Keystone Journal of Undergraduate Research 3(1): 7-13. 2015

Acute Cardiorespiratory and Kinematic Adjustments upon early exposure to Barefoot Running

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ABSTRACT

Running barefoot has gained much attention in recent years. Little research has explored the transitioning phase for those accustomed to shod running. Therefore, this study was designed to characterize oxygen uptake (VO_2) and kinematic adjustments during initial exposure to barefoot running and whether the adjustments persist at the onset of a second trial a minimum of 48 hours later. Eleven, moderately active subjects (male = 7; female = 4) naïve to barefoot running completed two, 11-minute barefoot running trials on a treadmill (5 mph). Expired gases (min 0-3 and 9-11) were analyzed for determination of running economy, respiratory exchange ratio, ventilation, and oxygen consumption. Cinematography evaluated stride frequency and length, along with joint angles and striking pattern to assess kinematic adjustments over the two trials. The group mean difference between initial VO_2 in Trial 1 to final assessment in Trial 2 revealed a 6.8% decrease in oxygen cost ($P<0.05$). Within Trial 2, VO_2 decreased by 5.2% from minute 3 to minute 11. Stride frequency non-significantly increased from Trial 1 to Trial 2 and from initial to final stages of both Trial 1 and Trial 2 ($P>0.05$). A subset of subjects who were analyzed kinematically revealed a great deal of variation in gait pattern adjustments. While acclimating to barefoot running, individuals may improve their economy by altering gait pattern as evidenced by changes in ankle angles among selected subjects. These changes may reflect the transition from a rearfoot strike to a forefoot strike pattern, contributing to improved running economy.

Keywords: Running economy; gait mechanics; stride frequency; stride length; VO_2

When comparing the running patterns of a shod runner versus a barefoot runner, biomechanical differences are evident. Research has shown that the primary difference occurs in striking pattern, with shod runners exhibiting more heel-strike and barefoot runners showing a mid or forefoot strike (Perl et al. 2012). However, there is minimal research concerning physiological differences that may arise during acclimation to barefoot running. For instance, differences in oxygen consumption may be seen when comparing shod running to barefoot running. It seems probable, then, that a number of adjustments must occur during the onset of barefoot running since humans have become accustomed to running with protective footwear. Currently, it is unknown how the human body responds physiologically or mechanically to acute bouts of barefoot running. Further, there is limited information regarding the acute adaptations the body may make from bout to bout.

The human body is capable of running long distance in hot, arid, and cold conditions. Running humans are able to store and release energy effectively in the lower extremity, which helps to maintain the body's center of gravity and overcome the thermoregulatory challenges of distance running (Saremi 2012). Lieberman explained that running uses a "mass-spring gait" of the lower extremity (2012). During the aerial phase of running, the center of mass falls and the elastic energy stored in the leg tendons results in recoiling during the second half of stance, pushing the body into the next aerial phase (Saremi 2012). Saremi (2012) has shown that landing on the forefoot recruits the muscles of the arch and also calf, slowing the descent of the heel to the ground. When the foot impacts the ground during a running movement, the muscles in the lower extremity aid in stability, propulsion, and energy return. Forefoot striking strengthens the muscles in the foot, especially in the arch. If a runner's foot is stronger they will experience less pronation. With the natural spring in the stride, runners appear to expend less energy when using a forefoot strike commonly seen when running barefoot (Lieberman 2012). Lieberman (2012) suggests that barefoot runners who use a forefoot strike generate smaller collision forces compared to shod rear foot strikers. The plantar flexed foot at landing and ankle conformity during impact decreases the force of body mass that impacts with the ground (Lieberman 2012). Thus, it is thought that a forefoot strike pattern may help to reduce injury risk associated with recurrent impacts from landing.

The majority of shod runners, 75%, typically exhibit rear foot strike patterns (Perl et al. 2012). Rear foot striking is defined as the moment that first contact is made by the heel with the ground. Biomechanically, habitually barefoot runners differ from those of shod runners (Hatala et al. 2013). Minimally shod or barefoot runners often exhibit forefoot strike patterns, where the ball of the foot contacts the ground before the heel, when performing on hard or rough surfaces because forefoot striking, compared to rear foot striking, generates lower impact peaks. The Achilles tendon stores and returns more elastic energy when forefoot striking compared to rear foot striking, especially when under minimal or barefoot running conditions, displaying a greater effect on running economy (Perl et al. 2012). The Achilles tendon does not stretch at impact, but stretches mainly due to dorsiflexion after the foot flattens and the tibia passes over the foot (Perl et al. 2012). Sometimes, minimally shod or barefoot runners contact the ground with the ball and heel of the foot simultaneously, commonly referred to as midfoot striking. Habitual barefoot runners with a forefoot or midfoot strike pattern do not generate high impact peaks, which are commonly associated with a rear foot striking pattern (Hatala et al. 2013).

Franz et al. (2012) suggest that barefoot running economy can improve with practice or as one becomes more trained. Hatala et al. (2013) found among habitually barefoot populations, that the difference in foot strike pattern seems to have little impact on running economy, but that stride length impacts running economy. Perl et al. (2012) suggest that running with a forefoot strike sustains no additional metabolic cost compared to running with a rear foot strike pattern. Mass-spring mechanisms of the tendons, ligaments, and muscles of the lower extremity differ with strike pattern in rear foot and forefoot patterns because of stored elastic energy during the first running stance (Perl et al. 2012). The recoil of elastic energy during the second half of the running stance helps push the body's center of mass upward and forward (Perl et al. 2012). These mechanical adjustments may confer advantages for economy of movement, thereby allowing the metabolic cost of running to be reduced.

The purpose of this study was to determine whether acute cardiorespiratory and kinematic adjustments occur during the first exposure to barefoot running for naïve moderately active subjects and if adjustments carry over from the initial barefoot session to another training session. It was hypothesized that there would be a decrease in energy cost due to acute mechanical adjustments associated with barefoot running. With novel exposure to barefoot running, the observed energy expenditure changes may be related to mechanical adjustments resulting from accommodation to barefoot running.

METHODS

Subjects

Eleven, moderately active individuals (4 males and 7 females; M±SD, age: 21.1±0.7 years, mass: 73.5±14.9 kg, height: 173.7±13.5 cm), who self-reported exercising five or more hours weekly, volunteered for the study. All subjects completed the Physical Activity Readiness-Questionnaire (PAR-Q) and medical history survey. Subjects were excluded from the study if they had a major injury in the past 6 months and/or a lower extremity abnormality. The subjects were naïve to barefoot running and nonsmokers.

Subjects were informed of potential risks and discomforts that could arise from running barefoot such as muscle fatigue, soreness, and foot abrasions. The study was approved by the Shippensburg University Committee for Research on Human Subjects and subjects provided written consent prior to participation in testing.

Metabolic data collection via indirect calorimetry was used to determine running economy, ventilation (Ve), and respiratory exchange ratio (RER). Other measured variables include heart rate (HR) and rate of perceived exertion (RPE) using the Borg 6-20 scale. Variables that were assessed through cinematography include stride frequency, stride length, knee angles and ankle angles.

Procedures

Each subject completed an orientation day involving shod running on a motorized treadmill (DesmoPro, Woodway Inc., Waukesha, WI) monitoring cardiorespiratory, metabolic, kinematic, and perceptual responses at a fixed running speed of 5.0 mph for 11 minutes. Several days before experimental testing, subjects completed an orientation session to become familiarized with cardiorespiratory testing equipment (ParvoMedics TrueOne, Sandy UT). Experimental trials for each subject were completed on two separate days, a minimum of 48 hours apart. The same treadmill was used for orientation and both running trials. For experimental testing, subjects were required to wear black form-fitting clothing.

Cardiorespiratory data were collected during the first 3 min and again during the final 2 min of each trial. Cinematography data were collected for 30 s periods beginning at 3.5 min and 9 min of each trial. HR and RPE were collected at the end of each minute. HR was continuously measured using telemetry (Polar s610i, Kempele, Finland). RPE was obtained every minute using the 6-20 point Borg RPE scale (Borg 1998). The same protocol was used on the day 2 running trial, which was conducted 48-96 h later.

Kinematic data collection

Kinematic data were collected using a 2D camera system (Panasonic GV-35, Newark, NJ) from the sagittal plane. The camera was positioned at a 90-degree angle to the treadmill and was positioned 3.33 m from the treadmill at a height of 1.12 m. A calibration of the frame was collected prior to testing. Reflective markers were secured onto the left side of the body at the following anatomical locations: base of the fifth metatarsal, posterior aspect of the calcaneus, lateral malleolus, lateral femoral epicondyle, greater trochanter of the femur, and the tip of the acromion-clavicular joint. Depending upon participants' attire and skin exposure, disruption of the reflective marker was avoided by using black tape, and by providing a non-reflective (black clothing) background. Floodlights were used to illuminate the field of view. Data were analyzed using the Peak Motus software (v.9.2, Englewood, CO.). Cinematography was collected in 30 s increments from 3:30-4:00 min and 9:00-9:30 min. The selected kinematic variables analyzed were stride length, stride frequency, knee angles, and ankle angles.

Cardiorespiratory data collection

Cardiorespiratory variables were measured in a controlled environment using a calibrated metabolic system (ParvoMedics TrueOne 2400 Metabolic Measurement System, Sandy, UT). Calibration of the device was completed prior to each testing session. A mouthpiece and nose clip were used to collect expired gases for determination of cardiorespiratory measures. Between each subject trial, the tubing and mouthpiece were cleaned and sanitized for reuse. Expired gases were collected from 0-3 min ("initial") and from 9-11 ("final") min of each test protocol (Trial 1 and Trial 2). The last one-min of data from each measurement segment was used for analysis to reflect steady state metabolism.

Statistical Analysis

Data were analyzed using a two-way ANOVA (SPSS, v.21.0, Chicago, IL), with independent variables as testing session (two levels: Trial 1 and Trial 2) and time (two levels: initial and final). Dependent variables included VO_2, Ve, RER, HR and RPE. In addition, a subset of runners (n=3) was analyzed to compare kinematic variables ankle angle and knee angle at impact. Outcomes of the kinematic

Table 1. Cardiorespiratory, heart rate (HR) and rating of perceived exertion responses (RPE) to running at a fixed speed of 5.0 mph (M±SEM).

Variable	Trial 1		Trial 2	
	Initial	*Final*	*Initial*	*Final*
VO_2 (ml/kg/min)	29.2±0.8	29.3±0.8	28.7±0.8	27.2±1.2*
HR (bpm)	148.6±6.1	161.1±3.8	152.5±4.0	161.0±3.5
RER	0.9±0.01	1.0±0.01^	0.9±0.03	1.0±0.04^
Ve (L/min)	40.7±2.4	41.0±2.0	41.5±2.5	39.5±2.6
RPE	9.1±0.5	11.3±0.5	8.5±0.6	11.5±0.7

*Different from Trial 1 Initial ($P<0.05$) ^Different from Initial ($P<0.05$)

analyses may be used to infer mechanisms for adjustments in cardiorespiratory measures. Pearson's product-moment correlation was used to determine the relationship between all tested variables. A P-value of 0.05 was set as the criterion for statistical significance.

RESULTS

Over the course of Trial 1, VO_2 increased slightly (<1%) and non-significantly from initial (min 3) to final (min 11). This indicates steady state had been achieved by the end of 3 min as is customary with lower intensity (submaximal) exercise (Figure 1). During Trial 2, VO_2 decreased substantially (5.2%), but non-significantly (trend present) from the initial to the final measurement point ($P=0.096$) (Figure 1). When comparing the initial VO_2 in Trial 1 to the final VO_2 measurement in Trial 2, the oxygen uptake had decreased by 6.8% ($P=0.048$).

Neither HR, Ve, or RPE were significantly altered either during or between trials (Table 1). The results revealed a significant difference ($P<0.05$) for RER within trials but not across trials. RER increased from the initial measurement to the final measurement on each day (Table 1) Stride frequency was non-significantly reduced during Trial 1 versus Trial 2 ($P>0.05$). Respectively, stride frequency increased non-significantly from the initial to the final stage of both trials ($P>0.05$; Table 2 and Figure 2). Table 2 also reveals results from the subset of subjects for whom kinematic analysis was performed. Due to the small sample size for kinematic analysis, statistical outcomes were non-significant. However, cardiorespiratory data from this subset were compared against kinematic changes to gauge whether the variables may be linked. Figure 2 shows the oxygen uptake changes in two subjects from the subset; while Figures 4 and 5 illustrate kinematic outcomes for these same subjects for ankle and knee angles, respectively, across trials.

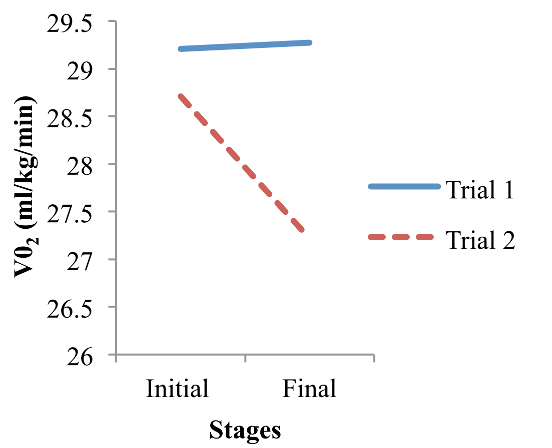

Figure 1. Mean initial and final oxygen consumption for the two trials.

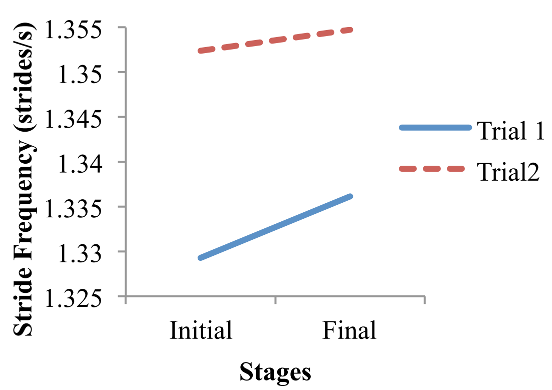

Figure 2. Mean initial and final stride frequency for the two trials.

Table 2. Kinematic measures and statistical and significance between trials (M±SEM).

	Trial 1	Trial 2	P-value
Ankle ROM Initial (degrees)	61.8	62.1	0.99
Ankle ROM Final (degrees)	49.4	53.9	0.29
Knee ROM Initial (degrees)	82.5	78.2	0.77
Knee ROM Final (degrees)	76.8	73.3	0.66
Stride Length Initial (m)	1.6±0.06	1.6±0.05	0.64
Stride Length Final (m)	1.7±0.04	1.7±0.03	0.59
Stride Frequency Initial (strides/s)	1.3±0.03	1.6±0.06	0.61
Stride Frequency Final (strides/s)	1.4±0.03	1.4±0.03	0.65

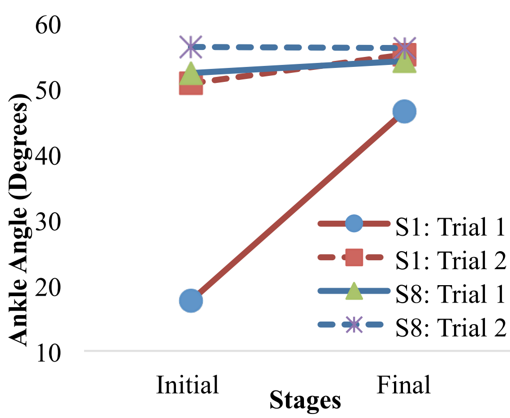

Figure 3. Subject 1 and Subject 8 ankle range of motion between initial and final in Trials1 and 2.

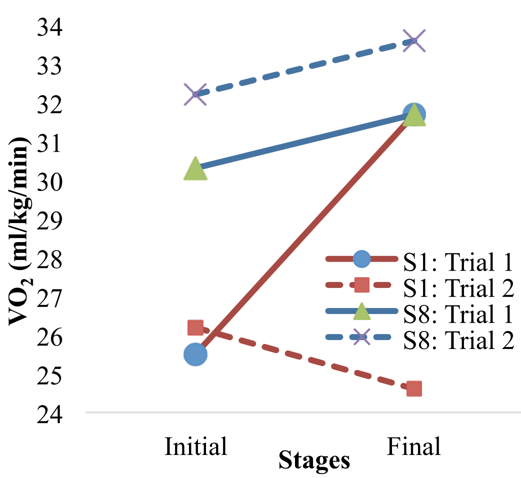

Figure 4. Subject 1 and Subject 8 VO_2 changes between initial and final in Trials 1 and 2.

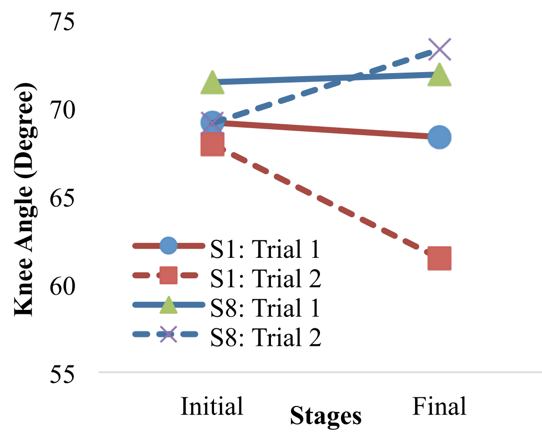

Figure 5. Subject 1 and Subject 8 knee angles between initial and final in Trials 1 and 2.

DISCUSSION

The results of the study show that after preliminary exposure to barefoot running in those naive to barefoot running, adjustments to the oxygen cost of transport can occur. While these adjustments did not result in significant changes in running economy during Trial 1, oxygen uptake during Trial 2 was found to be significantly lower. Further, from the initial measurement of Trial 1 to the final measurement of Trial 2, running economy was increased by 6.8% (signifying a lower energy cost to complete the running) (Figure 1). This reflects a considerable reduction in the energy cost of transport. It was evident based on these reductions in the oxygen uptake requirement that adjustments leading to improved economy of movement developed as a result of the initial exposure to barefoot running. It was also notable that a sizable energy savings for

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runners occurred with a short volume of barefoot running exposure. Exploration of the kinematic subset revealed that the participant who gained the most economy across trials also showed notable changes in kinematics. This subject transitioned to a forefoot strike resulting in an increase in ankle angle and a decrease in knee angle through the range of motion. These changes suggest that the mechanical adjustments may have played a crucial role in economical changes during early exposure to barefoot running. The findings of Hatala et al. (2013) support the hypothesis that a forefoot strike reduces the magnitude of impact loading. The subjects in the present study that adopted a forefoot striking pattern tended to reveal better running economy. Though non-significant, as stride frequency increased, a decrease in stride length occurred. This small decrease in stride length may be related to the shift from rearfoot to forefoot striking, which may be an attempt to decrease heel impact loading.

Running barefoot requires adaptations such as a highly arched foot when unloaded, and flattened arch when loaded (Robbins and Hanna 1987). Some factors that affect barefoot running are speed, surface texture, surface hardness, and fatigue (Lieberman 2012). The treadmill in the present study was a soft track, which may have been associated with the mechanical adjustments seen in the subset of runners, which were used for the kinematic portion of the study. The treadmill could have impacted ankle and knee angles, which could have potentially made the runners more economical. The results of our study show that the most economical runner experienced angle changes in both the ankle and the knee through the range of motion. This may be due to the change in strike pattern that the subject self-induced. The observed running pattern for the most economical subject was a rearfoot strike in Trial 1 to a forefoot strike in the second trial.

Barefoot running produces shorter strides and a faster stride rate (Lieberman 2012). The results found that as stride frequency increased from Trial 1 to Trial 2, stride length decreased, but non-significantly. Subjects with shorter strides were primarily forefoot strikers. This may be due to the medial arch rising and shortening due to the activation of intrinsic musculature, the activation of intrinsic muscles allows the foot to act dynamically rather than as a propulsion factor. Forefoot striking can strengthen the intrinsic muscles of the foot (Robbins and Hanna 1987). This increase in foot strength has been associated with less pronation during barefoot running leading to a decrease in impact forces; which may require less energy when using a forefoot strike (Nearman 2011).

An adaptation from rearfoot to forefoot striking during barefoot running was associated with a decrease in oxygen uptake. It is assumed that such acute adjustments contribute to the common finding that barefoot running is more economical than shod running. Research has shown that when running in shoes the mass, strike type, habitual footwear, and the strike frequency all contribute to the increased energy cost when running in shoes (Perl et al. 2012). Habitually shod runners increase their speed and alter the position of their foot at strike in order to cope with the higher collision forces associated with the greater speed. Since this study did not involve a comparison to shod running, the shift toward a lower VO_2 across trials would appear to be attributable to mechanical adjustments. However, further analysis of a larger data set is needed to confirm the association between mechanical adjustments and a change in the energy cost of transport.

Expansion of kinematic analyses could validate the increase in economy of subjects. Nearman (2011) concluded that even on hard surfaces, barefoot runners who forefoot strike produce smaller collision forces. The differences of the results found in Nearman's study were due to an increase in plantar flexion of the foot during landing, requiring the ankle to be more compliant during ground impact (Nearman 2011). The increased activation of the ankle can cause a decrease in the active mass of the body that strikes the ground.

A possible limitation of the study was the use of a lower running speed to prevent injuries. But this lower running speed could have altered the perceived exertion for each subject and was likely slower than preferred running speed for most participants. Gender limitations were present in the study, due to the small male sample pool in the study.

Anatomical differences in the sexes could have influenced knee and ankle angles; more research would need to be conducted to validate this limitation. A final limitation is that there was not a comparison to a shod run. However, previous research has already addressed the changes that are commonly seen when comparing barefoot to shod running (Franz et al. 2012; Lieberman 2012; Perl et al. 2012).

Further research on this topic should seek to establish the effects of ankle and knee angle on the striking pattern as a mediator of energy cost in barefoot and shod running. These variables could relate to stride length and frequency. It would be interesting to determine the chronic metabolic and mechanical changes associated with barefoot running.

In conclusion, the findings of this study imply that, with early mechanical adjustments during exposure to barefoot running, individuals can improve economy. Individual subject results suggest that as ankle angle increased, knee angle decreased while the subject was transitioning from a rearfoot strike to a forefoot strike, possibly contributing to improved economy and a lower cost of transport. Barefoot running could potentially drive an overall better economy for individuals that train barefoot but perform in minimalist footwear or shod conditions. Mechanical adjustments may reflect the natural disposition of the runner to reduce impact in effort to minimize injury during barefoot running.

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