**4**	**5**	**AVG**
ΔLeg Length Difference (mm)	-12.0	-20.6	-22.9	-17.3	-27.2	**-20.0**
Modeled ΔStep Freq. (steps/min)	+1.3	+2.1	+2.0	+1.8	+2.4	**+1.9**
Observed ΔStep Freq. (steps/min)	+6	+7	+15	+7	+7	**+8.4**

4 Discussion

There are multiple factors which could contribute to the increase in step frequency when a person transitions from shod to barefoot walking. In this study we sought to determine if properties of the shoe (e.g., mass, height) could account for the altered dynamics during barefoot walking.

We first tested shoe mass, to determine its effect on a person's self-selected step frequency. We found that the addition of shoe mass to barefoot walking had little to no effect on self-selected step frequency, and thus did not account for the observed barefoot vs. shod changes.

The second shoe metric examined was the effect of the shoe height, which effectively increases leg length. We found that the reduction in leg length when walking barefoot is expected to have a small increase on the step frequency (~1-2 steps/min), but this accounted for less than 25% of the observed barefoot vs. shod step frequency increase, which was >8 steps/min.

Since these intrinsic shoe characteristics failed to account for the observed change in step frequency, other factors must be considered. One of these is shoe length (and its effect on effective foot length), which will be investigated in ongoing/future trials. Another factor may be related to the subjective comfort/discomfort experienced as a result of not having shoe cushioning when walking barefoot. Previous studies on running and jump landing have demonstrated how cushioning can influence preferred movement strategies, and this effect may also be pertinent to walking. Although it is difficult to define and/or measure comfort, the lack of cushioning when walking barefoot could have a marked effect on a user's subjective preference and lead to altered behavior. Unfortunately these types of subjective factors are not typically captured in simulations of gait, and may indeed be challenging to assimilate into our theoretical understanding of locomotion.

When walking shod people tend to choose a step frequency that minimizes metabolic cost [1]. One might expect that during barefoot walking the self-selected frequency would also result in a minimal metabolic cost. However, in the barefoot condition 4 out of 5 of subjects exhibited lower metabolic cost at the self-selected shod frequency compared to the self-selected barefoot frequency. Additional subjects are being collected to determine if this is a statistically significant difference; however, the preliminary observation suggests that the self-selected step frequency in barefoot walking may not be metabolically optimal. Thus, the use of a metronome (at self-selected shod frequency) might be adequate to reduce the metabolic cost of walking barefoot. This a novel and intriguing result, as the majority of prior literature has suggested that humans intuitively select a step frequency that minimizes energy consumption during level-ground walking.

In summary, we found indications that when walking barefoot, people may choose a self-selected step frequency that is metabolically sub-optimal. The increased step frequency observed for barefoot (as compared to shod) walking was not well explained by the mass or height properties of the shoe. We speculate that cushioning provided by the shoe and/or subjective user comfort may be significant factors in the choice of self-selected barefoot walking frequency, factors which are generally not integrated into walking models or our theoretical understanding of gait. Shoe characteristics could potentially be manipulated to encourage desired locomotor behaviors, such as more favorable biomechanics or reduced joint loading associated with long-term injury risk.

References

[1] M. Y. Zarrugh, F. N. Todd, and H. J. Ralston, *Eur. J. Appl. Physiol.*, vol. 33, no. 4, pp. 293–306, 1974.

[2] D. W. GRIEVE and R. J. GEAR, *Ergonomics*, vol. 9, no. 5, pp. 379–399, Sep. 1966.

[3] N. Lythgo, C. Wilson, and M. Galea, *Gait Posture*, vol. 30, no. 4, pp. 502–506, Nov. 2009.

[4] J. Brockway, *Hum. Nutr. Clin. Nutr.*, vol. 41, no. 6, pp. 463–471, 1987.

[5] J. M. Donelan, R. Kram, and A. D. Kuo, *J. Biomech.*, vol. 35, no. 1, pp. 117–124, 2002.

[6] A. D. Kuo, *J. Biomech. Eng.*, vol. 123, no. 3, p. 264, 2001.