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DIFFERENCES IN KINETICS AND COORDINATION BETWEEN WALKING BAREFOOT AND WALKING IN ROCKER BOTTOM SHOES

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ABSTRACT

Different types of shoe constructions have been developed with an unstable base including rocker bottom shoes (RBS). RBS were developed to mimic barefoot (BF) walking. Studies have compared walking in RBS with walking in conventional shoes (CS) or running in CS with BF running. The purpose of the current study was to compare RBS with BF walking to describe differences in selected kinetic variables and their timing between the two conditions. Three-dimensional ground reaction force (GRF) and kinematic data for the lower extremities were recorded for 13 college age females during gait at self-selected speed. Similar results were observed between BF walking and walking in RBS. However, several of the observed characteristics of RBS walking were similar to characteristics reported in CS walking. Walking in RBS showed greater vertical GRF (loading response) and anterior-posterior GRF (braking force) than BF walking. Earlier transition from deceleration to acceleration phase was observed in RBS condition, and a shorter time between the peak in ankle plantar flexion moment and the push-of-peak of vertical GRF, and acceleration force in anterior-posterior direction, respectively. Results suggest different strategies between the two conditions to prepare for the swing phase of gait.

Keywords: Gait, Motion analysis, Rocker-bottom shoes.

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Contribution/ Originality

This study contributes to the existing literature by combining the coordinated timing kinematics and ground reaction force (GRF) differences between walking barefoot and walking in rocker bottom shoes (RBS). GRF and transition time differences between barefoot and RBS wear suggests different strategies are used in preparation for the swing phase of gait.

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1. INTRODUCTION

Recently, there has been accelerated interest in various types of shoe construction, especially shoes used for exercise or fitness. Balance and stability in stance are important during bipedal locomotion and the geometry of footwear sole construction strongly influences these characteristics (Landry *et al.*, 2010). Rocker bottom shoe (RBS) soles relocate the apex of the forefoot posterior to the metatarsal heads, creating instability in an anterior-posterior direction, increasing postural sway, thereby promoting midstance to toe off transition (Schaff and Cavanaugh, 1990; Van Schie *et al.*, 2000; Landry *et al.*, 2010). RBS advertisements are designed to appeal to consumer interest through increased skeletal muscle action, and thereby the potential for eventual enhanced performance. Masai Barefoot Technologies (MBT) has manufactured such RBS. The shoes have rounded soles in the anterior-posterior direction creating an unstable base that is intended to function as a therapeutic training device used during locomotion. One study found that without the stability and rigidity of a traditional shoe, the lower extremity is able to increase muscle activation for locomotion, thereby stimulating leg muscles (Romkes *et al.*, 2006). Conversely, other studies observed no differences in muscle activation (Sacco *et al.*, 2012; Santo *et al.*, 2012; Horsak and Baca, 2013). Interestingly, even without differences in muscle activation, differences in biomechanical gait characteristics between RBS and BF have been observed (Nigg *et al.*, 2006; Sacco *et al.*, 2012; Horsak and Baca, 2013). Conventional activity/fitness shoes used for walking and running have typically been constructed to incorporate features that enhance stability of the foot and body which are thought to be important for prevention and protection against injury (Stewart *et al.*, 2007). The difference in stability between the unstable shoe and the conventional activity shoe was demonstrated in a study by Stöggl, Haudum, Birklbauer, Murrer, & Müller in 2012. The authors observed provoked movement variability during treadmill walking when wearing RBS (MBT) with adaptations occurring after 10 weeks of wear which corresponded to level of conventional activity shoes (Stöggl and Müller, 2012).

While various sport shoe qualities have been touted, there is also resurgence in popularity of barefoot (BF) running and walking, which is believed to enhance running efficiency (Hanson *et al.*, 2001; Hsu, 2012). Interest in minimalist shoe construction includes the five-finger shoe and even those who advocate BF running and walking. In the 1980s BF running was popular (Burkett *et al.*, 1985; Garrick and Requa, 1988), following the contention that foot safety and injury prevention was higher among non-shoe wearers. This was largely unsupported by the literature. One of the findings of shod running with a cushioned heel, as seen in RBS, is that the ankle is in more of a dorsiflexed position at initial contact, which allows shod runners to land as a hind-foot striker, whereas in BF running the foot is more plantarflexed at initial contact. The greater plantarflexed foot position reduces the overall peak ground reaction force (GRF) as measured by the loading response based on body weight (BW) and the mean loading rate in BW/s is lower than that of habitually shod runners who are more prone to hind-foot strike, when running barefooted (Liberman *et al.*, 2010).

In previous studies, the common comparison has been between BF running and shod running with conventional athletic shoes (De Wit *et al.*, 2000; Liberman *et al.*, 2010). Also, the biomechanics of walking in RBS has been extensively compared to walking in conventional sport (athletic) shoes (Nigg *et al.*, 2006; Landry *et al.*, 2010; Stöggl *et al.*, 2010; Stöggl and Müller, 2012; Taniguchi *et al.*, 2012). The rationale for the development of the MBT shoe was that the shoe simulated walking BF on unstable terrain, since the human body is not created to walk on flat and hard surfaces (Stewart *et al.*, 2007; Stöggl *et al.*, 2010; Stöggl and Müller, 2012; Taniguchi *et al.*, 2012).

No previous studies compared RBS walking and BF conditions. Therefore, the present investigation was aimed to identify differences between RBS and BF walking. Traditional gait analyses have focused on parameters such as range, average, maximum and minimum amplitude of kinematic and kinetic variables (e.g., maximum joint angles, maximum and minimum impact forces, joint forces, joint moments, loading rate and power) (De Wit *et al.*, 2000; Hunt *et al.*, 2001a; Hunt *et al.*, 2001b; Stöggl and Müller, 2012; Taniguchi *et al.*, 2012), and one study focused on the timing of these variables (De Wit *et al.*, 2000). However, the timing of these parameters is essential to accurately describe stress on the body during gait. For example, at what time within the gait cycle or during stance phase is the body exposed to elevated levels of stress?

The current study focused on differences in kinetic variables in RBS compared to BF walking, including the timing of these variables. Since our future research will focus on the clinical population, specifically people with chronic ankle instability (CAI), the current study is focusing on kinetic variables at the foot and ankle joint. Because there is limited information on the differences between RBS and BF walking we will compare differences between walking in the RBS and BF walking in healthy controls to address the following research questions: 1) Are there differences in peak values of the vertical and anterior-posterior GRF and ankle joint moments between BF and RBS conditions? 2) Are there differences in the time these peak values occur during the stance phase between BF and RBS conditions? 3) Are there differences in time of occurrence of peak values for different variables between BF and RBS conditions (e.g., is the time period between the occurrence of peak GRF and ankle joint moment different when walking in RBS compared with BF walking)? Since RBS are designed to mimic BF walking, no differences in gait characteristics are expected between RBS and BF walking and it is hypothesized that no differences will be observed between RBS and BF conditions for any of the variables.

2. METHODS

2.1. Participants

Following IRB approval, thirteen healthy females (age: 20.8 ± 0.47 years, height: 152.4 ± 0.47 cm, body mass: 60.70 ± 0.47 kg) volunteered to participate in this research study and signed an informed consent. Exclusion criteria included known neurologic, cardiovascular or orthopaedic condition/impairment, lower extremity injury or joint pain that would have prevented the participants from performing the walking task. Only female subjects were tested to reduce the potential risk of gender differences creating a confounding effect. Healthy was operationally defined as no current or history of injury to the lower extremity or no current or past injuries that would alter lower extremity posture and/or gait mechanics. Participants had no prior experience walking in RBS. We were interested in testing the effect of the RBS on subjects who had no prior experience with this shoe type.

2.2. Apparatus

Three-dimensional ground reaction forces and moments of force were recorded using a force platform (Bertec Corp 4060, Columbus, OH, 1000 Hz). Simultaneous, kinematic data for the pelvis, thigh, shank, and foot of the dominant leg were recorded using a six-degree of freedom electromagnetic motion analysis system (Flock of Birds, Ascension Technologies, Burlington, VT, 100 Hz), interfaced with Motion Monitor Software (Innovative Sports Training Inc., Chicago, IL). System accuracy was 0.5° at 0.91 m (Tripp *et al.*, 2006). Kinetic and kinematic data collections were synchronized by the software using a foot contact threshold of 10 N to trigger data collection. Four electromagnetic sensors were placed on the dominant limb with double-sided tape and athletic tape over the sensor. The locations of the four sensors were: 1) anterior to the third metatarsal, 2) midshaft of medial tibia, 3) lateral aspect of the thigh (iliotibial band), and 4) sacrum. Participants' dominant limb was determined by asking which foot the participant would kick a ball. The Sketchers Shape-Ups Toning Shoes (RBS) were provided to the participants for testing (Fig.1).

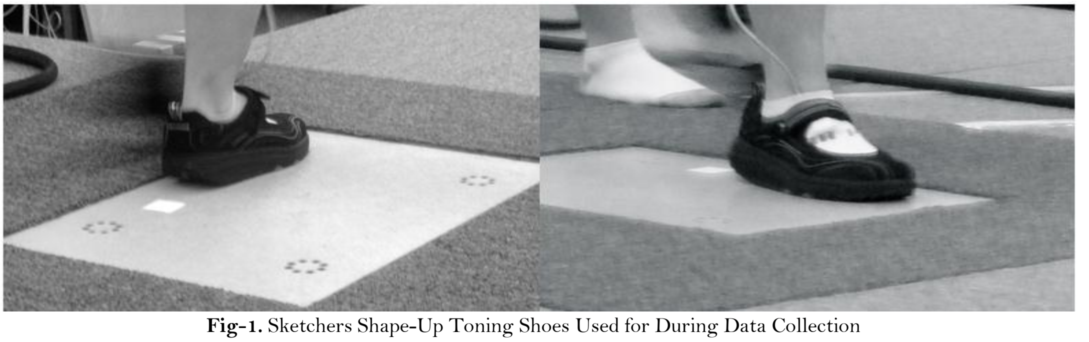


Fig-1. Sketchers Shape-Up Toning Shoes Used for During Data Collection

2.3. Testing Protocol

At the start of the experiment a static control trial was performed to determine participant's body weight and to determine the local coordinate systems of each body segment. The ankle and knee joint centers were estimated using the centroid method where the ankle joint center was calculated as the midpoint between the digitized medial and lateral malleoli and the knee joint center was calculated by the midpoint between the digitized medial and lateral femoral epicondyles. The hip joint center was determined by the Leardini method (Leardini *et al.*, 1999).

Prior to testing in the RBS study participants were shod, provided instructions regarding the walking task and were given 3-5 minutes to become familiar with the shoe sole construction, therefore the RBS walking task was novel for our subjects. Anecdotally, participants noted the unusual feeling they experienced with the RBS. For the main task, participants were instructed to walk over a force plate embedded in a 7.3 meter carpeted walkway for each walking condition, BF and RBS at a self-selected comfortable pace. Each participant was allotted at least 3 practice trials for each condition before recording to ensure accurate placement of the foot on the force plate. With each walking condition three successful trials were recorded and used for analysis. Researchers ensuring that the participant's foot hit completely on the force plate determined successful trials. RBS and BF conditions were counterbalanced between participants to minimize order effect; seven participants started with the RBS condition.

2.4. Data Analysis

Interpolation and filtering of kinematic and kinetic data as well as synchronization and time normalization of kinematic data with kinetic data were performed using Motion Monitor interface. Kinematic data were linearly interpolated to force plate data. Kinematic and kinetic data were low-pass filtered at 12 Hz using a fourth-order, zero-lag Butterworth filter. Joint motions were calculated using Euler angle definitions with a rotational sequence of X Z′ Y″ (Nigg *et al.*, 2006). Exported data were processed off-line using Matlab 7.6 software. Kinetic and kinematic data were examined during stance phase. The period from heel contact to toe off was time normalized to arbitrarily chosen 1001 data points. GRF was normalized to each participant's body weight (BW). Ankle flexion moment was normalized to each participant's body mass ($Nm \cdot BM^{-1}$).

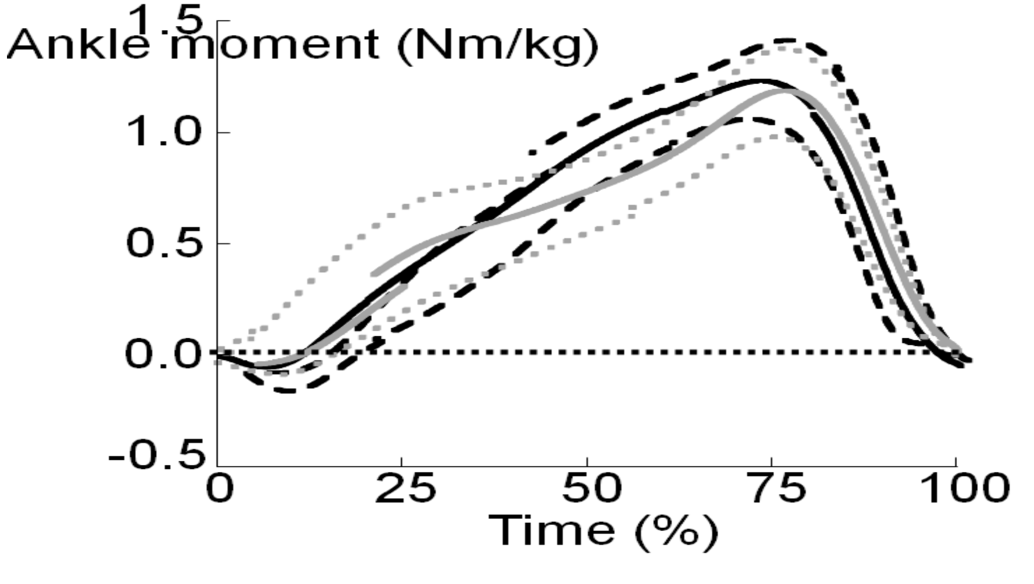
2.5. Statistics

Data analysis was performed with IBM SPSS Statistics Software for Windows-Version 19 (SPSS-Chicago, IL). From the three successful trials means were calculated for each of the variables. Shapiro-Wilk test showed that >93% of the data were normally distributed. Dependent Student t-tests were performed to determine differences in RBS and BF walking. The original alpha level (p-value) was set at $p \leq 0.05$. Bonferroni corrections were used to correct for multiple comparisons. We tested for each research question: five variables for question 1 ($p=0.05/5=0.010$), six variables for question 2 ($p=0.05/6=0.008$), four variables for question 3 ($p=0.05/4=0.013$) (Table 1).

3. RESULTS

All 13 participants were able to accurately step with the dominant (right) foot on the force plate under both RBS and BF conditions. Participants showed qualitatively similar time profiles for ankle flexion moments, anterior-posterior ground reaction forces (GRFAP) and vertical ground reaction forces (GRFV) during stance phase for RBS and BF conditions (Fig. 2). Heel contact was defined at 0 % and toe-off was defined at 100 % of the time cycle.

Research question	Variable	Abbreviation
Are there differences in peak values between BF and TS condition?	1. Peak plantar ankle flexion moment 2. Impact peak vertical ground reaction force 3. Push-off peak vertical ground reaction force 4. Minimum anterior-posterior ground reaction force in breaking phase 5. Maximum in anterior-posterior ground reaction force in acceleration phase	PAFMP GRFV_IP GRFV_POP GRFAP_MIN GRFAP_P
Are there differences in the time peak values occur within the stance phase between BF and TS condition?	1. Time of peak plantar ankle flexion moment 2. Time of impact peak vertical ground reaction force 3. Time of push-off peak vertical ground reaction force 4. Time of minimum anterior-posterior ground reaction force in breaking phase 5. Time of peak anterior-posterior ground reaction force in acceleration phase 6. Time point from breaking to acceleration phase in anterior-posterior ground reaction force	PAFMTOP GRFV_TOIP GRFV_TOPOP GRFAP_TOMIN GRFAP_TOP GRFAP_T0
Are there differences in the period of time between the occurrences of peak values of different variables?	1. Time period between peak of plantar ankle flexion moment and push-off peak vertical ground reaction force 2. Time period between peak of plantar ankle flexion moment and maximum anterior-posterior ground reaction force 3. Time period between impact peak vertical ground reaction force and minimum anterior-posterior ground reaction force 4. Time period between push-off peak vertical ground reaction force and peak anterior-posterior ground reaction force	PAFMTOP-GRFV_TOPOP PAFMTOP - GRFAP_TOP GRFV_TOIP-GRFAP_TOMIN GRFV_TOPOP-GRFAP_TOP



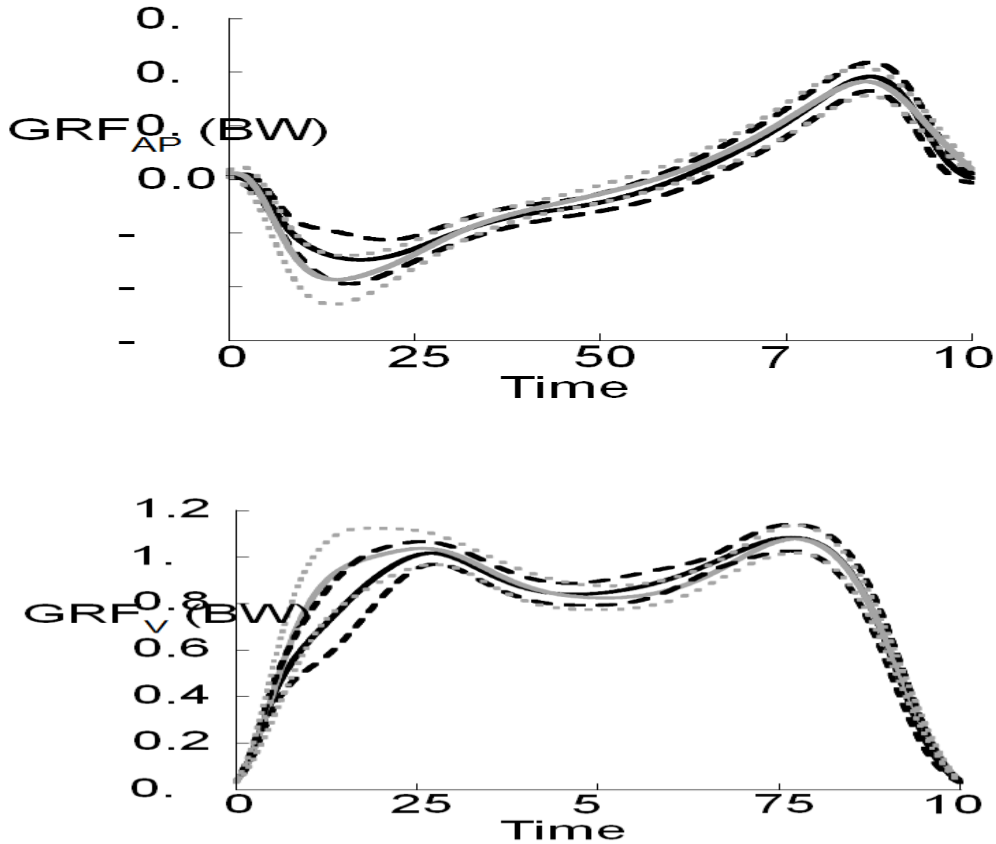


Fig.2- Average time profiles with standard deviation for ankle moment (Fig.1a, Top), anterior-posterior ground reaction force (Fig.1b, Middle) and vertical ground reaction force (Fig.1c, Bottom) during stance phase for rocker-bottom shoe (RBS) (grey) and barefoot (BF) (black) walking.

Similar peak values were observed between BF and RBS conditions for ankle flexion moment, GRFV and the acceleration phase of GRFAP, whereas the braking force of GRFAP was greater in RBS. The time profile of the ankle flexion moment (Fig. 2a, top) showed a plantar-flexion moment throughout the stance phase. At heel contact and toe-off peak ankle flexion moments were small. Peak ankle flexion moments increased gradually and reached similar peak values of 1.20 $Nm \cdot BM^{-1}$ (± 0.22) for RBS and 1.27 $Nm \cdot BM^{-1}$ (± 0.19) for BF. The peak values were not significantly different ($p \geq 0.05$).

Typical time profiles of GRFV were observed in both RBS and BF condition (Fig. 2b, middle). The first peak of GRFV represented the loading response immediately following heel contact, followed by a reduction in GRFV through mid-stance and another peak represented push-off at the end of the stance phase before toe-off. The loading response was slightly, but significantly higher for the RBS (1.09 BW ± 0.06) compared with the BF condition (1.03 BW ± 0.06) ($p \leq 0.05$). The peak values representing push-off were similar between RBS and BF conditions (TS: 1.08 BW ± 0.06; BF: 1.09 ± 0.06).The range of motion in ankle flexion was significantly ($p \leq 0.05$) smaller in RBS (19.4° ± 4.8) compared with BF walking condition (30.3° ± 4.9). GRFAP (Fig. 2c, bottom) can be stratified into typical deceleration and acceleration phases (Fig. 3). The braking force of -0.19 ± 0.04 BW in RBS condition was significantly ($p \leq 0.05$) lower than the -0.16 ± 0.04 BW in the BF condition. Peak values in the acceleration phase were similar and not significantly different for the two conditions ($p \geq 0.05$).

The transition from deceleration phase to acceleration phase was significantly earlier in RBS than in BF (Fig. 3). This was confirmed to be significant with a dependent Student t-test ($p \leq 0.05$). In the deceleration phase the peak in braking force also occurred earlier in the RBS compared to the BF condition. There were also differences in the timing of the loading response of GRFV, but these differences were not statistically significant ($p \geq 0.05$). In the acceleration phase the time of the peak of the ankle plantarflexion moment and the time of the peak of the vertical push-off force were later in RBS walking, whereas the time of the peak value of the GRFAP appeared earlier. However, there were no significant differences in these findings ($p \geq 0.05$).

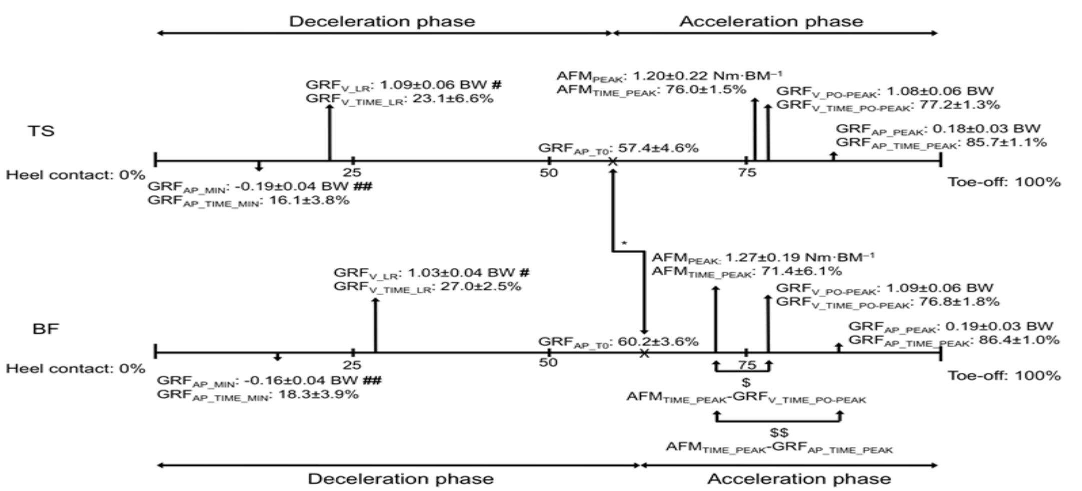


Fig.3- Schematic representation of timing and magnitude of the peak values of presented biomechanical variables under rocker bottom shoe (top) and barefoot (bottom) walking conditions during stance phase. GRF_{V_LR} = vertical ground reaction force – loading response, $GRF_{V\_TIME\_LR}$ = vertical ground reaction force – time of loading response, GRF_{AP_MIN} = ground reaction force in anterior-posterior direction – minimum value, $GRF_{AP\_TIME\_MIN}$ = ground reaction force in anterior-posterior direction – time of minimum value, GRF_{AP_T0} = ground reaction force in anterior-posterior direction – transition from deceleration to acceleration phase, AFM_{PEAK} = ankle flexion moment – peak value, AFM_{TIME_PEAK} = ankle flexion moment - time of peak value, $GRF_{V\_PO\text{-}PEAK}$ = vertical ground reaction force – push-off-peak, $GRF_{V\_TIME\_PO\text{-}PEAK}$ = vertical ground reaction force – time of push-off-peak, GRF_{AP_PEAK} = ground reaction force in anterior-

posterior direction – peak value, $GRF_{AP\_TIME\_PEAK}$ = ground reaction force in anterior-posterior direction – time of peak, AFM_{TIME_PEAK}-$GRF_{V\_TIME\_PO-PEAK}$ = period between peak of ankle flexion moment and peak of vertical ground reaction force push-off-peak, AFM_{TIME_PEAK}-$GRF_{AP\_TIME\_PEAK}$ = period between peak of ankle flexion moment and peak of anterior-posterior ground reaction force. $^{\#*\$}$Denote significant differences

Differences were observed between RBS and BF in the periods of time between the occurrences of peak values of different variables (Fig. 3). The time between the appearance of the braking force of GRFAP and the loading response of GRFV was shorter in the RBS (7.1 ± 4.2% than in BF (8.6 ± 3.5%), but this difference was not statistically significant ($p \geq 0.05$). In the acceleration phase, the peak in the plantarflexion moments of the ankle was the first to occur, followed by push-off peak of GRFV and then the peak of GRFAP. A later appearance of the peak in ankle plantarflexion moment in RBS led to a significantly shorter period of time until the appearance of the push-off peak of GRFV in the RBS (1.1 ± 1.6%) compared with the BF condition (5.4 ± 5.8%) ($p \leq 0.05$). A similar statistical result was observed between the time of the peak in ankle plantarflexion moment and the timing of the peak of GRFAP in the acceleration phase ($p \leq 0.05$) with the period of time in RBS (9.7 ± 2.0%) being smaller than in BF (15.0 ± 5.7%). No significant differences were observed between RBS and BF in the period of time between the occurrence of the GRFV push-off peak and peak of GRFAP.

4. DISCUSSION

In the current study BF walking was compared with walking in RBS on a variety of kinetic variables at the foot and the ankle joint, including the timing of these variables. Three research questions were formulated. The first question was related to peak values in GRF and ankle joint moments. The results showed differences between RBS and BF walking in the early stance phase with a greater loading response in the vertical GRF and a larger braking force (deceleration) in anterior-posterior direction in RBS walking. The curved sole in RBS reduces the size of the support area, thereby increasing instability during stance (Albright and Woodhull-Smith, 2009). The second and third questions were with respect to the timing of peak values within the stance phase. An earlier transition from deceleration to acceleration phase was observed in RBS condition. Furthermore, a shorter time period was observed in RBS between the peak of the ankle plantar flexion moment and the push-off force represented by the vertical GRF, as well as between the peak of the ankle plantar flexion moment and the peak of the antero-posterior GRF, both in late stance.

In general, similar kinetic results were observed between RBS and BF conditions. In our sample this finding supports the design of RBS, since this shoe is purported to mimic BF walking. However, the difference observed between RBS and BF walking are similar to differences between shod running and BF running reported in previous studies. Landing on the hind-foot in shod running leads to a larger impact force than the more plantarflexed foot strike in BF running (De Wit *et al.*, 2000; Divert *et al.*, 2005). The larger impact force while wearing shoes was also observed in the current study, suggesting similarities in the walking pattern between conventional shoes and RBS rather than similarities between RBS and BF walking. The smaller range of motion in ankle flexion under RBS condition observed in the current study might be caused by the stiffness of RBS. The range of motion observed under RBS condition in the current study (19.4° ± 4.8) was in agreement with the range of motion observed in RBS walking in previous studies (Buchecker *et al.*, 2012; Landry *et al.*, 2012; Taniguchi *et al.*, 2012). Furthermore, the landing on the hind-foot in RBS walking, and the larger braking force could explain an earlier transition from deceleration to acceleration force in RBS, required in preparation for the swing phase. With respect to BF walking, the time period between the peak of the ankle plantar flexion moment and the push-off-peak of the GRFV, and the peak of the GRF_{AP}, respectively, was longer in BF walking. This longer time period was primarily the result of an earlier appearance of the peak in plantar ankle flexion moment under the BF condition. Additionally, a larger peak in the ankle plantar flexion moment was observed in BF walking, even though not statistically significant. This may be due to the later transition from deceleration phases to acceleration phase in BF walking a larger moment of force earlier in the acceleration phase was produced by the ankle joint to prepare the foot for the swing phase. These results would suggest different strategies in preparation for swing phase under BF and RBS conditions.

This was a pilot project for which we wanted no practice effect and/or kinematic adaptation to the destabilizing effect of perturbed stance during walking gait, thereby increasing the potential for anterior posterior imbalance. A study from 2014, published in Foot & Ankle International tested the limits of stability by having subjects adapt and improve with 6 weeks of wear in RBS. Their findings were that subjects did not improve their limits of stability after 6 weeks of RBS wear (Vieira *et al.*, 2014). Therefore, in future investigations a longer period of adaptation needs to be implemented if the effect of practice and a learning effect is an important part of the research question.

Weaknesses in our investigation include: risk of Type II statistical error due to the p value adjustment, a low n, single gender testing, and walking speed was self-selected and some subjects could have walked at different speeds, although because the motion system was cabled one unintended consequence was that this controlled walking speed. Our focus was on participants walking on their self-chosen comfortable speed to simulate daily life walking. The difference in timing of the peak values of the variables discussed could have been the result of differences both between and within individuals. However, large differences in walking speed within and between participants were not noticed by the researchers, based on visual inspection during data collection. Furthermore, the limited practice trials (at least 3 trials per condition) potentially influenced the walking pattern. In future studies, a larger number of practice trials should be considered, particularly when walking in RBS. Future investigations will focus on 1) spatiotemporal data during the entire gait cycle rather than during the stance phase only and 2) clinical populations such including those with chronic ankle instability and the efficacy of RBS as a training/rehabilitation method. In conclusion, the present study is, to our knowledge, the first comparing RBS versus BF walking on a variety of kinetic variables at the foot and the ankle joint, including the timing of these variables. The results demonstrate that many kinetic characteristics when walking in RBS are similar to BF walking, including the selected timing characteristics of kinetic variables. However, other kinetic characteristics in RBS walking are similar to results reported in previous studies on shod running.

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Competing Interests: The authors declare that they have no competing interests.

Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

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