SHOD VS. BAREFOOT WALKING: WHY DO HUMANS CHANGE THEIR STEP FREQUENCY?

Matthew B. Yandell, Karl E. Zelik

Vanderbilt University, Nashville, TN USA
email: matthew.yandell@vanderbilt.edu, karl.zelik@vanderbilt.edu, web: https://my.vanderbilt.edu/batlab/

INTRODUCTION

Humans value economy of locomotion and seem to adopt a step frequency while shod that minimizes metabolic cost at a given walking speed [1]. It has also been observed that humans increase their step frequency when walking barefoot (as compared to shod) [2,3]; however, 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 expenditure.

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. We performed an experiment that compared shod versus barefoot walking, and estimated metabolic power 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 versus barefoot gait.

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). 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). Each subject performed acclimation trials at 1.25 m/s to determine their baseline self-selected step frequency for each footwear variant.

Next, each subject was asked to walk at 1.25 m/s while matching a metronome frequency for the five testing conditions in Table 1. A Cosmed K4b^2 system measured metabolic data for six minutes, and ground reaction force (GRF) data was collected during the last minute of each trial. Average metabolic power during the last 2.5 minutes of each trial was 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. Statistical comparisons between conditions were performed using analysis of variance with Holm-Sidak step down correction (alpha = 0.05).

Table 1: 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

We also estimated the effect of leg length difference (barefoot vs. shod, due to shoe height) on step frequency using regression equations reported in literature [2,6].

RESULTS AND DISCUSSION

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 ($P = 0.62$). Mean shoe mass in this study was 296 g.

We observed from metabolic data that 4 out of 5 subjects exhibited a lower gross metabolic power when walking barefoot at the shod self-selected step frequency (~112 steps/min, Table 2) 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.

The height of the shoe sole added 20 ± 6 mm (mean ± SD) 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. The predicted increase in step frequency was substantially smaller than the empirical increase of 8.4 step/min (Table 2) observed in this study.

Differences were also observed in COM power for barefoot vs. shod gait, specifically in terms of a reduced transient immediately following heelstrike during barefoot walking.

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**

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 could account for the altered dynamics.

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. Similarly, we estimated that the reduction in leg length when walking barefoot (due to the loss of shoe height) was only expected to lead to a small increase in 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. Although it is difficult to define comfort, the lack of cushioning when walking barefoot could have a marked effect on a user's subjective preference and lead to altered behavior.

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 biomechanical 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. Zarrugh MY, et al. *Eur. J. Appl. Physiol.* **33**, no. 4, pp. 293–306, 1974.
2. Grieve DW, et al. *Ergonomics* **9**, no. 5, pp. 379–399, 1966.
3. Lythgo N, et al. *Gait and Posture* **30**, no. 4, pp. 502–506, 2009.
4. Brockway JM. *Hum. Nutr. Clin. Nutr.* **41**, no. 6, pp. 463–471, 1987.
5. Donelan JM, et al. *J. Biomech.* **35**, no. 1, pp. 117–124, 2002.
6. Kuo AD. *J. Biomech. Eng.* **123**, no. 3, pp. 264-269, 2001.