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Metabolic responses of running shod and barefoot in mid-forefoot runners

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Background. **The purposes of this study were to compare the oxygen cost, metabolic parameters and temporalspatial variables between barefoot and shod running in trained mid-forefoot runners.**

Methods. **Experienced runners (N.=21; 30±10.9 years; 16 men) performed two separate 20 minute treadmill running bouts at ~77% of estimated maximal heart rate. Rate of oxygen consumption (VO_2), energy cost, fuel use and heart rate (HR) were collected continuously using a portable gas analyzer. Three-dimensional motion capture was used to measure temporalspatial parameters.**

Results. **Participants ran at a mean self-selected speed of 3.1±0.3 m/s for both conditions, at intensities corresponding to mean HR values of 146 bpm (shod) and 144 bpm (barefoot). Steady State VO_2 was not different between the shod and barefoot conditions (39.4± 4.7 mL/kg*min *vs.* 40±5.2 mL/kg*min, respectively). The total energy expended in the shod and barefoot conditions was 974±134 kJ and 979±142 kJ. The average non-protein respiratory exchange ratios, proportions and amount of fat and carbohydrate used were not different between conditions. Cadence was 2.5% higher and center of gravity vertical displacement was 0.5 cm less for the barefoot condition (P<0.05).**

Conclusion. **In trained mid-forefoot runners experienced with barefoot running, there are not significant metabolic differences between shod and barefoot running conditions. Barefoot running increases cadence and decreases foot contact time and vertical displacement. Experienced participants were likely able to titrate kinematics to standardize energy output and fuel use for a given running distance and speed irrespective of shoe wear.**

KEY WORDS: Running - Oxygen - Shoes.

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A recent surge in the popularity of minimalist and barefoot running has been founded on the concept that there is the potential for making improvement in running economy compared to wearing cushioned shoes,[1] and for decreasing the risk of injury.[2] The study of barefoot running is challenging, because several factors may influence metabolic parameters other than the presence of shoes.[1] What is known is that running barefoot is related to shorter stride length and increased cadence,[3, 4] both of which may help to minimize vertical excursion and decrease ground reaction force.[5] Minimizing cyclical vertical displacement and braking forces may help reduce energy waste, reduce heart rates and oxygen use and make barefoot running more economical compared to shod running. These factors may impact the fuels used during the running in different shoe wear conditions.

Several studies have attempted to address oxygen use and energy cost differences between barefoot and shod running, with mixed results. Equivocal results may be due to the lack of control with shoe types used during testing,[6] a foot strike pattern switch from heel striking to mid-forefoot striking during the testing without shoes,[7] and differential or no experience with minimalist shoes or barefoot running.[8, 9] Hence, additional studies in homogenous, trained runners with a mid-forefoot strike and barefoot running is warranted to improve the chance of detecting metabolic differences between conditions if any exist. Previous studies have evaluated the effect of footwear on metabolic activity, however none have controlled for foot strike pattern in the subjects tested. In general, when running without shoes, rear foot runners will naturally adopt a more mid-forefoot footstrike pattern. Changing footstrike pattern can have a significant impact on metabolic and biomechanical parameters that can confound the interpretation of the effect of footwear. A rigorous study in a homogeneous set of experienced runners with a common mid-forefoot strike and barefoot running exposure would provide directly comparable metabolic data between shod and barefoot conditions. Concomitant temporalspatial measures would also demonstrate the natural selection of running patterns adopted by these runners with or without shoes, and demonstrate whether these experienced runners are able to maintain similar metabolic responses with or without shoes.

Running economy (the oxygen consumption per submaximal workload) [10] is a meaningful assessment of endurance ability and running performance.[11] The rates of oxygen use and carbon dioxide production per given workload has implications for conservation of stored energy and prolonged time to fatigue. For example, greater reliance on fat oxidation for energy production during running may help minimize the risk for premature fatigue due to glycogen depletion. Recent studies have compared oxygen use and metabolic cost using mean O_2 consumption values for short running bouts (~4-7 min per condition).[1, 4] These studies indicate that a 'steady state' of O_2 use was achieved within 3-5 minutes of running. The performance value of oxygen cost savings and efficient use of fats becomes more important with longer duration running. Specifically, there is the potential that in bouts of running lasting longer than five minutes, differences in fuel use patterns or oxygen cost may manifest between shod and barefoot conditions. To our knowledge, a comprehensive oxygen cost and fuel use comparison has not yet been performed in runs longer than a few minutes. Decreasing the caloric expense of running, improving the use of fat as fuel and minimizing the impact force have collective implications on running performance.[9] Higher dependence on fat compared to carbohydrate and reduction of braking forces might prevent premature muscle fatigue. Both factors may help prevent fatigue-related changes in kinematics and kinetics [12] that could potentially contribute to lower performance times and injury.

The purpose of this study was to expand our current understanding of barefoot running relative to shod running by assessing oxygen cost, fuel utilization, temporalspatial and kinematic variables in an experienced group of mid-forefoot runners. Based on the anticipated adoption of temporalspatial changes in running barefoot, coupled with transporting less weight without shoes, we hypothesized that participants would: have a lower rate of oxygen consumption, have a greater reliance on fat as fuel, have lower heart rates, and demonstrate higher cadence in the barefoot condition compared with the shod condition.

Materials and methods

Study design

This repeated-measures, crossover study design compared two different conditions: treadmill running barefoot and treadmill running shod. Participants were randomly assigned to condition testing order. This study and its procedures were approved by the University of Florida Institutional Review Board and it complies with the guidelines of Declaration of Helsinki for the treatment of human subjects.

Participants

Trained runners (N.=21) were recruited using study flyers, web based advertisements and the clinical trials register. Inclusion criteria included men and women ages 18-60 years old, must have run in cushioned running shoes at least once per week and have had experience with barefoot running. All subjects ran a minimum of 32 km per week within the past six months with an established mid to forefoot running style. All participants completed a verification test for foot striking using a GaitMat® device and high speed filming on a treadmill. Exclusion criteria included any lower extremity injuries in the last six months, a heel striking running pattern, presence of any open wound or deformity, or neurologic injury that would preclude normal running activity. All participants read and signed an informed consent form approved by the university's Institutional Review Board after having the testing procedure. A health history and medical history form was completed for self-reporting of demographics, comorbidities, previous injuries, running experience and foot strike.

Sample size determination

Based on a previous study that determined the power to detect differences in oxygen cost if present (20 participants to detect significant differences),[1] the target enrollment in the present study was 22 men and women to account for potential drop-outs.

Shoe wear

Participants ran in their regular running shoes. To protect runners from skin abrasions from the treadmill belt and soreness during barefoot running,[13] a minimal layer of protective tape was placed without tension to the ball of the feet and toes. The study team performed comparative pilot tests where runners wore tape on these areas and no tape and ran on the treadmill for five minutes. High speed filming and analysis revealed no changes in running form between the taped and no-tape conditions, weight of the tape averaged 31 g per foot. During both testing sessions (barefoot vs. shod) all conditions (pace, marker placement, clothing) remained the same except for the presence of shoe wear. Shoe weight was determined from the manufacturer, and confirmed by weighing in the laboratory.

Study schedule

Participants were scheduled for a total of three visits. During the first visit participants went through the verification process in order to confirm a mid-forefoot running style. Once the running style was confirmed, the participant was then given an envelope stating the testing order beginning with either barefoot or shod condition. During the second visit the participants began testing in order of randomization. The third visit was scheduled a minimum of 48 hours and a maximum of one week apart from the second visit. Participants were scheduled around the same time of day after an overnight fast prior to testing.

Body composition

To characterize the participants, body composition measures were collected during visit three using air plethysmography. Air plethysmography (using the BOD POD®; Life Measurement Inc., Concord, CA, USA) is a reliable technique of body volume and composition, and is highly correlated to the gold standard of underwater weighing.[14]

Metabolic assessment

To determine whether there was a difference in oxygen cost between the two conditions, metabolic assessments were captured during each running session using a portable oxygen consumption (VO_2) device (COSMed, K4b²; Rome, Italy). The K4b² unit acquired a breath-by-breath measurement of gas exchange via a rubberized facemask and a turbine for gas collection. Prior to testing, the K4b² unit was warmed-up for a minimum of 30 minutes. After the warm-up period, the O_2 and CO_2 analyzers were calibrated using reference gases of known concentrations. Participants wore the K4b² unit continuously during a five minute pre-exercise baseline period, during the three minute treadmill warm-up, during the 20 minute running sessions and during the cool down. To ensure an adequate seal of the facemask during running, the study team used gel seals around the mask edge and cotton on the inside of the mask to secure the seal to the skin. Seals were tested before data collection by having the runner exhale hard while the tester blocked the front of the mask to detect if air leakage occurred.

The steady state VO_2 was determined by averaging the breath by breath values over the period of 3 minutes to 20 minutes. The overall oxygen use was calculated as the area under the curve (AUC) for the stable time period of minutes 3-20 during the running session. The AUC was chosen to permit capture of the overall oxygen consumption response and potential minor fluctuations rather than an average over time. The self-selected running speed represented a typical long distance training run pace. Because oxygen consumption does not increase linearly with body mass,[11] the VO_2 values were also allometrically scaled to prevent errors from occurring in metabolic calculations in persons with higher body weight. VO_2 values were raised to a recommended exponent of 0.75.[15] In addition to the VO_2 values, minute ventilation and non-protein respiratory exchange ratio values were collected. Heart rate (HR) was obtained continuously in parallel with the K4b[2] assessments with the use of an integrated telemetric heart rate monitor worn on the chest of the participant. All variables were captured continuously throughout testing and were averaged at 30 second intervals. The AUC values were determined from these intervals. The metabolic variables were captured from minutes 3, 12 and 19 to represent the initial stabilization of submaximal VO_2 values, at mid-point of the run and at the end of the run. The energy expenditure per step and the energy cost per unit distance were calculated as: energy expenditure per step = average rate of energy expended per min/steps per minute and energy cost per unit distance = average rate of energy expended per min/ (step length*cadence).

Temporalspatial variables and ground reaction forces

We determined whether or not any temporalspatial parameters from each running session could modulate metabolic responses. Temporalspatial parameters were evaluated using a three-dimensional high speed motion analysis system (Motion Analysis Corp, Santa Rosa, CA while participants ran on a treadmill. Surface mounted retroreflective markers were attached using a Helen Hayes marker configuration.[16] Kinematic data were collected at a rate of 200 Hz, and marker data were filtered using a low-pass filter (6 Hz). Kinematic data were processed using the Visual3D software package (C-motion, Inc., Germantown, MD, USA). Temporalspatial variables included cadence, step length, swing and stance times, stride width, and center of gravity displacement. After completing the treadmill run, participants ran overground on two force plates to obtain ground reaction force data (GRF; AMTI, Watertown, MA, USA). Participants ran over the plates until a total of three good trials for the right and left foot were obtained. Force data were averaged from the three trials and were normalized to the participants' body weight for further analysis. The peak GRF was identified as the highest force obtained during the stance phase of each foot. The time to peak GRF was calculated from the time at initial foot contact to the time when the peak GRF was obtained.

Statistical analysis

Statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS; v. 20.0). Data were managed using REDCap (Research Electronic Data Capture).[17] Descriptive statistics and frequencies were obtained to characterize the study group. Repeated measures analyses of variance (ANOVA) were performed to determine whether differences existed between conditions for the metabolic and biomechanical variables with shoe wear as the condition (shod, barefoot). Pearson correlations were performed on the steady state VO_2 and AUC VO_2 values. To determine whether there were differences in variables at time points during the running session, repeated measures ANOVAs were performed on the metabolic and biomechanical variables, where time point was the independent variable (min 3, min 12, min 19). Secondary hierarchical regression analyses were conducted to determine the contribution of the variance on metabolic and biomechanical variables use by shoe weight and heel drop on AUC VO_2 values. Body weight and age were added to the models first, followed by shoe weight or heel drop. Hierarchical regressions were also performed to determine the contribution of temporalspatial parameters on steady energy expenditure in each condition. Significance was established at $P<0.05$ for all statistical tests.

TABLE I.—*Participant characteristics. Values are means±SD or percent of the group.*

Age (yrs)	30±10.9
Men (%)	81.8
Height (cm)	173±7
Weight (kg)	68.6±10.9
Body fat (%)	15.6±5.1
Body mass index (kg/m²)	22.6±2.4
Caucasian (%)	90.9
Average weekly distance (km)	53.5±14.6
History running (yrs)	11.7±10.6
History of running mid-forefoot (yrs)	5.5±0.6
Shoe weight (g)	240±62.3
Shoe heel drop (mm)	5.7±3

TABLE II.—*Exercise responses during shod and barefoot conditions. Values are means±SD.*

	Shod	Barefoot
Running speed (m/min)	185±20	185±20
Rest HR (bpm)	69±11	68±10
Average exercise HR (bpm)	146±15	144±15
% Max HR	77.2±5.7	75.6±5.9
Rest np RER	0.81±0.07	0.80±0.07
Average np RER	0.89±0.07	0.88±0.07
Fat used (g)	22.7±15.6	20.9±14.2
Carbohydrate used (g)	65.2±24.2	66.3±21.3
Steady State VO_2 (mL/kg*min)	39.4±4.7	40.0±5.2
VO_2 (AUC; mL/kg*min)	1416±203	1415±222
VO_2 (AUC mL/kg*min$^{-.75}$)	230±25	230±27
Energy expended (kJ)	975±134	979±142
Rate of energy expenditure (kJ/kg*min)	0.84±0.08	0.85±0.08

Run time: 17 minutes after 3 minute warm up (steady state); np: non-protein; RER: respiratory exchange ratio; AUC: area under the curve.

Results

Participant characteristics

Characteristics of the study group are shown in Table I. Participants had considerable experience with running and using the mid-forefoot running style. None of the participants reported recent injuries or joint pain that interfered with normal gait. Average shoe weight was 240±62.3 g with an average shoe heel drop of 5.7±3 mm.

Cardiac and metabolic responses

The metabolic responses obtained from the two running conditions are shown in Table II and Figures 1 and 2. The average resting and exercise HR were not different between conditions. Neither the amount of fat and carbohydrates used nor the proportions of fat and carbohydrates used during the 20 minute tests were different between conditions, and this resulted in similar non-protein RER values in barefoot and shod conditions. Correlations between shod and barefoot steady state VO_2 values and AUC values were r=0.80 and r=0.7 (both $P<0.0001$). Overall oxygen use (AUC) irrespective of expression and caloric expenditure was not found to be different by running condition, nor by time interval (Figure 2). Because no differences were detected in average metabolic values, we examined whether or not there were condition effects based on time point during the run (minutes 3, 12 and 19). There were no differences between conditions over time for any metabolic variable. Body weight and age-adjusted

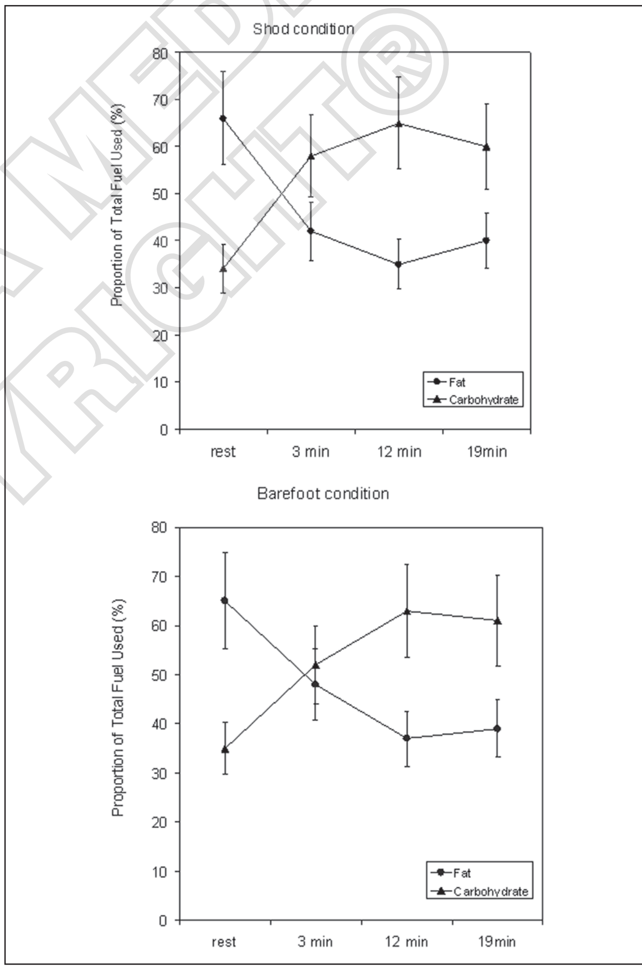

Figure 1.—A) Proportions of fuel use during a session of shod running; B) and during barefoot running. Values are based on non-protein RQ values and are means± SD.

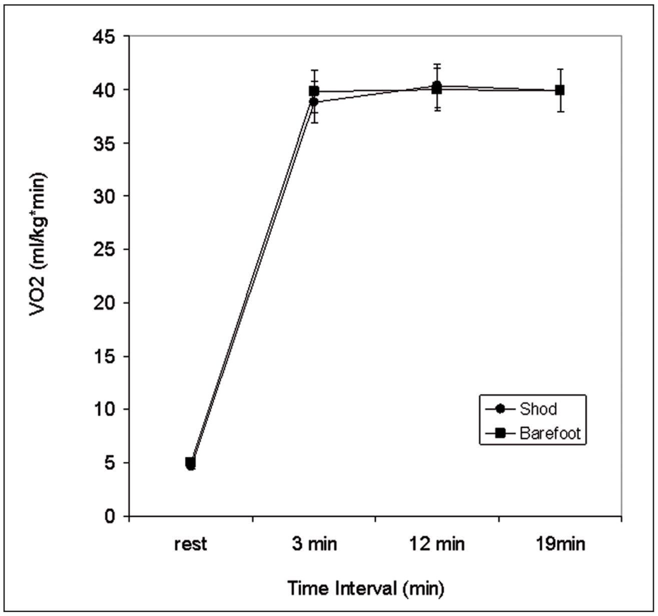

Figure 2.—VO_2 values during a session of shod running and during barefoot running. Values are means± SD.

regression models revealed that the contributions of shoe weight or heel drop to models of VO_2 AUC in barefoot and shod conditions were not significant (R^2 change values ranged from 0.001 to 0.070).

Temporalspatial variables and ground reaction forces

The motion capture analysis revealed that cadence was an average of 5 steps/min higher during barefoot running ($P<0.05$; Table III). Running speed was held constant between conditions, therefore we would expect that increased cadence would indicate a commensurate decrease in step length. Step length was slightly reduced during barefoot running, but because of variability, this change was not statistically significant. Stride width was significantly narrower during barefoot running compared to shod running. Stance time was significantly shorter during barefoot running compared to shod running, however there was no difference in swing time. Therefore, the increase in cadence can be attributed to decreased foot contact time. Peak impact force values were higher during the shod condition by approximately 3% ($P<0.05$), but the time to peak force development was not different based on running condition.

Regression analysis: contributors to rate of energy expenditure

Hierarchical regression models for the rate of energy expenditure at steady state are shown in Table IV for shod and barefoot conditions. After adding body weight into the models, specific temporalspatial parameters were added. For both barefoot and shod conditions, the step length was a significant contributor to variance about the rate of energy expenditure ($P<0.05$). While small differences in cadence and stance time were detected between conditions, neither variable contributed significantly to the rate of energy expenditure.

Discussion

This study examined whether barefoot running compared to shod running in experienced mid-forefoot strikers elicited a lower oxygen cost, different fuel utilization profiles and changes to temporalspatial gait parameters. The barefoot and shod condi-

Table III.—*Select temporalspatial parameters and ground reaction forces (GRF) of running shod and barefoot in mid-forefoot runners. Values are means±SD.*

	Shod	Barefoot
Cadence (steps/min)	170.8±10.8	175.6±12.4 *
Step length (m)	1.04±0.09 (L) 1.04±0.11 (R)	1.03±0.09 (L) 1.03±0.09 (R)
Stance time (% gait cycle)	0.32±0.04 (L) 0.32±0.03 (R)	0.29±0.06 (L) * 0.30±0.04 (R) *
Swing time (% of gait cycle)	0.38±0.04 (L) 0.39±0.050 (R)	0.39±0.05 (L) 0.038±0.05 (R)
Stride width (m)	0.09±0.02	0.08±0.02 *
Center of gravity vertical displacement (cm)	9.0±1.1	8.5±1.1 *
Peak GRF (N)	1756±310	1703±285 *
Time to peak GRF (s)	0.08±0.02	0.08±0.01
Energy cost per step (kJ)	0.32±0.04	0.30±0.04 *

*different than Shod condition at P<0.05; L: left foot; R: right foot.

TABLE IV.—*Hierarchical regression analyses for the steady state rate of energy expenditure in shod and barefoot running conditions. Body weight was added in the first step followed by specific temporalspatial parameters.*

Rate of Energy Expenditure	R^2	R^2 Change	Sign of *F* Change (p)	B (CI)
SHOD				
Body weight	0.274	0.274	0..164	0.91 (0.020 to 0.163)
Cadence	0.301	0.027	0..701	0.03 (-0.044 to 0.103)
BAREFOOT				
Body weight	0.303	0.303	0..523	0.105 (0.027 to 0.182)
Cadence	0.339	0.037	0..997	0.034 (-0.037 to 0.104)
SHOD				
Body weight	0.236	0.274	0..164	0.117 (0.051 to 0.182)
Step length	0.479	0.206	0..106 *	8.973 (1.901 to 16.044)
BAREFOOT				
Body weight	0.309	0.309	0..033	0.125 (0.052 to 0.199)
Step length	0.468	0.159	0..081 *	9.728 (0.623 to 18.83)
SHOD				
Body weight	0.274	0.274	0..164	0.094 (0.023 to 0.165)
Stance time	0.325	0.051	0..364	-12.850 (-35.962 to 10.263)
BAREFOOT				
Body weight	0.303	0.303	0..253	0.107 (0.026 to 0.187)
Stance time	0.304	0.001	0..017	-0.82 (-13.985 to 12.344)
SHOD				
Body weight	0.255	0.255	0..844	0.094 (0.017 to 0.171)
Center of gravity displacement	0.257	0.002	0..042	0.069 (-0.629 to 0.766)
BAREFOOT				
Body weight	0.318	0.318	0..841	0.099 (0.019 to 0.178)
Center of gravity displacement	0.344	0.027	0..740	-0.343 (-1.181 to 0.495)

B (CI): unstandardized B coefficient and confidence interval * denotes significant contribution to the model of rate of energy expenditure, P<0.05.

tions resulted in similar rates of oxygen consumption, heart rates, rates of energy expenditure and fuel proportions. The lack of differences in our metabolic parameters could be attributed in part to adaptations to barefoot running,[1] minor adjustments to temporalspatial parameters and muscle activation patterns during the gait cycle.[18] We surmise that these experienced participants were able to slightly adjust these parameters and to standardize energy output and fuel use for a given running distance during either barefoot or shod conditions.

Our data are in contrast with other evidence that shows shoe wear can increase oxygen uptake during running compared to bare feet or minimal shoes. Differences in oxygen cost have been attributed to higher elastic energy storage and release, Achilles strain or less knee excursion in barefoot running.[6, 13, 19, 20] In contrast to Hanson *et al*.[13] our findings did not support a significant contribution of shoe wear on the oxygen use during each running session. We found that barefoot condition resulted in slightly higher cadence (by ~5 steps/min), compared to the shod condition. Similar findings have been previously reported during shorter running bouts.[4] The increased cadence was accompanied by decreased stance but not swing time. Barefoot running primarily affects the timing of the gait cycle during foot ground contact, rather than throughout the entire gait cycle. This finding is contrary to a recent study that manipulated the step rate of shod runners and found no difference in stance duration for modest 5% changes in step rate. Heiderscheit *et al*.[21] reported that for shod runners an increase in cadence of 10% produces significant reductions in joint loading at the hip and knee. These findings suggest that running barefoot encourages a gait pattern that results in reduced joint loading.

While we did not collect electromyographic data, recent studies indicated that walking barefoot compared to shod conditions induces different muscle activation patterns in the peroneus longus, tibialis anterior and medial gastrocnemius.[22] Divert *et al*.[4] proposed that the muscle activation is based on the expected impact shock during foot contact; running barefoot is related to increased pre-activation of gastrocnemius, soleus and plantar flexor muscles to help reduce impact forces.[4] There is the potential that mid-forefoot runners with experience in both barefoot and shod conditions have optimized muscle activation patterns, so that irrespective of shoe wear, energy use and impact forces are similar. There was a similar caloric cost and fuel use between the conditions despite several small temporalspatial differences, and this could be interpreted that muscle activation pattern modifications may be mediating these metabolic responses. It is advantageous to fine tune cadence which allows the runner to adapt to different conditions [23] while minimizing the energetic cost of transport. One theory could be that our runners had already adapted to both barefoot and shod running conditions and they were able to quickly self-select the cadence and associated muscle activation patterns that would keep metabolism and fuel use constant irrespective of shoe wear. Computer simulations of human running suggest that there is an economy control strategy based on muscle activation.[24]

Previous studies have shown a metabolic advantage to lighter shoes, with a 1% increase in VO_2 for every 100 g of weight added to the foot.[19] This relationship would predict that the runners in this study would exhibit a 2.4% lower VO_2 while running barefoot compared to shod running (average shoe weight =240 g). However, this difference was not observed. There must be other factors counteracting the benefit of reduced weight. One possibility is that during each step, the impact force of the foot striking the ground must be absorbed and that force can be absorbed passively through shoe cushioning or through increased muscular activation. Lower leg muscles such as the lateral gastrocnemius are preactivated during barefoot running to absorb impact,[18] and this could counteract the benefits of no shoe weight. In one study, shoes were standardized and the joint powers were determined in shod rearfoot, shod forefoot and barefoot running trials.[25] Power absorption shifted from the knee to the ankle during barefoot running compared to shod rearfoot or shod forefoot trials. These authors postulated that small differences in gastrocnemius muscle work and foot strike position on the ground may exist between conditions.[25] Further studies are needed to investigate role muscle activation patterns play in anticipating and absorbing impact forces and expending energy.

We found in our regression analyses that step length, (but not stance time, center of gravity displacement or cadence) was a significant contributor to the rate of energy expenditure. The average step length difference was 10 cm between shod and barefoot conditions. From the energy conservation perspective, VO_2 and energy expenditure were nearly identical in the two conditions to run the same distance. From the practical application standpoint, this type of experienced runner may not obtain any added energetic benefit of switching from shod to barefoot conditions during a run. Additional research regarding the effect of barefoot and shod running in a natural outdoor environment may be useful. There is the potential that running surface may influence the temporalspatial parameters and VO_2 especially outdoors. One small study (N.=10) examined this concept, and found that irrespective of running surface (four conditions: barefoot *vs*. shod, treadmill *vs*. track), there was not an interaction effect on VO_2 or heart rate.[9] Temporalspatial or kinematic measures might have helped to explain this lack of difference among the four conditions. Future studies may consider the metabolic effects of running barefoot in grassy, sandy, and trail environments.

Conclusions

There are not significant metabolic differences and fuel use patterns between shod and barefoot running conditions in trained mid-forefoot runners. This might be due to training adaptations in temporalspatial parameters, force dampening at foot impact and muscle activation patterns that standardize oxygen use for the given running distance in either barefoot or shod conditions.

References

1. Franz JR, Wierzbinski CM, Kram R. Metabolic cost of running barefoot versus shod: is lighter better? Med Sci Sports Exerc 2012;44:1519-28.
2. Rothschild CE. Primitive running: a survey analysis of runners' interest, participation, and implementation. J Strength Cond 2011;26:2021-6.
3. De Wit B, De Clercq D, Aerts P. Biomechanical analysis of the stance phase during barefoot and shod running. J Biomech 2000;33:269-78.
4. Divert C, Mornieux G, Baur H, Mayer F, Belli A. Mechanical comparison of barefoot and shod running. Int J Sports Med 2005;26:593-8.
5. Altman AR, Davis IS. Barefoot running: biomechanics and implica-

tions for running injuries. Curr Sports Med Rep 2012;11:244-50.
6. Squadrone R, Gallozzi C. Biomechanical and physiological comparison of barefoot and two shod conditions in experienced barefoot runners. J Sports Med Phys Fit 2009;49:6-13.
7. Divert C, Mornieux G, Freychat P, Baly L, Mayer F, Belli A. Barefoot-shod running differences: shoe or mass effect? Int J Sports Med 2008;29:512-8.
8. Burkett LN, Kohrt WM, Buchbinder R. Effects of shoes and foot orthotics on VO_2 and selected frontal plane knee kinematics. Med Sci Sports Exerc 1985;17:158-63.
9. Hanson NJ, berg K, Deka P, Meendering JR, Ryan C. Oxygen cost of running barefoot *vs.* running shod. Int J Sports Med 2011;32:401-6.
10. Anderson T. Biomechanics and running economy. Sports Medicine 1996;22:76-89.
11. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Med 2004;34:465-85.
12. Kellis E, Liassou C. The effect of selective muscle fatigue on sagittal lower limb kinematics and muscle activity during level running. J Orthop Sports Phys Ther 2009;39:210-20.
13. Hanson NJ, Berg K, Deka P, Meendering JR, Ryan C. Oxygen cost of running barefoot vs. running shod. Int J Sports Med 2010;32:401-6.
14. Ginde SR, Geliebter A, Rubiano F, Silva AM, Wang J, Heshka S *et al*. Air displacement plethysmography: validation in overweight and obese subjects. Obes Res 2005;13:1232-7.
15. Faulkner JA, Woolley BP, Lambrick DM. The effect of estimation and production procedures on running economy in recreational athletes. J Sci Sports Med 2012 15:568-73.
16. Cappozzo A, Della Croce U, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry-Part 1: theoretical background. Gait Post 2005;21:186-96.
17. Harris PA, Taylor R, Thielke R, Payne J, Gonzalez N, Conde JG. Research Electronic Data Capture [REDCap] – A metadriven methodology and workflow process for providing translational research informatics support. J Biomed Inform 2009;42:377-81.
18. Giandolini M, Arnal PJ, Millet GY *et al*. Impact reduction during running: efficiency of simple acute interventions in recreational runners. Eur J Appl Phys 2012;113:599-609.
19. Frederick EC, Daniels JT, Hayes JW. The effect of shoe weight on the aerobic demands of running. In: Bachl, Prokop L, Suckert R, editors. Current topics in sports medicine. Vienna:Urna & Schwarzenberg; 1984. p. 616-25.
20. Perl DP, Daoud AI, Lieberman DE. Effects of footwear and strike type on running economy. Med Sci Sports Exerc 2012;44:1335-43.
21. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. Med Sci Sports Exerc 2011;43:296-302.
22. Scott LA, Murley GS, Wickham JB. The influence of footwear on the electromyographic activity of selected lower limb muscles during walking. Journal of Electromyography and Kinesiology 2012;2296:1010-5.
23. Snyder KL, Snaterse M, Donelan JM. Running perturbations reveal general strategies for step frequency selection. J Appl Physiol 2012;112:1239-47.
24. Miller RH, Umberger BR, Hamill J, Caldwell GE. Evaluation of the minimum energy hypothesis and other potential optimality criteria for human running. Proc Biol Sci 2012;279:1498-505.
25. Williams DSr, Green DH, Wurzinger B. Changes in lower extremity movement and power absorption during forefoot striking and barefoot running. Int J Sports Phys Ther 2012;7:525-32.

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