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A Test of the Metabolic Cost of Cushioning Hypothesis in Shod and Unshod Running

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A TEST OF THE METABOLIC COST OF CUSHIONING HYPOTHESIS IN SHOD AND UNSHOD RUNNING

by

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B.S., University of Colorado Boulder, 2010

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A TEST OF THE METABOLIC COST OF CUSHIONING HYPOTHESIS IN SHOD AND UNSHOD RUNNING

written by Kryztopher David Tung

has been approved for the Department of Mechanical Engineering

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Date________________

The final copy of this thesis has been examined by the signatories, and we

Find that both the content and the form meet acceptable presentation standards

Of scholarly work in the above mentioned discipline.

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Tung, Kryztopher David (M.S., Mechanical Engineering)

A Test of the Metabolic Cost of Cushioning Hypothesis in
Shod and Unshod Running

Thesis directed by Professor Rodger Kram

Advocates of barefoot running assert that it is more metabolically efficient than shod running. This idea makes sense because wearing shoes adds mass to the feet. However, previous studies that controlled for foot/shoe mass indicate that shoe or surface cushioning provides an energetic advantage over running barefoot. Further, running in lightweight shoes has about the same metabolic cost as running barefoot, suggesting that the positive effects of shoe cushioning may counteract the negative effects of added mass. We hypothesized that: 1) barefoot running would have the same metabolic cost as running with lightweight, cushioned running shoes and 2) the metabolic cost of barefoot running would be less on cushioned surfaces.

Eleven experienced barefoot runners ran at 3.35 m/s with a mid-foot strike pattern. Subjects ran barefoot (BF) and in lightweight cushioned running shoes (SH) (Nike Free 3.0; ~211 g /shoe) on a rigid treadmill. Subjects also ran barefoot on the same treadmill with 10 mm and 20 mm thick slabs of ethylene-vinyl acetate (EVA) foam affixed to the treadmill belt (Figure 1). The foam was identical to that used in the running shoes. Rates of oxygen consumption and carbon dioxide production quantified metabolic power. Our findings demonstrate that cushioning reduces the metabolic cost of running, and suggest that there may be an ideal amount of cushioning (e.g. < 20mm) beyond which metabolic benefits diminish.

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INTRODUCTION

Running is a bouncing gait in which the legs are modeled as springs (Figure 1) with predicted ground reaction forces (GRF) of $GRF = k\Delta L$ where k is the spring constant of the entire leg, and ΔL is the amount of leg compression that occurs with each step. The leg spring constant is determined by the leg geometry as well as the properties of the muscle, tendon, and ligament network inside the leg [Farley & Ferris 1998]. The spring-like properties of the leg reduce the mechanical work that the muscles must perform [Roberts 1997]. This results in metabolic energy savings [Cavagna 1977].

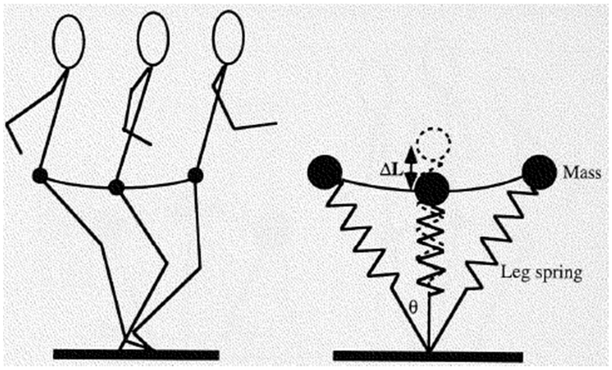

Figure 1. A graphic demonstration of running as a bouncing gait.

Similarly, the human foot and modern running shoes have elastic structural properties that may affect the rate of energy consumption during running at a particular speed, i.e. running economy. For example, the arch of the human foot stores and returns a substantial amount of elastic energy [Ker & Alexander 1987]. Shoes may provide elastic energy savings, but they also increase the energy cost of running due to the work required to move their mass. Frederick et al. [Frederick 1984] established that metabolic energy cost increases by approximately 1% for each 100 grams of mass added to each shoe. This “1% rule” was recently confirmed by Franz et al. [Franz 2012] for both shod and unshod running (Figure 2). Intriguingly, for equal total foot mass conditions, shod running was 3-4% less expensive. This begged the question, what was the key factor about shoes that reduced the energy cost of running? Frederick proposed the “cost of cushioning” hypothesis that stated that the unaccounted for savings was due to cushioning from the midsole, leading him to perform a follow-up study to investigate cushioning as a factor. That study investigated varying shoe midsole hardness but not thickness. Frederick et al. [Frederick 1983a] found that the cost of cushioning correlates with the kinematic adaptations, and adaptations correlated with midsole hardness, however, hardness did not correlate with oxygen cost.

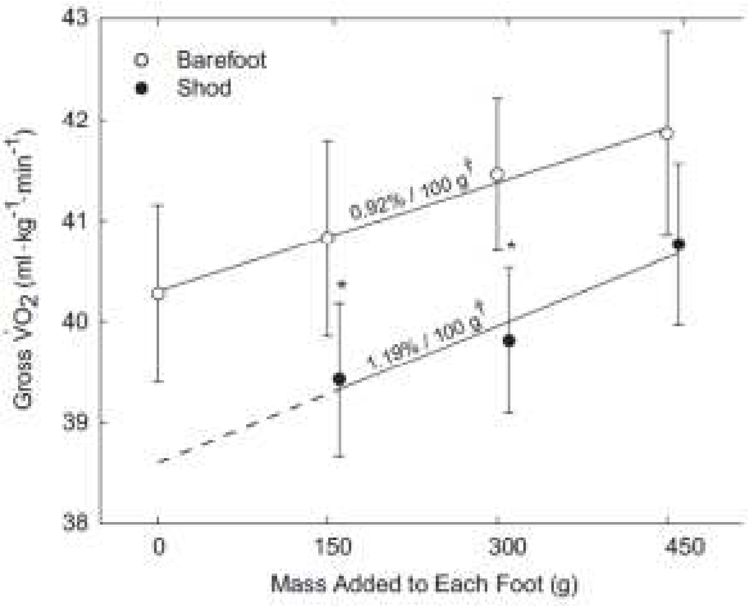

Figure 2. A comparison of barefoot and shod oxygen consumption as a function of mass [Franz, 2012].

Other studies have explored the biomechanics and energetics of running on compliant surfaces. McMahon et al [McMahon 1979] found that athletes ran faster times on an indoor track with a “tuned” compliance and attributed their faster times to the surface cushioning. However, they did not measure energy cost. Inspired by McMahon et al., Kerdok et al [Kerdok 2002] built a variable stiffness elastic surface into a treadmill and directly measured substantial energetic savings. They attributed the savings to the increased rebound from the compliant surface. Note that subjects in that study wore traditional running shoes. Thus, there are several lines of evidence that suggest shoe and/or surface cushioning can reduce the energetic cost of running.

In the present study, we isolated the variable of surface cushioning and quantified its effect on the energy cost of running. Similar to Kerdok et al., we altered the running surface compliance but used the same cushioning material composition found in the midsoles of most modern running shoes. Additionally, our subjects ran unshod on the cushioned surfaces. Finally, to understand the combined effects of shoe mass and shoe cushioning, subjects also ran in lightweight cushioned shoes on a rigid surface.

Our primary hypothesis was that metabolic cost of unshod running would decrease with a more cushioned surface. We also hypothesized that unshod running would have approximately the same metabolic cost as running with lightweight running shoes due to counteracting effects of cushioning and mass.

CHAPTER II

A TEST OF THE METABOLIC COST OF CUSHIONING HYPOTHESIS IN SHOD AND UNSHOD RUNNING

Methods

11 healthy runners (9M/2F, mean ± SD, age 30.2 ± 9.1 years, body mass 68.5 ± 6.5 kg and height 174.5 ± 5.9 cm) completed the study. These subjects were 30.22 ± 9.05 years old and reported running an average of 79.37 ± 60.49 km/week, of which, 59.46 ± 49.99 km/week (range: 11 to 177 km/week) were barefoot or in minimalist shoes. Subjects reported that their typical training-speed averaged 3.5 ± 0.6 m/s (range: 2.9-4.8 m/s). Our sample size was based on a preliminary power analysis calculation using G*Power statistical analysis software (http://www.psycho.uni-duesseldorf.de/aap/projects/gpower/). Additionally, Frederick et al. [Frederick 1983b] reported that with an expected coefficient of variation of 1.5-2% for repeated, within day measurements of oxygen uptake, a 1-2% difference between means could be resolved with a sample size range of 10-15 subjects. After being informed of the nature of the study, all subjects gave their written consent to participate as per the University of Colorado Institutional Review Board. The inclusion criteria were: over 18 years of age, mid-foot strike preference both shod and unshod, run a total of at least 25 km/week, of which, at least 8 km/week was barefoot or in minimal running footwear (e.g. Vibram Five Fingers) for at least 3 months, injury-free, self-reported ability to sustain 5 min/km (3.3 m/s) running pace for at least 60 minutes, and meeting the medical criteria of the American College of Sports Medicine for minimal risk for exercise [ACSM 2006]. Based on these reports, our inclusion criteria, and subject feedback, completing this experimental protocol was of low to moderate intensity and duration for all subjects.

In order to verify that the subjects preferred to run with a mid-foot strike pattern [Cavanagh 1980], we asked them run at their typical pace for a 10 km training run across a 30m runway equipped with a force platform (Advanced Mechanical Technology Inc., Watertown, MA) (to which a sheet of paper was affixed). We taped small pieces of marker pen felt to each subjects' right foot at 90, 70, and 33% of foot length (measured along the line between the heel and the distal end of the second toe). Force plate data were collected at 1000 Hz. Using the coordinate origin of the force platform, we tracked the center of pressure relative to the foot outline provided by the pen marks left on the paper as per Cavanagh and Lafortune [Cavanagh 1980]. We classified subjects as mid-foot strikers if the center of pressure at initial contact was between 33 and 70% of foot length and rear-foot strikers if the center of pressure started posterior to the 33% mark. We excluded one potential subject during this initial screening because of their rear-foot strike pattern preference while running unshod.

During a single experimental session, subjects completed a 5-minute standing trial, a 10-minute unshod running acclimation trial (with no surface cushioning), and four 5 minute running trials. A 3-minute rest period separated each of the running trials. In all running trials, subjects ran at a speed of 3.35 m/s on a Quinton 18-60 motorized treadmill that we modified to have a calibrated digital readout speed. Note that this treadmill has a rigid steel deck and a thin belt with no significant cushioning or damping properties. For the duration of the experiment, subjects wore very thin, slip-resistant yoga socks for traction and hygienic purposes.

In random order, subjects completed one shod (Nike Free 3.0; ~211 g/shoe) running condition on the normal treadmill belt surface and three unshod running trials: on the normal treadmill belt surface, with 10 mm thick slabs of cushioning attached to the belt and with 20 mm thick slabs of cushioning attached to the belt. The cushioning slabs consisted of the same material used in the midsole of the Nike Free running shoes (phylite, 60% phylon and 40% rubber with an Asker Type C durometer reading of 52-58). We sewed the slabs of phylite (length x width x thickness; 10 mm: 33.7 x 18.8 x 10 mm; 20 mm: 21.4 x 37.7 x 20 mm) to 2.5 cm wide nylon webbing. The loop part of the Velcro was then sewn to the webbing and the hook part of the Velcro was glued to the treadmill belt. Thus, the slabs of foam could be easily put in place and removed.

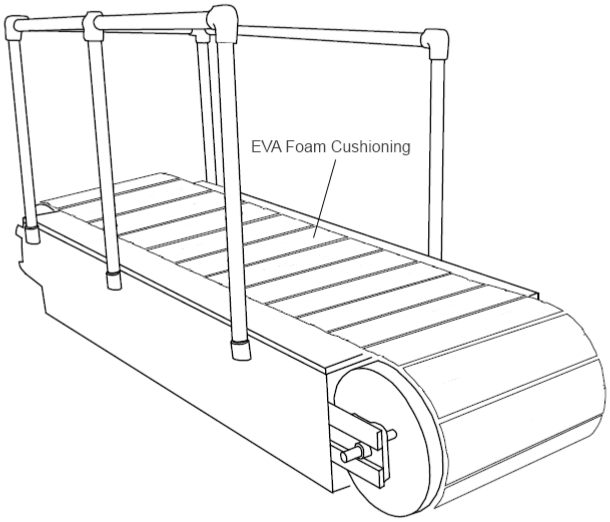

Figure 3. Experimental treadmill with foam cushioning attached.

During the running trials, we offered verbal instructions to each subject to maintain a mid-foot strike pattern whether barefoot or shod. Further, we confirmed foot strike throughout each trial visually as well as with high speed video recordings (Casio EX-FH20, 210 FPS). We did not control the stride frequency/stride length so as to compare "normal" unshod and shod running. The video recordings were also used to determine contact time and stride frequency.

During the standing and running trials, we used an open-circuit respirometry system (TrueOne 2400, Parvo Medics, Sandy, UT) to collect the subject's expired gases and calculate the STPD rates of oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$). Prior to each experiment, we calibrated the system using reference gases and a 3 L syringe. We averaged $\dot{V}O_2$, $\dot{V}CO_2$, and respiratory exchange ratios (RER) for the last 2 minutes of each trial. All subjects' RER values remained below 1.0. We report gross $\dot{V}O_2$ values in mlO2·kg^{-1}·min^{-1} but also the average standing value (mean ± s.d., 4.84 ± 0.39 mlO2·kg-1·min-1) to allow calculation of net $\dot{V}O_2$. We normalized using the subject's body mass while not wearing shoes. From $\dot{V}O_2$ and $\dot{V}CO_2$, we calculated gross metabolic power in W·kg^{-1} using the Brockway equation [Brockway 1987].

$$Power\ (W/kg) = 16.58 * \dot{V}O_2(ml\ \ O_2/kg/sec) + 4.51 * \dot{V}CO_2(ml\ \ CO_2/kg/sec)$$

Though Fletcher et al. [Fletcher 2009] recommended that metabolic power is a more representative expression of running economy than $\dot{V}O_2$ alone, we report both $\dot{V}O_2$ and metabolic power.

A repeated measures ANOVA tested for significant main effects of varied cushioning levels and of footwear (unshod vs. shod). We then used a Student's paired t-test between all unshod conditions. We used a criterion of $p<0.05$ for statistical significance.

Results

Treadmill cushioning significantly decreased the rates of oxygen consumption ($\dot{V}O_2$) as well as metabolic power ($p=0.004$). The average metabolic cost for unshod running was 1.83% cheaper on the 10 mm foam compared to the rigid surface ($p=0.027$) (Figure 4). The reduction in metabolic cost on the 20mm thick surface from unshod was not statistically different from unshod on the rigid surface (0.92%, $p=0.322$). On the rigid treadmill surface, metabolic power requirements for running unshod and in lightweight shoes were not significantly different (Mean ± SD, USH: 13.48 ± 1.32 W/kg, SH: 13.59 ± 1.20 W/kg; $p=0.35$). For more detailed condition versus condition statistical analysis, please see the table below (Table 1).

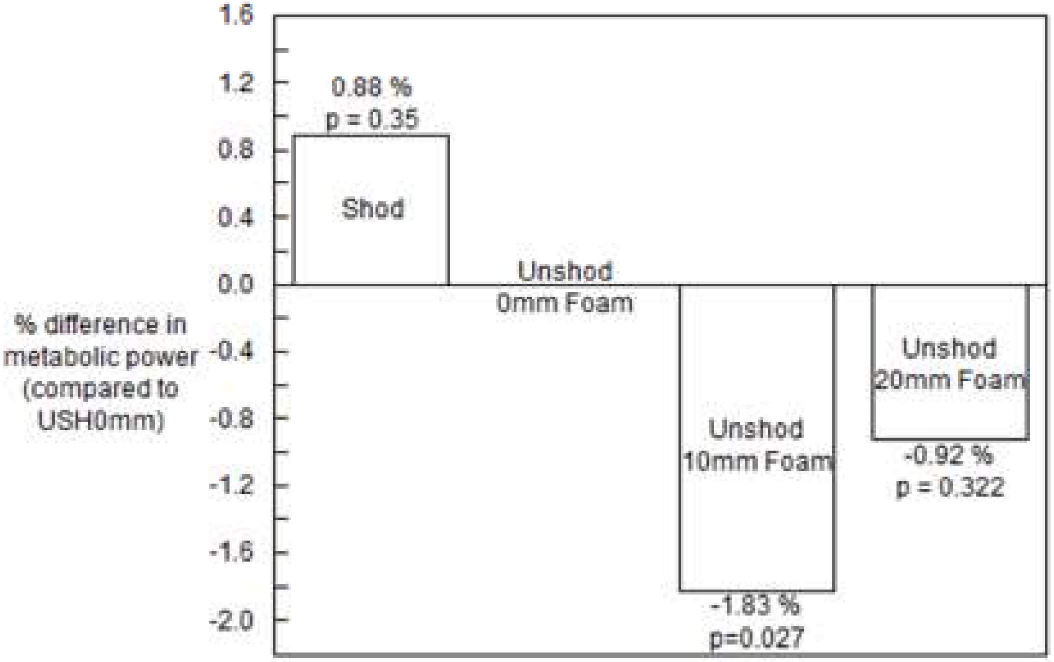

Figure 4. Graphical comparison of percent differences between the shod and unshod conditions.

Condition	Metabolic Power (W/kg)	Stride Frequency (Hz)	Contact Time (sec)
Unshod	13.48 ± 1.32	1.671 ± 0.14	0.238 ± 0.013
Unshod 10mm	13.23 ± 1.13	1.666 ± 0.129 (n.s.)	0.236 ± 0.016 (n.s.)
Unshod 20mm	13.35 ± 1.13	1.651 ± 0.136 (n.s.)	0.238 ± 0.015 (n.s.)
Shod	13.59 ± 1.20	*1.628 ± 0.124 (p=0.004)	#0.251 ± 0.015 p<0.005

*Table 1. Stride frequencies (Hz ± S.D.) and contact times (sec ± S.D.) for each test condition. * indicates significantly different from unshod on rigid surface. # indicates significantly different from all unshod conditions.*

Discussion

In this study, we quantified the effects of surface cushioning and shoes on the metabolic cost of running, controlling for foot-strike pattern, barefoot/minimalist running experience, and footwear. In our group of experienced mid-foot striking barefoot runners, 1) the metabolic cost of unshod running was reduced when subjects ran on the 10 mm cushioned surface, and 2) unshod running had the same metabolic cost as running with lightweight, cushioned running shoes.

To further clarify, hypothesis 1 stated that the metabolic cost of unshod running would decrease with a more cushioned surface. While the 10 mm cushioning did, in fact, have a lower metabolic cost than the hard treadmill surface alone (p=0.027), but the 20 mm cushioning condition was not statistically different from the 0 mm (p=0.322) or 10 mm (p=0.134) conditions; since the benefit of cushioning appears to diminish after a certain point, we strictly speaking must reject hypothesis 1.

Kerdok et al. [Kerdok 2002] found that the cost of running on an elastic compliant treadmill steadily decreased with greater compliance. However, we did not find that the metabolic cost of running further decreased with thicker cushioning. A possible explanation for this discrepancy is the fact that Kerdok's treadmill surface acted as a leaf spring, and therefore, provided greater energy return with increased compliance. In contrast, our cushioned treadmill used a material with significant damping. Hardin et al. [Hardin 2004] performed a study in which the effect of shoe sole hardness, surface hardness, and impact duration were tested on both the oxygen consumption rate as well as joint kinematics. The main relevant take away from that paper is that oxygen consumption actually increased for softer surfaces and decreased as harder surfaces were used. This is relevant but not analogous to our study in the sense that we did not vary hardness, but rather, the thickness of cushioning with a constant hardness.

Upon closer inspection of our data, it seems there may be a parabola like trend in the data across varied cushioning thickness (Figure 5). This would indicate that there may be an optimal cushioning thickness which would result in a minimal metabolic power. It should be noted that with an R squared value in the range of 0.1, this is an extremely poor approximation and the parabolic trend is only an assumption. Upon taking the derivative of the parabolic regression equation (y') and setting it equal to zero, we find the energetically optimal thickness (x) to be 11.47 mm. Since we only had three unshod conditions, a more accurate equation may exist with more levels of cushioning. When comparing the economy improvement between this equation and the 1% rule via Frederick et al. [Frederick 1984], we find that adding or subtracting a few millimeters of cushioning varies the mass very little, so we are able to use the optimal level of shoe cushioning identified by the cushioning equation, 11.47 mm. If one were to construct a cushioned "barefoot" running track using a material of hardness range 52-58 Asker C (the durometer reading for the treadmill cushioning material studied), it would ideally be made our previously defined 11.47 mm to minimize energetic cost. It should be noted, however, that according to our data, any greater cushioning thickness would actually diminish the energetic savings. This means, running shod on the track would actually be more energetically costly than running barefoot, not only due to the mass effect, but to the cushioning effect as well. Depending on the thickness of the shoe midsole, there is a possibility that running shod on the track would actually be more costly than running shod on hard ground.

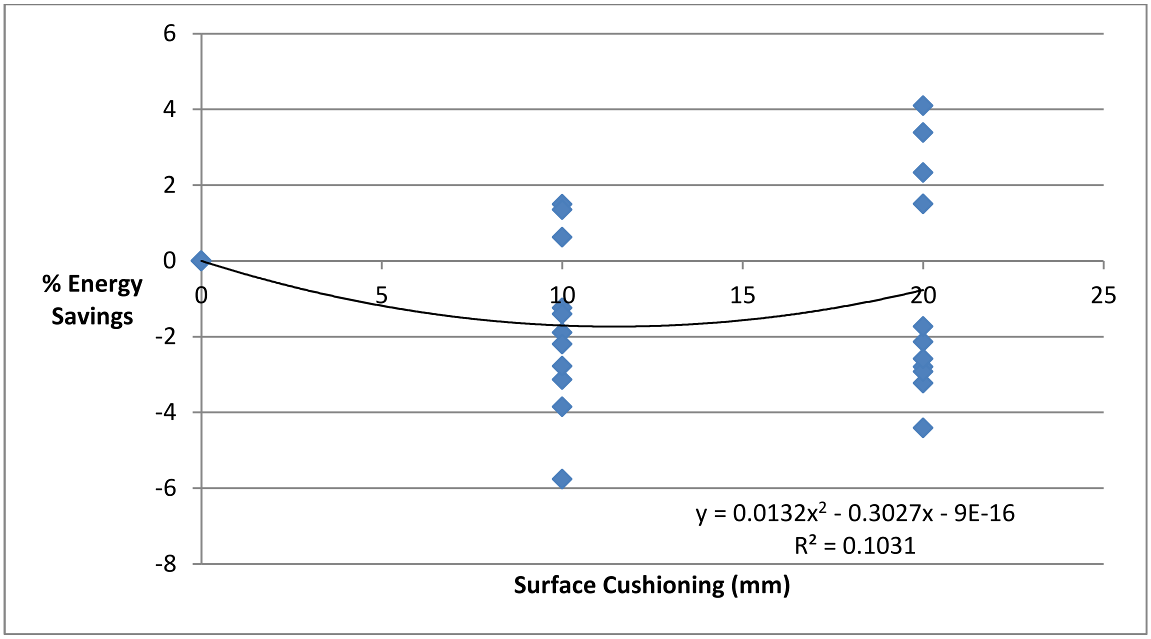

Figure 5. Curve fit of % energy savings as a function of surface cushioning thickness.

Hypothesis 2 stated that unshod running would have approximately the same metabolic cost as running with lightweight shoes due to counteracting effects of cushioning and mass. This was supported by our data so hypothesis 2 was accepted.

The previous study in this series by Franz et al. [Franz 2012] investigated the effects of mass on metabolic cost and metabolic power during shod and barefoot running. In accordance to findings from Frederick et al. [Frederick 1983a], it was found that for every 100g of mass added to a runner's foot, the rate of oxygen consumption would increase by 1%. Based on this "1% rule" alone, we would expect that running in 210g shoes to be 2.10% more expensive than barefoot running. However, according to our data, the energetic costs were statistically the same. 10 mm of foam cushioning (approximately the thickness of the forefoot shoe midsole) afforded an energetic savings of 1.83%. Thus, it appears that the positive effects of shoe cushioning counteract the negative effects of added mass, resulting in a metabolic cost for shod running approximately equal to that of barefoot running.

Based on the results of this study and Franz et al. [Franz 2012], we suggest that the optimal shoe would minimize mass while achieving a cushioning thickness of as close to 11.47 mm as possible. Nike has developed a new technology known as Flyknit in which the upper portion of the shoe is composed of a single piece of knit fabric (http://www.freshnessmag.com/2012/02/22/nike-fly-knit-a-closer-look/) that is then attached to the sole/midsole. This new shoe upper has a mass of a mere 34 grams. A sole of uniform thickness of the same surface area as the shoes that were tested in this study at the critical thickness would comprise 89.99 g of mass, resulting in a combined theoretical 0.94 % (0.89% cost increase due to the mass plus a 1.83% cost decrease) reduction in metabolic cost when compared to unshod running (calculation is based on density of midsole cushioning, which was found to be 2.68 x 10^{-4} kg/mm^3, as well as the 1% rule from Frederick et al.) [Frederick 1983a]. The hypothetical shoe could actually be lighter than this since the calculation assumes a uniform midsole without any traction/flexibility grooves.

Re-plotting the percent difference in metabolic power for each condition from the USH 0 mm condition per subject with respect to mass, each condition gives us approximately a parabolic curve, suggesting that there is an optimal range of mass of runners that benefit the most from this particular midsole material. It should be noted, however, that the R squared value is in the range of approximately 0.5, meaning it is far from a perfect fit, so the parabolic fit is once again just a speculation. Additionally, it should be noted that the blue markers represent the male subjects and the red markers represent the female subjects. Since we only had N=2 females, we are unable to draw a conclusion as to whether they follow the trend or not.

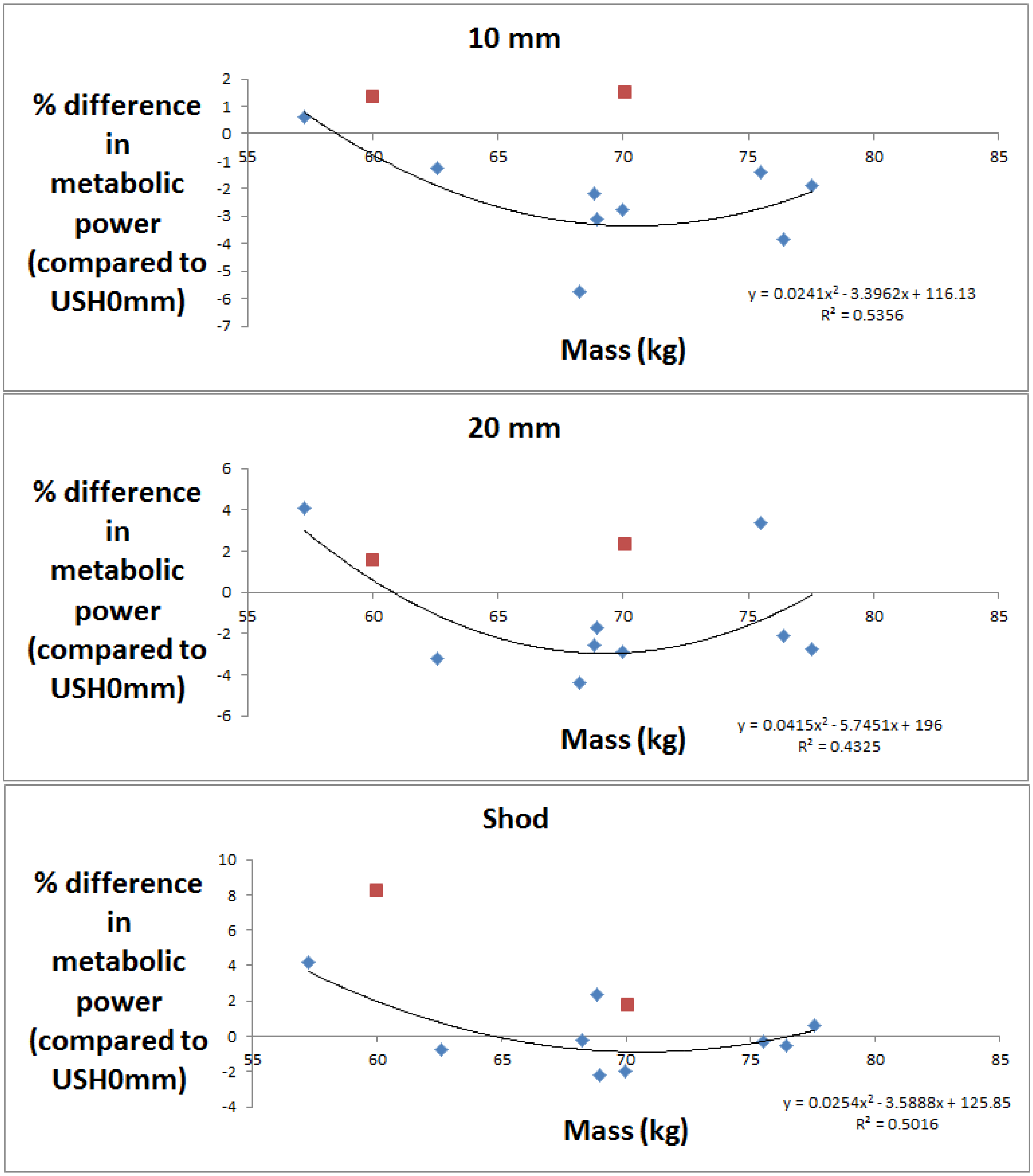

Figure 6. Percent difference in metabolic power from the USH 0 mm condition versus subject mass (kg) for each condition: a) USH 10 mm, b) USH 20 mm, and c) SH. Red markers represent female subjects while blue markers represent male subjects.

There were several limitations to this study. First, in order to maintain consistency between subjects, we utilized the same model of running shoes per subject; therefore, our findings may not translate to other running shoe models. Due to the demographics of volunteers, our subjects were predominately male. The most notable limitation of this study is the fact that we did not study more thicknesses of cushioning. If we had more experimental conditions (e.g. 5mm, 10mm, 15mm, 20mm, 25mm, etc…), we may have been able to derive a more accurate data trend and better identify an optimal thickness of cushioning at which runners have a minimum oxygen consumption value.

Future research on this topic should utilize more levels of cushioning. The varying levels of cushioning could be composed of the exact same type of foam utilized in this study. The aim of this would be to better identify the energetically optimal cushioning thickness that would minimize the metabolic demand on running. Alternatively, cushioning foam of various hardness values could be implemented in order to further test the effects of specific surface hardness on metabolic cost while keeping thickness constant.

Conclusion

In summary, we found that the addition of a modest amount of cushioning to the treadmill did, in fact, reduced the metabolic cost of running. Additionally, VO2 and metabolic power did not differ between the unshod and shod conditions on a hard surface. Finally, there seems to be an optimal amount of cushioning after which, the benefit of cushioning diminishes.

Conflict of Interest: Nike Inc. donated the cushioning and shoes used in this study; however, no funding was provided and Nike Inc. was not involved in the conception, planning, design or interpretation of the study.

CHAPTER III

LITERATURE REVIEW

Shoe Mass

Russell and Belding 1946

The first study performed to quantify the effects of shoe mass on the economy of locomotion. Subjects performed barefoot walking as well as shod in shoes ranging between 1.4 to 3.4 kg per pair. Shoe mass was found to drastically increase the cost of locomotion. Additionally, adding weight to a pouch carried at the waist was approximately 25% of the energetic cost as adding that same weight to the feet (in other words, adding weight to the feet affected energetic cost four times more than adding to the waist).

Catlin and Dressendorfer (1979)

This study compared the energy consumption rate of runners when wearing two models of shoes that had a difference of 350 grams per pair. It was found that the heavier shoe required an average of 3.3% more energy. It was concluded that the discrepancy was primarily due to the mass difference; however, it should be noted that shoe model was not controlled for and other factors may be affecting this energetic difference.

Frederick, Daniels Hayes 1984 (The effect of shoe weight on aerobic demands of running)

This study was performed as a follow-up to the Catlin and Dressendorfer (1979) study. In this study, two pairs of identical shoes were used where mass could be added. According to the results from this study, the Catlin and Dressendorfer study should have only produced an energetic difference of 1.8% rather than 3.3%. This indicates that over half of the increased energy demand was due to some other factor. It is through this study that the "1% rule" referenced later on originates from. The 1% rule states that for every 100g of mass added per foot to a runner, the oxygen consumption rate during running increases by approximately 1%.

Divert 2008

This study investigated the effects of both mass effects and shoe effects of the mechanics and oxygen consumption of running. Subjects ran on a 3-D treadmill ergometer (used to measure ground reaction forces during successive steps) at 3.61 m/s barefoot, in thin diving socks unloaded and loaded (loaded at 150g and 350g), and two shod conditions (150g and 350g). The results showed that there was a significant mass effect but no shoe effect. Leg kinematics; however, were altered when running in shoes. It was also found that runners had a lower net efficiency when running shod. The damping material seemed to take away from the runner's ability to store and release elastic energy, which could explain this.

Franz 2012

The goal of this study was to determine the effect of mass on metabolic economy during both barefoot and shod running. The barefoot setup consisted of a customized "barefoot" shoe (Figure 7) that allowed for the attachment of additional mass. Runners ran barefoot with the following amounts of mass attached to their feet: 0g, 150g, 300g, and 450g. The shod conditions consisted of runners in Nike Mayfly shoes (~150g) with no mass attached, with 150g (total 300g), and 300g (total 450g). A consistent increase in oxygen consumption was found with each increment of mass added (regardless of barefoot or shod). However, the shod conditions had a consistently lower metabolic cost than barefoot when equivalent mass was added; this leads to the question of how much of a role does cushioning play in improving running economy?

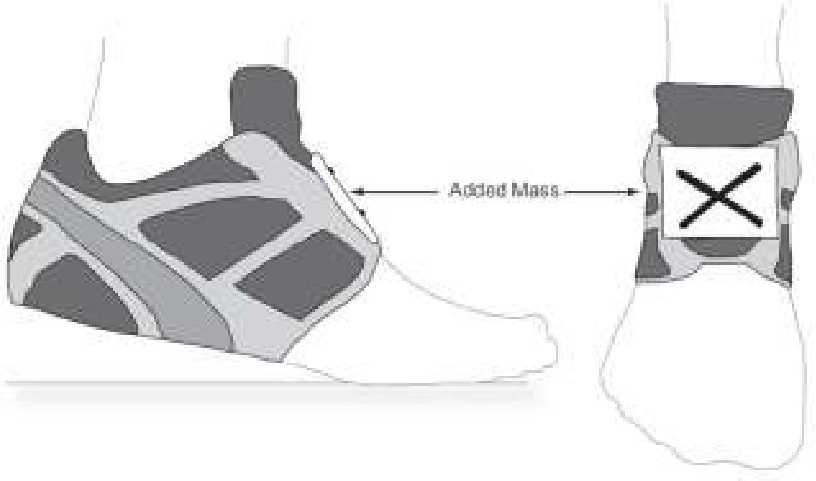

Figure 7. Franz barefoot with mass experimental setup.

Cushioning Effect

Frederick 1983 (The effects of shoe cushioning on oxygen demands of running)

In this study, 10 well-trained male subjects each ran in 5 identical shoes (with the exception of midsole composition) on a treadmill (3 sessions at 3.83 m/sec each) as well as one barefoot condition. It was found that the cost of cushioning correlates with the kinematic adaptations, and adaptations correlated with midsole hardness, however, hardness did not correlate with oxygen cost. (Please note that even though this study was published before Frederick 1984, it was performed after as a follow-up)

Nigg 2003

This study tested the effect of midsole material properties on muscle activation and oxygen consumption. It is important to note that the study focused on heel-toe running. The two pairs of identical shoes with the exception of the midsole composition were used. One was primarily elastic (shore C = 45) and the other was viscoelastic (shore C = 26). The changes in heel material did not yield any significant difference in oxygen consumption between conditions. However, the EMG results indicate that muscle activities before and after heel strike compose two different events. The authors speculate that EMG activities before heel strike are determined by the expected impact shock and are related to a "muscle tuning" activity; EMG activities after heel strike are more of a reflex event.

Hardin 2004

The purpose of this study was to investigate the influence of midsole hardness, surface stiffness, and running duration on running kinematics. For the applicable portion of the experiment, a custom pair of shoes was designed that allow the midsoles to be swapped out (midsoles of hardness 40 Shore A and 70 Shore A were utilized). Additionally, the hardness of the treadmill bed was varied by using a treadmill bed of surface stiffness 100, 200, and 350 kN*m. Some degree of damping was provided by the treadmill as well. According to the results, a stiffer sole surface resulted in a lower oxygen consumption rate. While it is important to keep this information in mind, it should also be noted that my thesis research does not deal with varying levels of compliance, but rather, varying thickness of cushioning of the same compliance.

Surface Effect

McMahon 1978

The purpose of this study was to determine the effect of varying track stiffness on the step length and ground contact time of distance runners through both a mathematical model as well as experimentation. From this research, the springy indoor track at Harvard University was developed; the track consisted of wooden boards mounted on support posts underneath. The compliance of the track was altered by moving the posts closer or farther from each other. Because this altered the compliance, it also altered the amount of energetic return due to spring properties of the material. It was concluded, both experimentally and mathematically, that there is a certain level of compliance that results in an equal or improved step length and ground contact time.

Kerdok 2002

The goal of this study was to relate human running biomechanics to energetics on surfaces of varying stiffness's. This was inspired by the McMahon 1978 study and, therefore, used a very similar setup. Rather than a track, a treadmill was customized so the bed (rigid component located under the belt) was replaced by the same post and plank setup as the Harvard track (as seen below). Once again, the compliance was varied by changing the positioning of the supporting posts (2 and 8). It was found that increased compliance significantly reduces metabolic cost while only slightly affecting limb kinematics. Additionally, it was found to be a unidirectional variance of metabolic cost with respect to surface compliance, which is contrary to what we would expect to find after looking at the results from McMahon 1978.

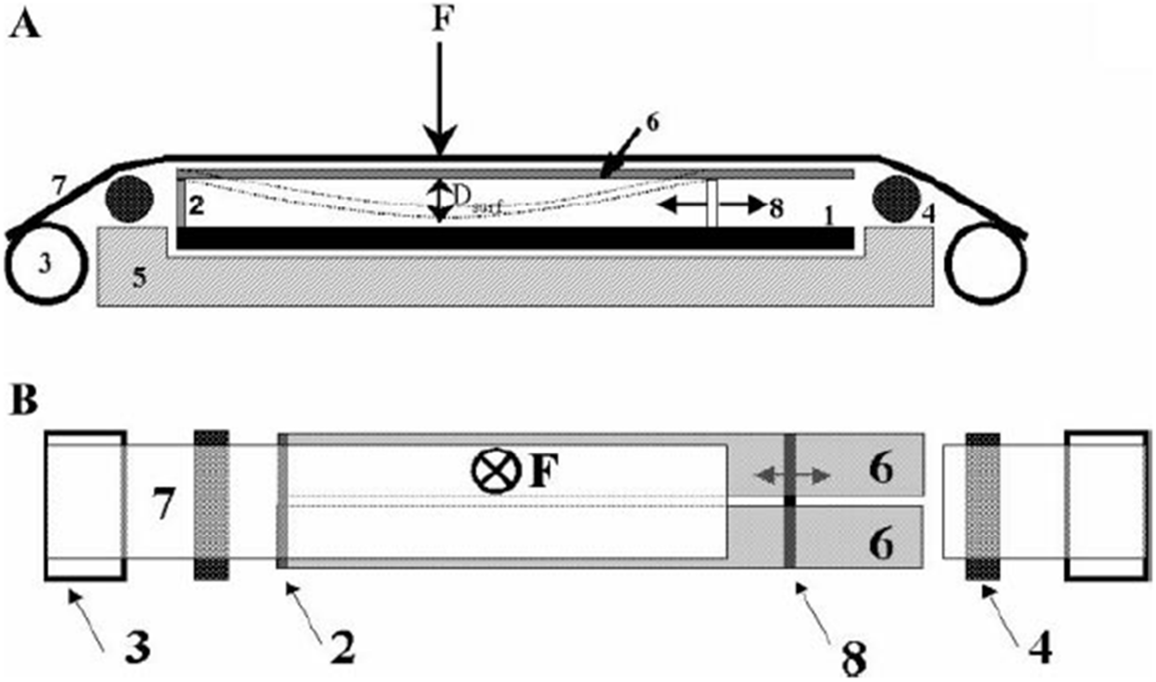

Figure 8. Kerdok treadmill setup.

Barefoot vs. Shod

DeWit 2000

Subjects ran across a force platform planted under a running track both shod and barefoot at three different speeds. Video data was collected for joint configuration and limb kinematics analysis. It was found that barefoot running results in a larger external loading rate and flatter foot placement at touchdown in barefoot running. There was a correlation ($p<0.05$) between a flatter foot placement and lower peak heel pressures. Therefore, it is assumed by the authors that runners adopt a flatter foot placement in barefoot running in order to limit the local pressure at the heel. Shorter step length and greater step frequency were primarily due to changes in touchdown geometry. An overall increase in leg stiffness during barefoot running was also observed. These adaptations carried through all three running velocity conditions. However, there was no uniform adaptation strategy for runners regarding rear foot kinematics.

Hanson 2011

The goal of this study was to determine whether barefoot or shod running is more efficient. In order to determine this, subjects took a VO_2max test in order to determine their peak velocity. After this, subjects were made to run at 70% of this peak velocity for both treadmill and over ground conditions (one barefoot and one shod for each). It was determined that in both the treadmill and over ground conditions, barefoot running was more efficient. Before considering these results to be valid, however, the following paragraph should be noted.

Divert 2008 was referenced, Hanson seems to have grossly misinterpreted the results or even the point of that paper in saying that the “350 g weighted socks and the 350 g shoe showed significantly higher VO 2 values than when the subjects were barefoot”. The point of Divert’s study was to determine the mass effect on both shod and barefoot conditions, meaning the diving socks were meant to represent barefoot running with additional mass. Furthermore, this study did not seem to control for the model of footwear (since no shoe model was mentioned, I am assuming this meant they just let the subjects run in whatever shoes they decided to wear that day).

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APPENDIX A

QUESTIONNAIRES AND COVER LETTERS TO SUBJECTS IN THE RESEARCH STUDY

Subject Screening Form

Biomechanics and Energetics of Cushioning During Running

Investigator: Rodger Kram, Integrative Physiology Dept.

Name (please print) : ____

Date of Birth: Day: _____ Month ______ Year _______Describe briefly your typical weekly physical exercise. Indicate approximate duration frequency and intensity. For example: " I run 5 miles, 3 times per week at 7 minute per mile." or "I walk to school every day, about a mile", or "no regular exercise".

____

____

____

____

____

Do you run barefoot?
Please circle one: Yes No
If yes, please specify for how long you have run barefoot, and the percentage of your total weekly mileage that is run barefoot:

____

____

____

Do you run in minimalist footwear, e.g. Vibram 5-finger shoes?
Please circle one: Yes No
If yes, please specify for how long you have run in minimalist footwear, and the percentage of your total weekly mileage that is run with that footwear:

____

____

____

To the best of your knowledge:

Are you in good general health?
Please circle one.

Yes No

If no, please specify any known problems:

____

____

____

Do you have any difficulty with walking, running or mobility in general?

Please circle: yes or no

If yes, please specify: ____

____

____

Do you have any problem with balance or dizziness?

Please circle: yes or no

If yes, please specify: ____

____

____

Have you ever experienced a serious musculoskeletal injury of your legs, feet or back?

Please circle: yes or no

If yes, please briefly describe the nature of the injury and approximate date.

____

____

____

Do you currently have lingering symptoms or pain related to that injury (injuries)?
Please circle: yes or no

If yes, please specify: ____

____

____

Have you ever experienced chest pain or shortness of breath with exertion?

Please circle: yes or no

If yes, please specify: ____

____

____

Do you have hypertension (high blood pressure)?

Please circle: yes or no

If yes, please specify: ____

____

____

Have you ever had a heart attack?

Please circle: yes or no

If yes, please specify: ____

____

____

Is there a history of heart attacks in your family?

Please circle: yes or no

If yes, please specify: ____

____

____

Do you have dyslipidemia (high cholesterol)?

Please circle: yes or no

If yes, please specify: ____

____

____

Do you smoke cigarettes?

Please circle: yes or no

If yes, please specify: ____

____

Do you have diabetes or prediabetes (high blood sugars)?

Please circle: yes or no

If yes, please specify: ____

____

____

Please sign your name: ____

Today's Date: _____________________

Biomechanics and Energetics of Cushioning During Running
Principal Investigator: Rodger Kram, Ph.D.
PARTICIPANT INFORMED CONSENT FORM
Revised 1/04/2011

Please read the following material that explains this research study. Signing this form will indicate that you have been informed about the study and that you want to participate. We want you to understand what you are being asked to do and what risks and benefits—if any—are associated with the study. This should help you decide whether or not you want to participate in the study. You are being asked to take part in a research project conducted by Prof. Rodger Kram, a faculty member in the University of Colorado at Boulder's Department of Integrative Physiology, 354 UCB, Boulder, CO 803090354.
Prof. Kram can be reached at (303) 4927984.

Project Description:
The purpose of this research study is to measure the biomechanics and energy cost of cushioning the lower limb during running. Biomechanics refers to the forces and motions involved in activities like walking or running. We are studying normal, healthy, physically active people.
You are being asked to be in this study because you are a healthy person older than 18 years of age. It is entirely your choice whether or not to participate in this study. Eventually, up to 40 people will be invited to participate in this research study.

Procedures:
If you agree to take part in this study, you will be asked to run at a comfortable speed under several conditions. You will be asked to run normally both with and without shoes at a submaximal speed on a standard treadmill and on a treadmill belt covered with a cushioned mat. You will also be asked to run while wearing small weights attached to your feet. Each run will last about 7 minutes and we will ask you to do 12 runs or less. You will rest for at least 3 minutes between runs. You can have more rest time if you need it.
While you run, we will measure the rate at which you consume oxygen by analyzing the air that you breathe out. This will involve wearing a mouthpiece and nose clip. We will record the electrical activity of your muscles using electrodes placed on your skin (electromyography, or EMG). To attach the electrodes, we will first shave your skin, if necessary, clean it with alcohol, and rub a small area lightly with sandpaper. The electrodes are attached with an adhesive gel. We will measure the forces that you exert on the ground, and we may attach small reflective balls to your skin so that we can record your leg movements. We no longer use video tapes and only the motions of the reflective markers are saved in the computer files. We will ask you your age and measure your leg length and weight.
Participating should take no more than two hours of your time on up to two separate days. The study will take place at the Locomotion Laboratory, Room 111C Clare Small Building at times arranged to be convenient for you.
4/19/2011 - 4/18/2012

If you complete the study, you will be offered the opportunity to do a VO2max performance test. If you want to do this test, it will be scheduled for a different day from the study procedures described above. This test measures the maximum capacity of your body to transport and use oxygen during intense exercise. You will run on a treadmill at your 10K pace for about two minutes. The treadmill incline will be increased 1% each minute until you tell us that you cannot run anymore or would like to stop the test. You do not have to do this test to be in the research study. The results of this test will not be used for our research.

Risks and Discomforts:

There are some potential risks if you take part in this study. The potential risks associated with this study are similar to those involved in recreational athletics or working out in a gym. None of the procedures should cause discomfort. However, if you do experience any discomfort, you may terminate the experiments at any time. Due to the adhesive, you may experience mild skin irritation when we remove the electrodes. This possible irritation would be similar to that experienced after removing a bandaid.

There is a risk of falling from the treadmill and injuring yourself. To minimize this risk, you will be instructed in proper safety procedures before the treadmill is turned on. It is very important to always grab the handrails when the treadmill is starting or stopping. You may feel some mild muscle discomfort or fatigue in your legs for a few days after participating in this study.

If you decide to do a VO2max performance test after you have completed the main study, you should know that the test also has risks. The test can cause fatigue and minor discomfort. About 1 in 100 people will have an irregular heart beat during the VO2max test. About 4 in 10,000 people have chest pain or a heart attack and 1 in 10,000 people die during a VO2max test.

Benefits:

The benefits of being in this study are also similar to those gained from recreational athletics. For example, you will get some modest exercise as part of being a subject. Otherwise, there are no direct benefits to you from taking part in this study. Your participation in this study will help us to discover basic information about how we walk and run which may be used to guide medical treatment of others.

Source of Funding:

Funding for this study is being provided by an individual grant from the Undergraduate Research Opportunities Program at the University of Colorado.

Cost to Participant:

There is no cost to you for participating in this study.

Subject Payment:

You will not be paid for participation in this study.

If You Are Injured or Harmed:

If you feel that you may have been harmed while participating in this study, you should inform Prof. Kram at (303) 4927984
immediately. The cost for any treatment will be billed to you or

your medical or hospital insurance. The University of Colorado at Boulder has no funds set aside for the payment of health care expenses for this study.

If you experience injury that requires medical attention, contact the investigator, Prof. Kram
(303) 4927984
and your personal physician immediately (if it is a medical emergency, first call
911).

Ending Your Participation:

You have the right to withdraw your consent or stop participating at any time. You have the right to refuse to answer any question(s) or refuse to participate in any procedure for any reason. Refusing to participate in this study will not result in any penalty or loss of benefits to which you are otherwise entitled

Confidentiality:

We will make every effort to maintain the privacy of your data. Your individual privacy will be maintained in all published and written data resulting from this study. You will be assigned a random number/letter code and all data will be kept only according to that code. Prof. Kram will keep the code that links to your name in a separate location from the data files. If individual data are to be published, your data would only be referred to by the number/letter code. Data will be kept in Prof. Kram's locked office for 10 years following the end of the study.

Other than the research team, only regulatory agencies such as the Office of Human Research Protections, the University of Colorado Institutional Review Board may see your individual data as part of routine audits.

Questions?

If you have questions about this study, you should ask the investigator before you sign this consent form. If you have questions or concerns during or after your participation, please contact Prof. Rodger Kram at (303) 4927984.

If you have questions regarding your rights as a participant, any concerns regarding this project or any dissatisfaction with any aspect of this study, you may report them confidentially,
if you
wish to
the Executive Secretary, Institutional Review Board, ARCE Room A15, 3100 Marine
St., University of Colorado at Boulder, Boulder, CO 803090563
or by telephone to (303) 7353702.

Authorization:

I have read this paper about the study or it was read to me. I know the possible risks and benefits. I know that being in this study is voluntary. I choose to be in this study. I know that I can withdraw at any time. I have received, on the date signed, a copy of this document containing 4 pages.

Name of Participant (printed) ____
Signature of Participant ____________________________ Date ______________.
(Also initial all previous pages of the consent form.

4 of 4 initials ______

APPENDIX B

STATISTICAL ANALYSIS OUTPUT

Statistical comparison of metabolic power across test conditions

1 = 0 mm

2 = 10 mm

3 = 20 mm

4 = shod

Metabolic Power Pairwise Comparisons

Measure:MEASURE_1

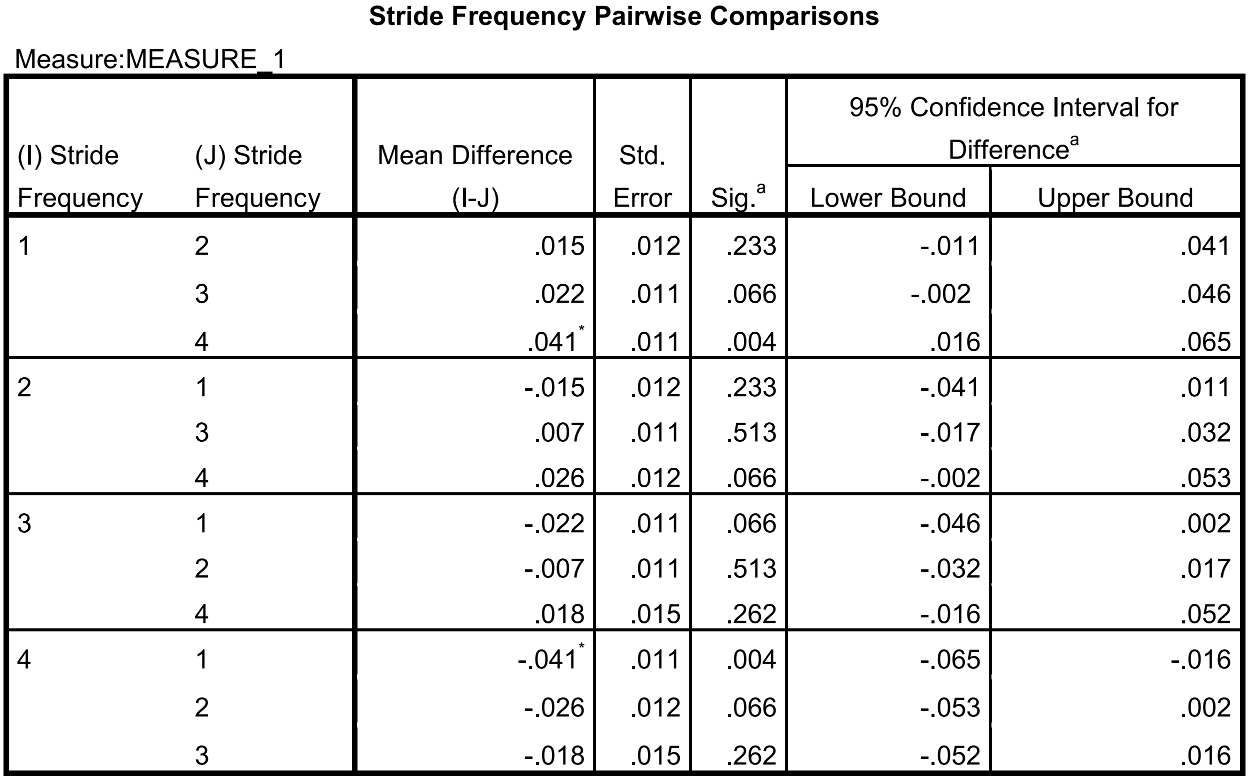
(I) MetPwr	(J) MetPwr	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.246*	.095	.027	.035	.457
	3	.124	.119	.322	-.141	.388
	4	-.119	.122	.351	-.392	.153
2	1	-.246*	.095	.027	-.457	-.035
	3	-.123	.075	.134	-.290	.045
	4	-.366*	.091	.002	-.569	-.163
3	1	-.124	.119	.322	-.388	.141
	2	.123	.075	.134	-.045	.290
	4	-.243	.115	.062	-.500	.014
4	1	.119	.122	.351	-.153	.392
	2	.366*	.091	.002	.163	.569
	3	.243	.115	.062	-.014	.500

Based on estimated marginal means

*. The mean difference is significant at the .05 level.

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

Statistical comparison of stride frequencies and contact times across conditions.



Stride Frequency Pairwise Comparisons

Measure:MEASURE_1

(I) Stride Frequency	(J) Stride Frequency	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.015	.012	.233	-.011	.041
	3	.022	.011	.066	-.002	.046
	4	.041[*]	.011	.004	.016	.065
2	1	-.015	.012	.233	-.041	.011
	3	.007	.011	.513	-.017	.032
	4	.026	.012	.066	-.002	.053
3	1	-.022	.011	.066	-.046	.002
	2	-.007	.011	.513	-.032	.017
	4	.018	.015	.262	-.016	.052
4	1	-.041[*]	.011	.004	-.065	-.016
	2	-.026	.012	.066	-.053	.002
	3	-.018	.015	.262	-.052	.016

Contact Time Pairwise Comparisons

Measure:MEASURE_1

(I) StanceTime	(J) StanceTime	Mean Difference (I-J)	Std. Error	Sig.[a]	95% Confidence Interval for Difference[a]	
					Lower Bound	Upper Bound
1	2	.002	.002	.403	-.003	.006
	3	2.597E-5	.002	.988	-.004	.004
	4	-.013[*]	.003	.001	-.019	-.007
2	1	-.002	.002	.403	-.006	.003
	3	-.002	.002	.461	-.006	.003
	4	-.015[*]	.002	.000	-.020	-.009
3	1	-2.597E-5	.002	.988	-.004	.004
	2	.002	.002	.461	-.003	.006
	4	-.013[*]	.004	.005	-.021	-.005
4	1	.013[*]	.003	.001	.007	.019
	2	.015[*]	.002	.000	.009	.020
	3	.013[*]	.004	.005	.005	.021

Based on estimated marginal means

a. Adjustment for multiple comparisons: Least Significant Difference (equivalent to no adjustments).

*. The mean difference is significant at the .05 level.