The separate effects of shoe mass and cushioning on

the energetic cost of barefoot vs. shod running

By

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Abstract

One might intuit that running barefoot would exact a lower energetic cost than running in shoes since shoes add mass to the foot. Although this is true for typical weight running shoes, lightweight cushioned shoes and barefoot have been shown to have similar costs. Other studies have indicated that there is an energetic cost of cushioning in running. Thus, the cost of barefoot running may reflect the combined effects of a decrease due to lower mass and an increase due to greater muscle actions for cushioning. We hypothesized that running barefoot on a cushioned surface would minimize both the mass cost and the cushioning cost. **PURPOSE:** To quantify the separate effects of shoe mass and cushioning on the energetic cost of running. **METHODS:** 12 male experienced barefoot runners ran at 3.35 m/s with a mid-foot strike pattern. Subjects ran both barefoot and in ultra-light cushioned racing shoes (~150 g /shoe) on a treadmill with a rigid deck and barefoot on the same treadmill equipped with a cushioned belt made with foam slats. In additional trials, small lead weights were added to the feet/shoes (~150, ~300, ~450 g). We measured the subjects' rates of oxygen consumption and carbon dioxide production to quantify energetic cost. **RESULTS:** The mass effect was similar for all footwear conditions: approximately 1% increase in oxygen consumption per 100 g of mass added to each foot. The energetic costs of running barefoot with and without the treadmill surface cushioning were not different (p=0.52). Contrary to our hypothesis, running in ultra-light cushioned racing shoes had the lowest energetic cost: 3.4% less than the weight-matched barefoot condition (p=.02). There was no significant difference between the energetic cost of running barefoot with no added mass and shod with the ~150 g running shoe. **CONCLUSIONS:** Our findings suggest that when mass is controlled for, cushioned shoes provide an energetic advantage over running barefoot.

Introduction

The topic of barefoot running recently has garnered a large amount of publicity and seems to be gaining in popularity. Barefoot running was featured on the cover of *Nature* in January, 2010, barefoot running clubs have formed nationwide, and the best-selling book *Born to Run* by Christopher McDougall has inspired many to leave their shoes at home. Since anyone could potentially try running barefoot, studies in this area are relevant to all runners from the performance athlete to those who run for fun and fitness. Based on the fossil record, some anthropologists argue that humans have run barefoot for long distances for nearly two million years (Bramble & Lieberman, 2004), but specific cushioned running shoes have been developed in just the last 50 years.

There are many anecdotal claims that barefoot running is better, but there has been very little scientific research examining the specific risks or benefits. One claim in particular that we set out to investigate is that barefoot running is more energetically efficient than running in shoes. Barefoot Ted, a prominent barefoot enthusiast and coach was quoted as saying "If you are looking for an answer to the question 'how can I run better, more efficiently…?' I have a potential answer for you...learn how to run barefoot" (www.barefootted.com/coach). Michael Sandler, organizer of the Boulder Barefoot Running Club and author of *Barefoot Running* claims, "Barefoot running naturally promotes better, more efficient running posture and allows runners to surpass any speed they were ever able to attain with shoes"(www.runbare.com/about). This claim has spread through the barefoot community and internet forums. "Many individuals turn to barefoot running because it can be more efficient than running with running shoes" according to Wisegeek.com (www.wisegeek.com/what-is-barefoot-running.htm). This assertion of efficiency is also used to sell new barefoot/minimalist products. Invisibleshoe.com, vendor of huarache running sandals advertises on their site, "Bare foot running …changes how you run to a more efficient technique." Even some medical doctors claim that running barefoot should be more efficient. Dr. Jeff Hurless a podiatrist and surgeon was quoted as saying, "I would agree barefoot running is slightly more efficient than running with shoes" (www.healthyfeetblog.com).

These assertions have generally been shown to be true for comparisons of barefoot vs. normal weight running shoes. However, studies comparing the efficiency of barefoot running vs. running in lightweight cushioned running shoes have found no significant difference in oxygen consumption. That is still puzzling because shoes are obviously heavier than no shoes.

Table 1. Literature Summary

Author(s), year	Conditions	Added mass (per foot)	Major oxygen consumption finding(s) (mL/kg/min ±SD)
Burkett et al., 1985	Barefoot (BF) Shod (SH) Shod w/ orthotics (SH + orthotics)	Masses of shoes and orthotics were not controlled for, but in terms of mass BF<SH<SH+orthotics	Increased $\dot{V}O_2$ with increased mass. BF<SH<SH+orthotics
Frederick et al., 1986	Hard-soled running flat (HSRF) Soft-soled running flat (SSRF)	HSRF = 323.45 g SSRF = 338.9 g	SSRF 2.4% < HSRF
Flaherty, 1994	Barefoot (BF) Shod (SH) Barefoot with equated weight to shoe (BFW)	Shoe: avg. 356g	BF 4.7% < SH (~350g)
Kerdok et al., 2002	Flat soled running shoes 5 treadmill platforms of different stiffness	Shoe mass same for each subject	More compliant cushioned surface reduced oxygen consumption by as much as 12%
Divert et al., 2008	Barefoot (BF) Diving sock (SK) Shod (SH)	Sock: 50,150,350g Shoe: 150, 350g	$BF = SH_{150}$ BF (40.7±2.9), SH150 (40.6±3.1), SH350 (42.1±2.3) Mass effect (p<.01), but no shoe effect or shoe/mass interaction.
Hanson, 2009	Barefoot (BF) Shod (SH)	Range of Shoe mass: ~250g to ~450g / shoe	BF $\dot{V}O_2$ = 35.0± 7.2 ml/kg/min SH $\dot{V}O_2$ = 36.4± 7.3 ml/kg/min BF 3.82% <SH (p<.05).
Squadrone & Gallozi, 2009	Barefoot (BF) Vibram 5 fingers (VF) Shod (SH)	Five fingers: avg. 148g Shoe: avg. 341g	$BF = SH_{341}$ VF<SH BF(45.6±2), VF(45.0±2), SH(46.3±2)

Several well-done scientific studies have shown that the energetic cost of running increases with shoe mass. For example, Divert et al. (2008) attached small lead weights to neoprene socks and found that the energetic cost of the runners increased by about 1% for each 100 grams of added mass (per foot). Given this finding, one would expect to find that running barefoot would use about 3% less energy than running in typical 300 gram shoes. That expectation was contradicted by the research of Squadrone and Gallozzi (2009). They found that the rate of oxygen consumption of barefoot running was not statistically different from the oxygen consumption of the shod condition in which the mass of the shoe was 341 g.

These counter intuitive findings could be due to a factor other than mass. Frederick et al. (1986) suggested that there is another factor influencing energetic efficiency - a "cost of cushioning." They compared two shoes which differed only in the cushioning of the outsole and midsole. One was a training flat with a stiff EVA midsole while the other was constructed with a 1cm thick air cushion encapsulated in low density polyurethane foam to make the wedge and midsole. They found that the shoe with the more cushioned sole exacted a 2.4% lower energetic cost during running. Studies on barefoot running consistently find that barefoot runners land with more plantar flexion of the ankle (i.e. striking the ground first with the middle part of the foot, rather than the heel) which serves as a shock-absorbing strategy (Lieberman, 2010). This adaptation may require increased contraction of muscles in the lower leg and thus might increase energy expenditure. If muscle actions play a role in cushioning the body during running then this could account for an energy expenditure comparable to shod running during barefoot running even though the shoe mass is zero.

A study by Kerdok et al. (2002) examined the relationship between energetic cost of running and cushioning by quantifying the effect that treadmill surfaces of different stiffness had on energy expenditure. They found that energy expenditure decreased by as much as 12% with more compliant surfaces. There may be a point beyond which a surface becomes too compliant, but this study demonstrated that some cushioning can reduce energy expenditure considerably.

In the present study we chose to focus on how cushioning and shoe mass independently affect the energetic cost of running.

We sought to answer the following questions:
1. Is barefoot running less energetically demanding than running in shoes?
2. Is there an energetic cost of cushioning associated with barefoot running?

We tested the following hypotheses:

1. Barefoot running on a hard surface will have about the same energy expenditure as running in cushioned shoes that weigh 150 g each.

2. Barefoot running on a cushioned surface will be less expensive than running barefoot on a hard surface.

To test these hypotheses, runners with barefoot experience ran under three conditions: barefoot (BF), shod (SH), and barefoot on a cushioned surface (BFC) (See figure 1).

Methods and Materials

Subjects:

Twelve healthy male runners volunteered for this study (Age 29.75 ± 7.26 (mean $\pm$ standard deviation) years, body mass 75.50 kg $\pm$ 7.06 kg and height 179.20 ± 5.26 cm). All participants reported that they had been running barefoot or in Vibram Five Fingers/ huarache sandals/ similar minimalist footwear products for at least 3 months out of the last year at a minimum of 5 miles per week. All subjects reported being injury-free at the time of the experiment. The University of Colorado Institutional Review Board approved this project. After being informed of the nature of the study, subjects gave their written consent to participate.

Determination of Foot strike type for inclusion:

Using duct tape, we attached small pieces of dry erase marker felt to subjects' right foot at 90, 70, and 33% of the foot length (measured on the line between the heel and the distal end of the 2nd toe). Then, subjects ran barefoot over an AMTI force plate (Advanced Mechanical Technology Inc., Watertown, MA 02472-4800 USA) embedded in a runway and covered with paper. Force plate data were collected at 1000 Hz. We tracked the center of pressure relative to the foot outline provided by the dry erase marks left on the paper as per Cavanagh and Lafortune (1979). We classified subjects as mid-foot strikers if the center of pressure started between the 70 and 33% of foot length and rear-foot strikers if the center of pressure started behind the 33% mark. Only mid-foot strikers were included in the study. We excluded one potential subject because of his surprising rear foot strike pattern while running barefoot.
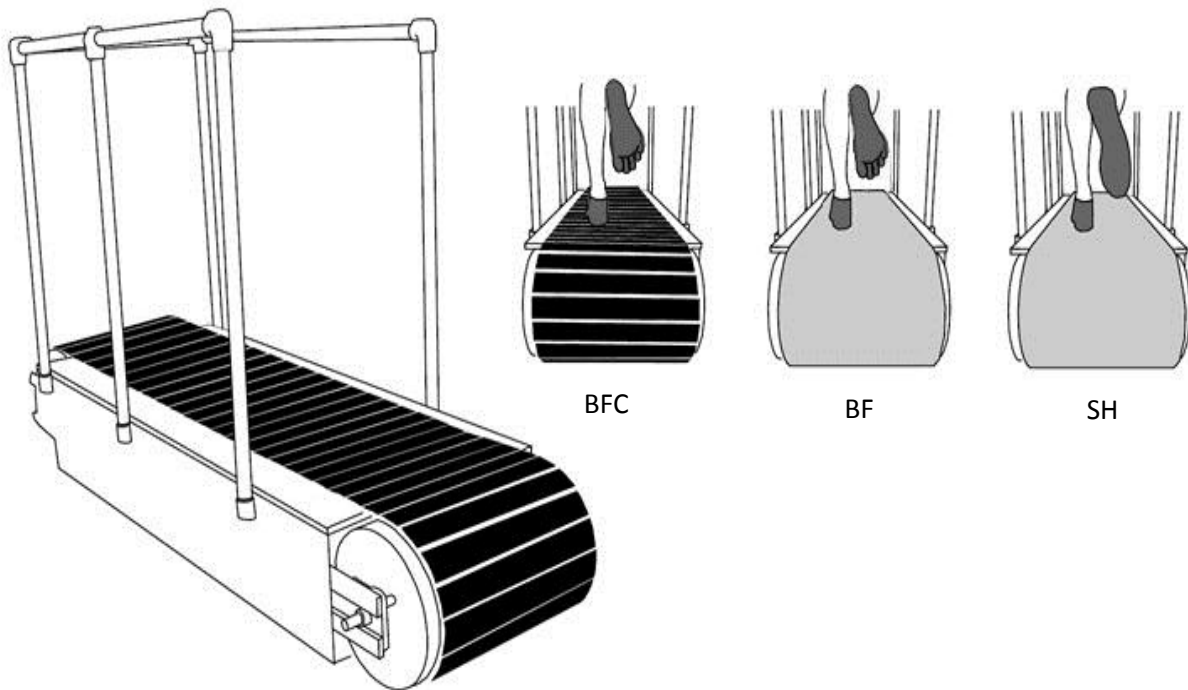
Materials

Figure 1. Treadmill and cushioning conditions. (right to left) Quinton Instruments treadmill (model # 18-60) with EVA slats (cushioned surface), barefoot on cushioned surface (BFC), barefoot on regular rigid surface (BF), shod on regular rigid surface (SH).

Cushioned Treadmill Surface

One novel portion of our experiment was the use of a cushioned treadmill surface. We used EVA (Ethylene Vinyl Acetate) foam (durometer = 65 Shore C), similar to the type of foam used to make running shoe midsoles. We cut the EVA into 5 cm x 46cm slats and then attached them to the treadmill belt using Velcro which allowed for the cushioning to be removed when necessary.

Figure 2. Sole-less half shoe and added mass attachment. A men's running shoe with the sole and front portion of the upper removed (mass = ~150 g). For added mass trials, we attached lead weights over the foot's center of mass using the shoe laces.

Added Mass Attachment

      We modified the uppers of a pair of running shoes to allow for easy attachment of lead weights while still simulating the barefoot condition. We removed the outsole and midsole along with the front portion of the upper leaving only the portion of the upper posterior to the proximal head of the fifth metatarsal, heel counter, thin fabric arch section, tongue and laces. Because all of our subjects were mid-foot strikers, this design exposed the plantar surface of the foot that would strike the ground during barefoot running, eliminating the influence of cushioning. For the weighted trials, we secured lead weights by lacing them in above the center of mass of the foot, along the shoe tongue.

Metabolic Protocol:

Table 2: Running Trials

Added Mass per foot	Barefoot	Barefoot (cushioned)	Shod
0g	BF_{0M}	BFC_{0M}	---
~150 g	BF_{1M}	BFC_{1M}	SH_{1M}
~300g	BF_{2M}	BFC_{2M}	SH_{2M}
~450g	BF_{3M}	BFC_{3M}	SH_{3M}

Subjects completed a standing trial and 11 running trials in various footwear conditions (See Table 2). In all running trials, subjects ran at a speed of 3.35 m/sec for 5 minutes. For the duration of the experiment, subjects wore slip-resistant yoga socks for safety and hygienic purposes. The baseline mass for this experiment was defined as M, the mass of each ultra-lightweight shoe. Thus, M was specific to shoe size (M= 135.6 g for size 9, 142.3 g for size 10 and 150.2 g for size 11). For the "barefoot" portion of the experiment, subjects ran on the treadmill under 4 conditions: barefoot (BF_{0M}), barefoot with ~150 g of added mass per foot (BF_{1M}), barefoot with ~300g of added mass per foot (BF_{2M}), and barefoot with ~450g of added mass per foot (BF_{3M}). For the shod portion of the experiment, subjects ran in the same model of ultra-lightweight running shoes (Nike Mayfly). Subjects ran on the treadmill under three conditions: ultra-lightweight running shoes (SH_{1M}), ultra-lightweight running shoes weighted with an extra ~150 g for a total of ~300 g per foot (SH_{2M}), and ultra-lightweight running shoes with ~300 g added for a total of ~450 g per foot (SH_{3M}). In the cushioned treadmill part of the experiment, the subjects completed the four "barefoot" trials again on the cushioned treadmill belt to simulate a "massless virtual shoe" condition. The mass of the sole-less shoe was included in the added mass total.

Metabolic Data Collection:

We collected the rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) using an open-circuit respirometry system (Parvo Medics, TrueOne 2400) during all conditions. Before each experiment, we calibrated the gas analyzers using reference gases and a 3 L syringe. Average $\dot{V}O_2$, $\dot{V}CO_2$, expiratory ventilation ($\dot{V}E$) and respiratory exchange ratios were calculated for the last 2 minutes of each trial. Subjects' respiratory exchange ratio (RER) had to remain below 1.0 in order for their data to be included. One subject was excluded due to high RER.

Statistics:

We implemented an analysis of variance for repeated measures to compare each subject's metabolic rate across conditions with a significance level of $p < 0.05$.

Results

Table 3: Gross Rates of Oxygen Consumption, $\dot{V}O_2$ (mL/kg/min) (mean, standard deviation)

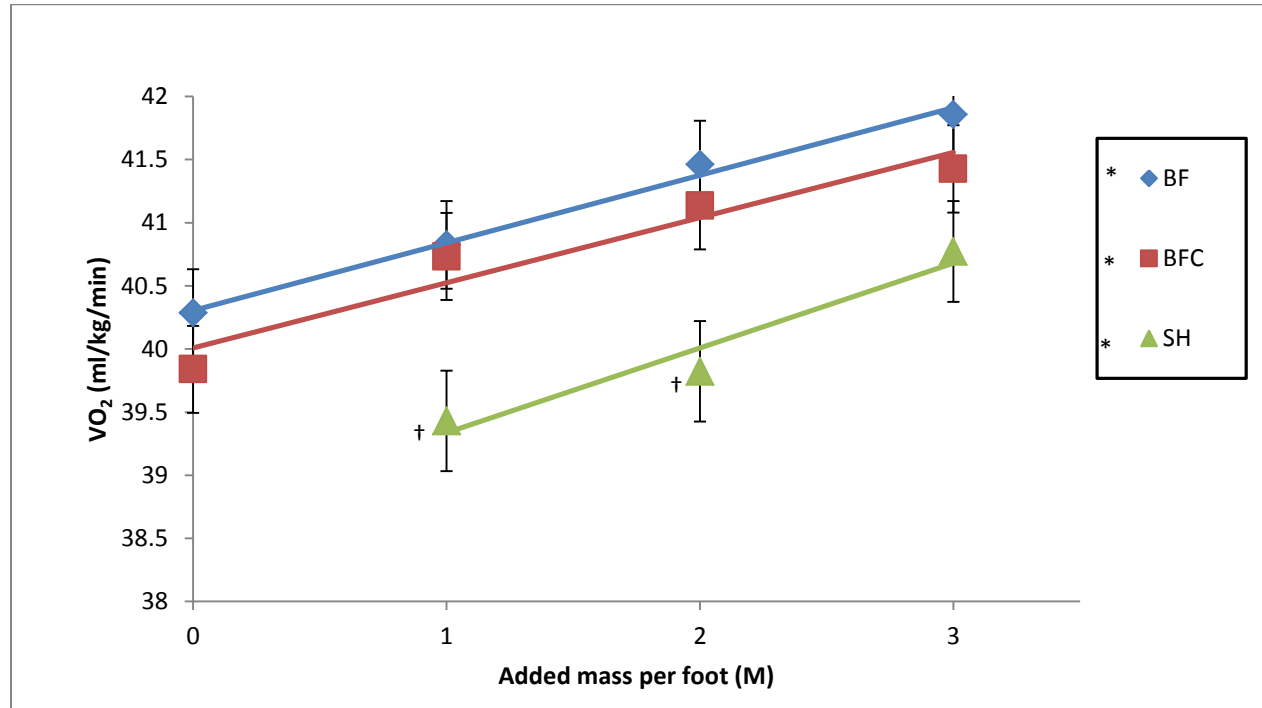| Added mass	BF	BFC	SH
0M	40.28(± 3.04)	39.84 (± 2.31)	---
1M	40.83(± 3.33)	40.73 (± 2.64)	39.43 (± 2.61)
2M	41.46(± 2.63)	41.13 (± 2.54)	39.82 (± 2.48)
3M	41.86(± 3.47)	41.43 (± 2.26)	40.77 (± 2.76)

Figure 3. Rates of Oxygen Consumption vs. Shoe Mass. M = ~150g of added mass per foot. * = significant mass effect within the footwear condition. †= significant footwear effect within the given weight-matched conditions. All 3 conditions (Barefoot, Barefoot on a cushioned surface, and Shod) showed a similar mass effect of 1.02%, 0.95% and 1.46% per 100g of added mass respectively. $\dot{V}O_2$ for BF and BFC were not statistically different for any of the mass conditions. The SH condition proved to be the least energetically costly compared to the weight-matched BF and BFC conditions. Means ± SE.

Mass Effect

Adding mass significantly increased the rates of oxygen consumption for each footwear condition. RMANOVA (BF p<0.001, BFC p=0.007, SH p=.001). The increases in the rates of oxygen consumption were roughly 1% for each 100 g added per foot (BF 1.01 %, BFC 0.95%, and SH 1.45%)

Footwear Effect

When mass was controlled for, running in lightweight cushioned shoes was less energetically demanding than running barefoot. For both the 1M and 2M weight-matched conditions SH was statistically significantly lower than BF; 3.4% lower in the 1M condition (p=0.035) and 3.96% lower for the 2M condition (p=.008). In terms of the natural shod condition compared to the natural barefoot condition, SH_{1M} was numerically 2.1% lower than BF_{0M} however this difference was not statistically significant (p=.092) despite the fact that 8 out of 12 of the participants displayed this trend. There were no statistically significant differences between BF and BFC for any of the weight-matched conditions.

Discussion

Our hypothesis that running barefoot would elicit the same energy expenditure as running in cushioned lightweight shoes was supported by our data. There was no significant difference between BF_{0M} and either SH_{1M} or SH_{2M}. The numerical difference between BF_{0M} and SH_{1M} was 2.1%, but failed to reach significance. SH_{2M} was numerically only 1.1% lower than BF. It appears that the energetic differences between our mass conditions were small enough to be within the experimental noise. Our results are consistent with the findings of Squadrone and Gallozi (2009) and Divert et al. (2008). Those studies found no difference between barefoot and shoes weighting ~350 g and ~150 g respectively. In answer to our first question: "Is barefoot running less energetically demanding than running in shoes?" we can answer that barefoot is not less energetically demanding than normal shod conditions, and in fact when the conditions are weight-matched, shoes become significantly less demanding.

Our second hypothesis that barefoot running on a cushioned surface (BFC) would be less expensive than the barefoot condition on the rigid deck (BF) was not supported by our data. We found no significant difference between BF and BFC for any weight-matched comparisons. We expected that BFC_{0M} would simulate a "massless shoe" (a theoretical SH_{0M}). However, if we were to extend the regression line for the SH condition to the y axis, it intercepts at 38.6 ml/kg/min, 3.6% lower than the actual value for BFC_{0M}. The mean $\dot{V}O_2$ for BFC was consistently slightly lower than BF, but there was large individual variation.

Table 4: Stride lengths during barefoot, barefoot cushioned and shod conditions

	Barefoot	Barefoot (cushioned)	Shod
Avg. stride length (m)	2.16	2.17	2.23*†

* = significantly different than BF p< .05 †= significantly different than BFC p< .05 There was no significant difference between BF and BFC.

There are several possible explanations for why our treadmill cushioning did not produce the expected result. One promising idea is that stride length, rather than cushioning, is what drives the difference between barefoot and shod oxygen consumption. We measured stride frequency for each subject and calculated mean stride length. SH had a 3.2% longer average stride length than BF (2.23 m and 2.16 m respectively, p =.001). According to Cavanagh and Williams (1982), there is an optimal stride length at which energetic cost is least. Any deviation to a longer or shorter stride length increases $\dot{V}O_2$. This suggests that the shorter stride length adopted by runners while running barefoot may have exacted a higher metabolic cost compared to the more optimal stride length adopted while running in shoes. Also, according to Snyder & Farley (in press) a 3% shorter stride increases $\dot{V}O_2$ by 1-2%. In terms of the comparison between BF and BFC, subjects adopted very similar stride lengths (only 0.3% different, 2.16 m and 2.17 m respectively). This could account for the lack of difference between the oxygen consumption of BF and BFC. BFC is still barefoot and surprisingly it appears that when running barefoot subjects tend to adopt a shorter stride length regardless of the surface on which they are running.

Alternative ideas for why our treadmill cushioning hypothesis was not supported include the heel lift on the ultra-lightweight cushioned running shoes, the possibility that the treadmill cushioning that we used was insufficient, or that the cushioned surface was too novel. The cushioned shoe that we used had a heel lift of ~9 mm. None of our subjects were rear foot strikers which means that they were not landing directly on the heel. However, the heel lift does prevent the heel from resting all the way to touch the running surface after mid-foot strike (as is common in mid-foot strikers) Thus, the range of motion required of the ankle is decreased compared to running barefoot. This could potentially save energy in the shod condition. Another explanation involves the qualities of the EVA that we used to create the cushioned treadmill surface. It is possible that the EVA we used was less resilient than the cushioning used in the ultra-lightweight shoe which would decrease its effectiveness at absorbing the shock during

barefoot running. This would explain why the energetic cost of running on the rigid deck was so similar to running on the cushioned surface. Alternatively, the fact that the EVA was applied as slats with small gaps in between rather than one continuous surface could have caused higher energy cost. One subject commented that running on the cushion felt "like running on a trail" in that the cushioned surface felt rougher than the rigid deck alone. If subjects had the perception of unsure footing or were sensitive to landing on the spaces between the slats, then that could have increased $\dot{V}O_2$ during the cushioned trials.

Further research in this area should seek to establish the separate effects of stride length, heel lift and cushioning characteristics. To test stride length, one could record the preferred stride frequency of subjects running shod and then enforce that stride frequency while running barefoot at the same speed (and thus the same stride length). That would control for stride length, so that any difference found between these two conditions would be due to some other factor. A metabolic comparison of running barefoot (BF) and barefoot with a heel lift (BFH) attached to the foot would determine whether the heel lift acts to decrease energy cost. It would be important to control for mass by adding the weight of the heel lift to the BF condition. The cushioning could be improved by making the cushioned belt continuous rather than slatted to decrease novelty. Also, comparisons of cushioned surfaces of different stiffness could better answer the question of whether there is a cost of cushioning which affects the oxygen consumption while running. If one could provide optimal cushioning with optimally low mass, then there could potentially be shoes which exact an even lower energetic cost compared to the natural barefoot condition.

In conclusion, running barefoot is not more energetically efficient than running in lightweight shoes despite the fact that shoes add mass. It is unclear what role cushioning plays in terms of metabolic cost. At this point we cannot conclude that cost of cushioning is responsible for increasing the energetic cost of running barefoot. There must be some factor other than mass that accounts for the metabolic cost of running barefoot, but the mechanism remains elusive.

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Figure 1 was provided courtesy of Jason Franz

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