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An unstable shoe with a rocker bottom redistributes external work

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Abstract

The purpose of this study was to examine the external work performed by individuals wearing a rocker bottom shoe compared to a standard shoe. It was hypothesized that individuals wearing a rocker bottom shoe would have changes in the amount of work over the course of contact with the ground. External work on the body's centre of mass (BCOM) was calculated for individuals in both conditions. Comparisons for external work were done for positive and negative work for the entire stance phase as well as the initial double support, single support and terminal double support periods. The results revealed that while wearing the rocker bottom shoes, individuals performed an increased amount of negative work and decreased positive work in the initial double support followed by increased positive work in single support compared to a standard sole shoe. Individuals also performed a decreased amount of positive and negative work in terminal double support when wearing the rocker bottom shoes. There were no differences, however, when the stance phase was considered undivided to subphases for either positive or negative work. The results indicate that use of rocker bottom shoes redistributes external work to earlier in the gait cycle, which may not be as energetically efficient. This shift will probably result in increased metabolic energy expenditure as it will require more energy output from proximal hip musculature, which is not as mechanically efficient as the ankle joint in late stance. This could be desirable for individuals who are wearing the shoes for increased caloric burn such as an exercise setting. Furthermore, the increased external work in single support may be causing additional work from the hip extensor musculature (i.e. gluteus maximus). This could possibly be desirable for strengthening and conditioning of the hip extensors.

Keywords: Masai Barefoot Technology; locomotion; gait analysis; centre of mass; biomechanics

Introduction

A novel design of shoes that incorporates a rocker bottom-shaped outsole has been made commercially available. Masai Barefoot Technology® (MBT) was among the first to offer such shoes. MBT shoes are marketed as being able to create instability (altered dynamic balance) in gait (MBT 2011). Marketing claims state that the purpose of such a shoe design is to recreate the natural interaction between feet and uneven surfaces, an interaction that standard shoes have supposedly altered and thereby artificially stabilized by providing a flat surface (MBT 2011). By providing an induced instability, the person wearing the unstable rocker bottom shoes would need to increase lower limb muscle activation to allow for sufficient stability during upright standing and walking, thus resulting in better posture and/or strengthening of certain specific muscles (i.e. gluteus maximus) (MBT 2011). To date, these claims have limited scientific support.

Recent analyses using surface electromyography (EMG) (Nigg *et al.* 2006, Romkes *et al.* 2006) offer some evidence to support the claims of altered muscle activity during walking in rocker bottom shoes. Romkes *et al.* (2006) reported increased activity throughout the gait cycle in six of seven lower limb muscles tested. The tibialis anterior, a primary dorsiflexor, was the only muscle that had decreased activity that occurred at heel contact (Romkes *et al.* 2006). Nigg *et al.* (2006) found similar trends for EMG when subjects wore the rocker bottom shoes during walking. Specifically, they documented trends of decreased activity from the tibialis anterior and biceps femoris and increased activity from other lower limb muscles, although none of the EMG changes were statistically significant.

Kinetics analyses during walking have provided limited evidence for any altered muscle activity. Nigg *et al.* (2006) examined joint moments and powers over the stance phase of gait and did not find any significant differences between a standard sole shoe and the rocker bottom shoes. The results from EMG analyses combined with a lack of evidence for any kinetic changes could suggest that kinetics are not altered and instead EMG changes are only reflecting increased co-contractions to stabilize lower extremity joints. However,

increased EMG activity from the quadriceps muscles does not coincide with any increases from the hamstring muscles (Romkes *et al.* 2006) and in fact there is decreased activity from the biceps femoris (Nigg *et al.* 2006), providing evidence that increased co-contractions is not the case. Furthermore, during heel contact, when the body is preparing for weight acceptance, lower limb joints demand a large amount of support. However, heel contact is marked by increased plantarflexor activity and decreased dorsiflexor activity in rocker bottom shoes (Romkes *et al.* 2006).

Nevertheless, it is possible that the rocker bottom shoes are causing changes within the kinetic chain. These adjustments at each joint may be subtle and unable to reach statistical significance with typical piecewise kinetics analyses (joint moments and powers). As each subtle adjustment travels proximally along the kinetic chain, the combined changes may have a large impact on the body's centre of mass (BCOM). External work quantifies the mechanical energy performed by an external force (i.e. ground reaction forces) on the BCOM to move the individual a certain distance (Cavagna *et al.* 1963, Donelan *et al.* 2002 b). Thus, examination of the external work produced when wearing the rocker bottom shoes may provide a better insight into altered gait mechanics. Furthermore, when considering a shoe that is marketed as creating instability, external work may be an ideal metric. Specifically, any stabilizing mechanism by the body will serve to control the motion of the BCOM. Failure to control the motion of the BCOM will result in instability and possibly a fall. For the case that the rocker bottom shoes are creating instability, measuring the effect directly at the BCOM is logical.

Therefore, the purpose of this study was to examine the external work produced by individuals wearing a standard sole shoe as well as a rocker bottom shoe. It was hypothesized that individuals wearing a rocker bottom shoe would have changes in the amount of external work over the course of contact with the ground.

Method

Subjects

Ten healthy young subjects [mean (SD): age 22.80 (2.25) years; height 182.51 (7.30) cm; weight 78.84 (9.16) kg; two females] gave informed consent according to the regulations of the university's Institutional Review Board and were subsequently enrolled in the study. Inclusion criteria required the absence from any cardiac, pulmonary, neuromuscular or musculoskeletal pathology that can affect ambulatory function. Subjects were excluded if they had previously worn rocker bottom shoes (i.e. Masai Barefoot Technology®, Skechers Shape-Ups®).

Experimental design and procedures

All subjects participated in two data collections. Prior to the collections, 27 retro-reflective markers were placed bilaterally at specific lower extremity anatomical locations (Vaughan *et al.* 1992). Each subject walked across a 10-m walkway at a self-selected speed while three-dimensional (3D) marker trajectories and ground reaction forces were collected. Eight high-speed, digital motion capture cameras (EvaRT 5.0.4, Motion Analysis Corporation, Santa Rosa, CA, USA) sampling at 60 Hz recorded the 3D marker trajectories. A force platform (Kistler Instrument, Winterthur, Switzerland) sampling at 600 Hz recorded the ground reaction forces. Five successful trials were collected for each shoe. A trial was determined successful if only the leg of interest contacted the force platform and landed entirely within the platform's boundary.

Subjects wore their own standard sole shoes during the first data collection. Subsequently, subjects were (1) properly fitted with the rocker bottom shoes (Masai Barefoot Technology®, Roggwil, Switzerland), (2) instructed in proper rocker bottom shoe technology wear, and (3) underwent 45 min of monitored rocker bottom shoe training. Subjects then wore their rocker bottom shoes for 7 days to allow acclimation. Subjects were instructed to wear the rocker bottom shoes during all activities through the course of the 7 days. Each subject then returned to complete the second data collection with the rocker bottom shoes.

Data analysis

Walking speed for each subject was calculated as the average velocity of the sacral marker as the subject walked through the 10-m walkway. External work was calculated throughout the stance phase as the real time integral of the dot product of the 3D ground reaction force of the leg while in contact with the force platform and the 3D velocity of the BCOM (Cavagna *et al.* 1963, Donelan *et al.* 2002 b). This produces instances

of positive work when the overall force and velocity are at an obtuse angle (force is overall in the same direction as velocity) and negative work when the force and velocity are at an acute angle (force opposes velocity). The velocity of the BCOM was calculated as the derivative of the sacral marker position (Cavagna *et al.* 1963, Willems *et al.* 1995). Sacral marker position data were filtered through a low-pass fourth-order Butterworth digital filter with a 6-Hz cut-off.

Table 1. Group means (standard deviation) for negative and positive external work (J kg^{-1}) at different periods of the stance phase and also for the entire stance phase.

	Initial double support		Single support		Terminal double support		Total stance	
Standard sole	0.75 (0.37)	-12.50 (7.09)	8.21 (4.23)	-15.72 (4.61)	18.47 (2.71)	-0.88 (1.04)	27.43 (5.72)	-29.10 (9.11)
Rocker bottom sole	0.35 (0.35)*	-14.88 (7.22)*	11.77 (5.31)*	-14.10 (3.94)	16.98 (3.17)*	-0.41 (0.65)*	29.11 (7.66)	-29.38 (9.40)

*Significant difference from standard sole ($p < 0.05$).

The stance phase was determined using the vertical ground reaction force while the heel and toe marker trajectories were used to divide the stance phase into three subphases: initial double support, single support, and terminal double support (O'Connor *et al.* 2007). Initial double support corresponds to the time period in which the ipsilateral foot comes in contact with the force platform while the contralateral leg is still in contact with the walkway. During initial double support, negative work occurs as the ipsilateral foot is the leading leg and experiences early stance loading. During single support, the contralateral leg is in swing phase. Terminal double support corresponds to the time period in which the ipsilateral foot is still in contact with the force platform and the contralateral foot is in contact with the walkway.

Initial double support, single support, and terminal double support were analysed for positive and negative work for each subject in both conditions (standard sole and rocker bottom). In addition, total positive and negative work over the entire stance phase was calculated. All calculations were executed using custom Matlab software (Matlab 2009, Mathworks Inc., Concord, MA, USA). The right leg for both the standard sole and rocker bottom shoe was selected for comparison of work output using dependent *t*-tests (SPSS v.16, IBM Corporation, Armonk, NY, USA). Walking speed was compared through dependent *t*-tests as well for subject's average speed in each condition. The significance level was set at 0.05.

Results

During initial double support, the rocker bottom shoes resulted in significantly less positive work ($p = 0.002$) and a greater amount of negative work ($p = 0.013$) as compared to the standard shoe (Table 1, Figure 1). During single support, individuals in the rocker bottom shoe performed more positive work ($p = 0.003$). In terminal double support, wearing the rocker bottom shoe resulted in a decreased amount of both positive work ($p = 0.026$) and negative work ($p = 0.035$). However, these changes in external work throughout different periods of stance phase did not result in any differences in positive work ($p = 0.118$) or negative work ($p = 0.839$) summed across the entire stance phase. Self-selected walking speed for the rocker bottom shoes ($1.33 \pm 0.03 \text{ m s}^{-1}$) was slightly greater than for the standard shoes condition ($1.28 \pm 0.03 \text{ m s}^{-1}$; $p = 0.048$).

Discussion

Walking with a rocker bottom shoe resulted in redistribution of external work through the stance phase. Individuals wearing the rocker bottom shoe performed greater amounts of negative work and less positive work in the initial double support period. This period coincides with the time when the leg is accepting a transfer of the body's weight and is dominated by negative work (Kuo *et al.* 2005). Negative work involves dissipation and storage of energy. The tibialis anterior is typically largely responsible for dissipating energy as it slows the plantarflexion of the foot following heel contact (Perry 1992), yet the EMG studies mentioned previously do not support increased tibialis anterior activation during this time (Romkes *et al.* 2006). It seems more plausible that the Masai Sensor and Balancing Area® (MBT 2011), the soft thick heel region of the MBT

rocker bottom shoe, affords a large amount of energy dissipation and storage. The decrease in positive work is probably a result of the curved heel shape as opposed to a standard rigid heel lever. This leads to the conclusion that, whereas there is less activity from the tibialis anterior, there is overall more energy dissipation (in the rocker bottom shoe).

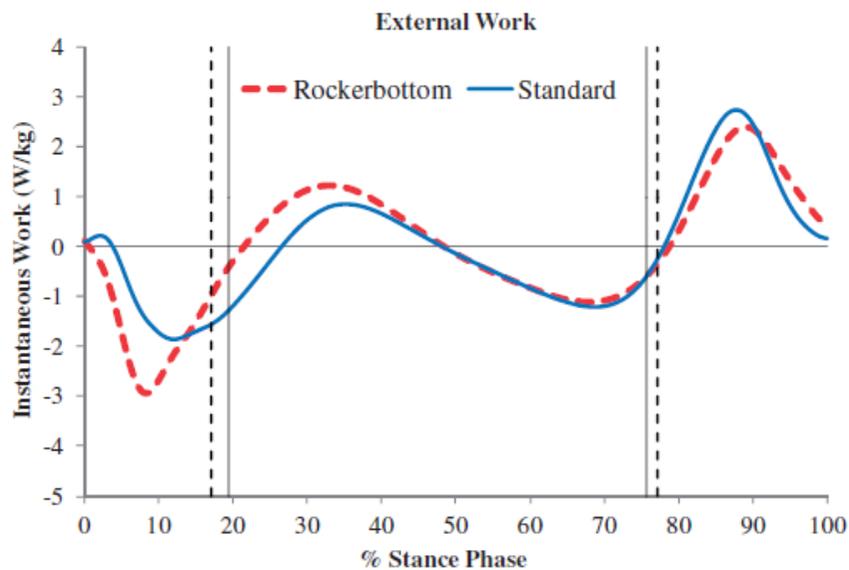


Figure 1. Mean ensemble curves for external work during stance phase for subjects wearing standard sole shoes and the rocker bottom shoe. Subjects produced less positive work and an increased amount of negative work in the initial double support, increased positive work in single support, and decreased amounts of positive and negative work in terminal double support. Vertical solid and dashed lines demarcate divisions between the three time periods for the standard sole and rocker bottom shoes, respectively. Note that the figure is presented with normalized time; however, calculations for work were performed with real time.

The findings within the initial double support when the leg is accepting the body's weight combined with the previous EMG findings (Nigg *et al.* 2006, Romkes *et al.* 2006) suggest that the use of the rocker bottom shoe may have positive therapeutic effects for individuals consistently struggling with medial tibial stress syndrome. Medial tibial stress syndrome has been linked with excessive eccentric contraction of the ankle dorsiflexors (Yates & White 2004). However, further research is needed to verify this effect with patients with this syndrome.

During single support, individuals performed an increased amount of positive work. The positive work in this period of gait has been labelled as 'rebound' (Kuo *et al.* 2005) because of the large amount of work that is expected to be returned from the negative work just prior. It is not clear if this rebound energy is within the leg or the shoe. It makes sense that an increased amount of negative work during initial double support would be followed by increased positive work as energy is returned to the gait cycle (Kuo *et al.* 2005). Furthermore, during single support, it is the hip extensors (gluteus maximus and hamstrings) that are in the best position for providing any forward momentum as the knee is fully extended and the ankle is dorsiflexing (Perry 1992, Kuo *et al.* 2005). As a result, a portion of the increase in positive work during single support may be attributed to increased hip extensor activity. This would seem to justify anecdotal claims for gluteus maximus strengthening when wearing the rocker bottom shoes.

In terminal double support, the leg is primarily producing a 'push-off' as it generates positive work (Donelan *et al.* 2002 a). This positive work is dominated largely by the plantarflexors at the ankle joint (Kuo *et al.* 2005). A lack of differences in EMG activity during this time by the plantarflexors (Romkes *et al.* 2006) would not suggest any changes in work output at this time. However, while wearing the rocker bottom shoes, subjects produced less positive work as they terminated stance. Although this initially may seem counter to EMG activity, further consideration of the shoe design provides a reasonable explanation. Specifically, the rocker bottom shoe is designed with a radius under the sole that the person rolls over. This rolling shape would cancel out the plantarflexing of the foot, similar to effects seen when walking in sand, where the surface gives way. Thus, the ankle musculature and mechanics may not be different but the power transferred to the BCOM is decreased. The result of this effect needs to be further examined to understand the impact on metabolic energy

demands as a lack of transfer of power to the BCOM could increase metabolic energy to cover the same distance (i.e. distal joints doing the same amount of mechanical energy but less is transferred to the BCOM). The decreased amount of negative work in the terminal double support appears to be a result of a time shift with the individual's remaining in single support longer (Figure 1). The mean ensemble curves display how the increased single support time would only affect the amount of negative work in terminal double support and not positive work.

The results from this study should be regarded with consideration to the study's limitations. First, previous work has shown estimates of the BCOM to be more accurately measured from dual force platform integration compared to derivation of a sacral marker position (Gard et al. 2004). The laboratory was limited to a single force platform and thus unable to capture the force of both legs simultaneously to perform an integration of ground reaction forces. However, we do not believe this had a strong impact on our findings as all subjects for both conditions were subjected to the same method for estimating motion of the BCOM. In a crossover study design, any changes to an individual from the standard sole to the rocker bottom shoe would be a result of true kinetic changes and not error resulting from the methodology. A single force platform does, however, prevent the inability to compare the simultaneous positive and negative work during double support. Second, subjects were not monitored for the week of adaptation to the rocker bottom shoe. Subjects were instructed to wear the shoes during all activities for the week of adaptation and all reported this to have been the case. However, without monitoring shoe wear, it is impossible to know this to be completely accurate. Furthermore, physical activity levels between subjects may have varied, and certain subjects who may have worn the rocker bottom shoes for all activities may not have been active enough to properly adapt. Nevertheless, the observed changes in external work were consistent across all subjects, suggesting that the impact of physical activity and adaptation may not have such a strong influence on the results. In addition, the proper adaptation time period for rocker bottom shoes remains to be determined. The rocker bottom shoes condition also resulted in slightly greater walking speed on average. Walking speed will affect the kinetics, specifically external work in this case. We chose to allow subjects to ambulate at a self-selected speed to observe their natural mechanics in the shoes. It is possible that the increased speed is the reason for the increased external work. However, if the effects measured were only a result of increased speed, then a concurrent increase in the amount of work for the entirety of stance would be expected. Instead, there was a distinct redistribution of work within the gait cycle. Therefore, despite the slight difference in walking speeds, we do not consider that changes in external work were only an effect of walking speed but were a true effect of the rocker bottom shoe. Finally, future work should investigate the force and velocity vector contributions to the work calculation to examine whether changes in work are due to force changes or velocity vector changes.

In conclusion, the unstable design of the MBT rocker bottom shoes alters the kinetics of locomotion. There is a shift of increased external work to earlier points in the gait cycle. This shift will probably result in increased metabolic energy expenditure as it will require more energy output from proximal hip musculature, which is not as mechanically efficient as the ankle joint in late stance. This could be desirable for individuals who are wearing the shoes for increased caloric burn such as in an exercise setting. Furthermore, the increased external work in single support may be causing additional work from the hip extensor musculature (gluteus maximus). This could possibly be desirable for strengthening and conditioning of the hip extensors.

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