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Title: Foot motion character during forward and backward walking with shoes and barefoot

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Disclosure statement

No potential conflict of interest was reported by the authors.

Foot motion character during forward and backward walking with shoes and barefoot

Abstract

Backward walking (BW) has been extensively used in athletic training and orthopedic rehabilitation as it may be valuable for enhancing balance. The present study identified the differences in foot inter-segment kinematics (forward walking (FW) vs. time-reversed BW) and plantar pressure parameters of sixteen healthy habitually shod individuals walking FW and BW with flexible shoes (SH) and barefoot (BF). BW was found to have shorter stride length (SL) and higher stride frequency (SF) under BF conditions compared with SH, which indicates a better BW gait stability under BF conditions. Decreased HX/FF dorsiflexion at HO in BW walking induced less plantar aponeurosis tension which may inhibit the windlass mechanism compared to FW walking. Increased forefoot relative to hindfoot (FF/HF) pronation and sequentially hindfoot relative to tibia (HF/TB) eversion combined with medially distributed plantar pressure and higher plantar contact area in the medial side in BW-BF maybe beneficial to maintain balance. These results indicate that BW training may be more reliable under BF conditions compared to SH conditions based on more sensory information feedback from the plantar area and better biomechanical behavior.

Keywords: Foot kinematics, Backward walking, Shoes, Barefoot

Introduction

Forward walking (FW) and backward walking (BW) have been researched extensively in the past twenty years, distinct advantages of BW were found over FW for both fitness training and rehabilitation (Grasso, Bianchi, & Lacquaniti, 1998)(Sedhom, 2017). During BW, the absence of visual cues and peripheral visual feedback implies that BW relies more heavily on proprioception than FW. The variation in visual information, as well as the simple novelty of the task may require a remodeling of sensory feedback to maintain dynamic balance. Therefore, BW has been used as an intervention for enhancing balance to improve mobility function after stroke(D. A. Winter, Pluck, & Yang, 1989)(Tseng, Jeng, & Yuan, 2012). BW has less mechanical strain on the knee joint, which has been used in orthopedic rehabilitation and in increasing the strength and power of the quadriceps(Rose, Demark, Fox, Clark, & Wludyka, 2018). FW and time-reversed BW showed similar gait patterns and the characteristics of angular displacement in all lower limb joints during the gait cycle. Thus, the similarity led some researchers to suggest that the neural control may originate from the same “spinal” automatisms in each walking pattern(Van Deursen, Flynn, McCrory, & Morag, 1998). However, some findings do not agree with this suggestion. Some studies have recorded differences in knee and ankle angular displacement, joint torques and electromyography (EMG) between FW and time-reversed BW patterns(Shu et al., 2016)(Jansen et al., 2012). Reversing walking direction from FW to BW was found in slower walking speeds and shorter stride length among both young and older adults(Fritz et al., 2013). BW was reported more variable compared to FW, more specifically, knee and hip range of motion (ROM) presented to be more variable during BW. BW is suggested to have lower local dynamic stability than

FW, which makes BW a more demanding task of motion control(Katsavelis, Mukherjee, Decker, & Stergiou, 2010)(Bollens, Crevecoeur, Detrembleur, Warlop, & Lejeune, 2014).

The foot plantar contains 104 cutaneous mechanoreceptors and the receptor is primarily distributed where the foot is in contact with the ground(Kennedy & Inglis, 2002). Backward barefoot walking may provide more tactile feedback from the foot sole which compensates for limited visual input. Footwear was found to hinder the kinesthesia while walking barefoot has demonstrated greater awareness of foot position and movement control compared with wearing athletic footwear(Morio, Lake, Gueguen, Rao, & Baly, 2009). Walking with various types of shoe and barefoot was found to affect the FW pattern and balance control. Flatter foot placement and increased forefoot spreading were reported during barefoot walking(Chard, Greene, Hunt, Vanwanseele, & Smith, 2013). Habitual barefoot walkers exhibit increased knee flexion, reduced peak vertical ground reaction force and peak plantar pressures(D'Août, Pataky, De Clercq, & Aerts, 2009). These studies suggest that footwear may be interfering with the functional ability of the human foot. Winter et al., (D. a. Winter, 1984)demonstrated that similar knee and hip angle patterns but different ankle angle patterns exist between FW and BW. A single foot segment model may disregard the important inter-segmental motion that occurs within the foot, the foot bend and torsion are obscured. Thus, for clinical gait analysis and human movement research, the traditional one segment foot model is beginning to be replaced by various multi-segment foot models (MSFM). The addition of kinematics to the multi-segment model may provide additional insight into the foot and ankle complex functions(Pothrat, Authier, Viehweger, Berton, & Rao, 2015). However, no studies to date have compared the foot inter-segment kinematics of FW and BW with shoes (SH) and barefoot (BF).

The purpose of this study was to examine the differences on foot inter-segment kinematics, and plantar pressures of healthy individuals walking forward and backward with shoes or barefooted. We hypothesized that the foot inter-segment motions of hindfoot, forefoot, and hallux will vary significantly between FW and time-reversed BW and substantial asymmetrical differences exist especially in the sagittal and frontal planes, the foot motions under shod conditions will be constrained significantly compared with barefoot conditions. We also hypothesized that the plantar pressure would be redistributed under the foot sole during BW, wearing shoes may significantly decrease plantar pressures during both FW and BW patterns.

Methods

Subjects

Sixteen healthy male subjects (age: 25.75±2.62 years, height: 1.72±0.62m, weight: 66.78±7.20 kg, BMI: 22.57±0.71 kg/m^2) volunteered to take part in this study. The inclusion criteria of the subjects were no abnormal findings on a foot X-ray radiograph and no history of fracture or surgery in the lower limbs. All participants were without any musculoskeletal injury or pain during the data collection period. All the subjects were rear-foot strikers and the dominant foot was the right one based on the test of kicking a soccer ball, so all statistics concerning the tests are based on data from the right feet of all subjects(Sun, Mei, Baker, Jia, & Gu, 2017). The subjects wore the same sock and shoe model with flat outsoles and without any cushioning system. The shoes were fitted according to their foot size. The subjects provided written informed consent to participate in this study. Ethical approval was obtained from the Ethics committee of Ningbo University (No. ARGH 20171124).

Instrumentation setup

An eight MX-Cameras VICON motion analysis system (Oxford Metrics Ltd., Oxford, UK) were used to capture the foot inter-segment kinematics at a frequency of 200Hz. Calibration of the motion capture system was performed before the gait trials. A 0.6m×0.8m force plate (AMTI, Watertown, USA) was fixed into the middle of the walkway and utilized to obtain the GRF data at a frequency of 1000Hz (Figure 1). The marker trajectories and force plate data were captured synchronously using the VICON Nexus software package (Version 1.8.5, VICON, UK). Simultaneously, the in-shoe plantar pressure measurement system (Novel GmbH, Munich, Germany) was used in this study to measure the plantar pressure and contact area exerted on the insole pressure sensors with a frequency of 50 Hz. Each pressure insole is approximately 2.6 mm thick and consists of 99 capacitive pressure sensors in the matrix array.

---*Insert Figure 1 near here*---

Experimental protocols and procedures

This study was conducted at the Sports Biomechanics Laboratory of Ningbo University. All walking trials were performed on a 15m straight walkway. Firstly, subjects were required to walk forward and backward barefoot and with shoes on the 15m walkway for familiarization. Then subjects completed a minimum of fifteen self-selected speed forward and backward walking tasks under barefoot and shod conditions, respectively. Ten trials per condition with complete data sets were selected for analysis. A standard reflective marker set was based on the Oxford Foot Model (OFM) and Plug-In-Gait model (PIG) as described by Stebbins et al(Stebbins, Harrington, Thompson, Zavatsky, & Theologis, 2006). A set of 36 markers (9 mm) were placed bilaterally on bony landmarks to model the tibia, hindfoot, forefoot, and hallux(Wang, Thur, Gutierrez-Farewik, Wretenberg, & Broström, 2010). 20mm holes were cut in the shoe upper material to obtain in-shoe foot kinematics, the position of each hole was referenced to the underlying anatomical landmarks based on the OFM(Wolf et al., 2008). Good consistency in kinematic waveform estimation and good intra-rater reliability of the in-shoe multi-segment foot kinematics were approved in previous studies. The OFM used in this study simplified complex anatomical foot structures to three rigid segments (tibia, hindfoot and forefoot) and one vector (hallux). Foot kinematics and plantar pressure data were measured and time synchronized in this study. During plantar pressure measurement, the plantar insoles were secured to the participants' feet with double-sided tape, and a standardized thin cotton sock was worn to incorporate plantar pressure insoles under barefoot condition. When shod walking, the insoles were placed in the shoes. Pressure insoles were placed bilaterally and are designed in different sizes to adjust the foot and shoe size in this test. A pressure pump was used to calibrate all the insoles used in this experiment to minimize the error during measurement. Ten successful trails were selected for further analysis under each condition.

Data analysis

Walking speed was calculated as the anterior-superior displacement of the anterior-superior iliac spine marker (PIG model) divided by the corresponding time. Stride length (SL) was recorded as the anterior-posterior distance between the right heel marker (RHEE) in one gait cycle. Stride frequency (SF) was computed as the inverse of one gait cycle duration(Fu et al., 2016). Stance time (ST) was calculated as the duration from the right foot strike onto the force platform to the right foot move off the platform. The stance phase of FW was defined as the duration from right foot heel-contact (HC) to toe-off (TO). Conversely, the stance phase of BW was defined from toe-contact (TC) to heel-off (HO). FW (HC/TO) and BW (HO/TC) had opposite contact positions (heel/toe) for the same gait events (initial contact/push-off). Therefore, time-reversed foot inter-segment angle curves of BW were used to compare the kinematic pattern of FW to adjust for the purpose of this study. Foot kinematics were time normalized to 0-100% of the stance phase. The right side (dominant) walking pattern during one stance phase was analyzed for all kinematic and kinetic variables. Marker trajectory was captured, tracked and labeled in VICON Nexus and post-processing performed in Visual 3D (C-Motion Inc., USA). The foot kinematics were filtered with a fourth-order zero-phase lag Butterworth filter having a cutoff frequency of 12 Hz. The foot inter-segment angles were calculated according to the method proposed by Grood and Suntay (flexion, adduction, and rotation)(Grood & Suntay, 1983). The following foot inter-segment kinematic variables were selected in this study: hindfoot relative to tibia (HF/TB), forefoot relative to hindfoot (FF/HF) and hallux relative to forefoot (HX/FF, sagittal plane only). For foot kinematic variables, angle values at HC/HO and TO/TC, as well as peak angles and range of motion (ROM) values in the stance phase were derived(Mei, Fernandez, Fu, Feng, & Gu, 2015). The foot was divided into seven anatomical regions: including big toe (BT), other toes (OT), medial forefoot (MFF), central forefoot (CFF), lateral forefoot (LFF), midfoot (MF) and heel (H). Variables include peak pressure (peak pressure distributed to each region measures from pressure insole) and contact area (the number of the pressure insole sensors activated).

Statistical analysis

Statistical analysis was conducted using a commercial statistical package (SPSS 22.0, SPSS Inc., Chicago, IL, USA). Shapiro-Wilks test was used to check the normality of each variable and that each one was normally distributed. A two-way ANOVA (forward/backward walking × barefoot/shod condition) with post-hoc Bonferroni pair-wise comparisons to examine spatiotemporal parameters including walking speed, SL, SF and ST; foot inter-segment kinematics including initial contact angles, peak angles, push-off angles and ROM; foot sub-region peak plantar pressures and contact area. Bonferroni post-hoc pair-wise comparisons were carried out to provide details of significant differences. Data are presented as Mean ± Standard Deviation (SD). All significance levels were set at p=0.05.

Results

Spatial-temporal parameters

Main effects of FW/BW walking patterns

There was a significant decrease in walking speed (BF: p=0.026; SH: p=0.013, post-hoc test) and stride frequency (SF) (BF: p=0.007; SH=0.016) during BW, relative to FW. On the contrary, a significant increase in stride length (SL) (BF: p=0.002; SH: p=0.005) and stance time (ST) (BF: p=0.013; SH: p=0.004) were found in BW compared with FW (Table 1).

Main effects of BF/SH conditions

Significantly higher SL was found under shod condition during both FW and BW (FW: p=0.021; BW: p=0.009). However, there was a significantly decreased SF under shod condition during FW and BW (FW: p=0.023; BW: p=0.018), relative to BF condition.

Interactions

There were no statistically significant interactions ($p=0.088-0.909$) between FW/BW patterns and BF/SH conditions for the spatiotemporal parameters.

---Insert Table 1 near here---

Foot inter-segment kinematics

Foot inter-segment kinematic patterns of the hindfoot relative to tibia (HF/TB), forefoot relative to hindfoot (FF/HF), and hallux relative to forefoot (HX/FF) are plotted against percent of stance for the FW and time-reversed BW patterns under BF/SH conditions (Figure 2). The selected crucial points of foot angle characteristics of HF/TB, FF/HF and HX/FF are presented in Table 2, Table 3 and Table 4, respectively.

Main effects of FW/BW walking patterns

For the HF/TB angles, in the sagittal plane, HC/HO angles were significantly decreased (BF: $p<0.001$; SH: $p=0.002$) in BW compared with FW. Significant increase of maximum HF/TB dorsiflexion angle (BF: $p<0.001$; SH: $p<0.001$) and DF/PF ROM (BF: $p=0.003$; SH: $p=0.001$) in this plane existed in BW, relative to FW. In the frontal plane of HF/TB, the HC angles in FW under BF and SH conditions were $-1.8\pm4.3°$ and $-3.0\pm5.1°$. Note that a negative angle value is defined as eversion, therefore an eversion tendency of HF/TB motion was found in the HC during FW compared to BW in the HO. Significantly greater maximum HF/TB inversion (BF: $p=0.005$; SH: $p=0.002$) was found in BW compared with FW. In the transverse plane of HF/TB, external rotation in HO was also found in BW in comparison with FW in HC under both conditions. Significant decrease of peak internal rotation (BF: $p=0.013$; SH: $p=0.018$), peak external rotation (BF: p<0.001; SH: p=0.004) and IR/ER ROM (BF: p<0.001; SH: p<0.001) in this plane existed in BW compared FW. For the FF/HF angles, in the sagittal plane, the plantarflexion/dorsiflexion was significantly different at TO/TC. Pairwise comparisons revealed the forefoot dorsiflexion with respect to hindfoot in BW significantly greater than FW at TO/TC (BF: p<0.001; SH: p<0.001). In the frontal plane of FF/HF, significantly greater peak pronation (BF: p=0.021; SH: p=0.033) was shown in BW compared with FW. The TO/TC pronation angles in BW showed significantly more pronated (BF: p<0.001; SH: p<0.001) comparison with FW. In the transverse plane of FF/HF, BW was at a more abducted position in HO. A significant decrease of FF/HF peak ADD (BF: p<0.001; SH: p<0.001) and ROM (ABD/ADD) (BF: p=0.015; SH: p=0.027) at TO/TC was found in comparison with between BW and FW. For the HX/FF angles, only sagittal plane included for analysis. A significant decrease of dorsiflexion angle (BF: p<0.001; SH: p<0.001) at HC/HO was found in BW at both conditions. The maximum dorsiflexion angle in FW was found significantly greater (BF: p<0.001) compared to BW only under BF condition. The peak plantarflexion angle (BF: p<0.001; SH: p<0.001) in BW were found significantly higher than FW. However, DF/PF ROM of HX/FF showed significantly lower in BW under BF condition (BF: p<0.001).

Main effects of BF/SH conditions

For the HF/TB angles, in the sagittal plane, SH walking showed a greater peak DF angle (FW: p=0.012; BW: p=0.008) compared with BF walking. While SH walking showed significantly smaller peak PF angle (FW: p=0.021; BW: p=0.016) compared with BF walking in both walking patterns. In the frontal plane of HF/TB, at HC/HO, SH walking was less dorsiflexed (FW: p=0.022) in FW and more plantar-flexed (BW: p=0.017) in BW compared with BF walking. For the FF/HF angles, in the sagittal plane, the TO/TC angles were found more dorsiflexed (FW: $p<0.001$; BW: $p=0.011$) in SH walking compared to BF walking. In the frontal plane of FF/HF, peak pronation angles of SH walking were significantly greater (FW: $p=0.023$; BW: $p=0.031$) than BF walking. In the transverse plane of FF/HF angles, the HC/HO angles were presented more abducted (FW: $p=0.007$; BW: $p<0.001$) in SH compared to BF walking. Significantly decreased peak adduction angles (FW: $p=0.005$; BW: $p=0.009$) of SH walking existed compared to BF walking at both walking patterns. For the HX/FF sagittal plane angles, a significantly smaller dorsiflexion angles (FW: $p=0.022$; BW: $p=0.012$) at HC/HO were shown in SH condition compared to BF condition. Post-hoc analysis indicated less dorsiflexion (FW: $p<0.001$) in SH condition during FW pattern. The HX/FF ROM was also significantly smaller (FW: $p<0.001$) in SH condition compared with BF condition only during FW walking pattern.

Interactions

For the HF/TB angles, There was a Pattern × Condition interaction ($F=7.593$, $p=0.022$) existed in the HC/HO angle in the frontal plane of HF/TB. For the FF/HF angles, Pattern × Condition interactions were only found in the transverse plane. There was a Pattern × Condition interaction ($F=28.261$, $p<0.001$) for the ADD/ABD ROM. For the HX/FF sagittal plane angles, there was a Pattern × Condition interaction ($F=24.643$, $p<0.001$) for the DF/PF ROM.

---Insert Figure 2 near here---

---Insert Table 2 near here---

---Insert Table 3 near here---

---Insert Table 4 near here---

Plantar pressures

Peak pressure and contact area were collected in this study to evaluate foot loading characteristics of FW/BW patterns under BF/SH conditions. The comparison of peak pressure and contact area in the plantar sub-sections is shown in Figure 5 and Figure 6, respectively.

Main effects of FW/BW walking patterns

The peak pressure of BW was significantly higher in the big toe (BT) (BF: $p<0.001$; SH: $p<0.001$) and medial forefoot (MFF) (BF: $p<0.001$; SH: $p<0.001$) compared to FW. Conversely, peak pressure in other toes (OT) (BF: $p<0.001$; SH: $p<0.001$), midfoot (MF) (BF: $p=0.012$; SH: $p=0.007$) and heel (H) (BF: $p=0.023$; SH: $p<0.001$) were significantly smaller in BW compared with FW. Significantly greater contact area were found in BT (BF: $p<0.001$; SH: $p=0.006$), MFF (BF: $p=0.031$; SH: $p<0.001$) and MF (BF: $p=0.018$; SH: $p=0.003$) in BW compared to FW. While greater contact area were found in OT (BF: $p=0.011$; SH: $p=0.004$), lateral forefoot (LFF) (BF: $p<0.001$; SH: $p<0.001$) in FW compared to BW.

Main effects of BF/SH conditions

The peak pressure of SH condition was significantly decreased in central forefoot (CFF) (FW: $p<0.001$; BW: $p<0.001$), lateral forefoot (LFF) (FW: $p<0.001$; BW: $p=0.004$) and H (FW: $p=0.021$; BW: $p<0.001$) compared with BF condition. The contact area of the SH condition was found significantly increased in OT (FW: p<0.001; BW: p=0.007). While the SH condition showed reduced contact area in MF (FW: p<0.001; BW: p<0.001) and H (FW: p=0.014; BW: p=0.008) compared with BF condition.

Interactions

Significant statistical interaction was only found in the peak pressure of the heel region, which showed a Pattern × Condition interaction (F=24.654, p<0.001) for this parameter.

---Insert Figure 3 near here---

---Insert Figure 4 near here---

Discussion

The purpose of this study was to analyze differences of FW and BW walking patterns under BF and SH conditions via caparisoning of biomechanical parameters. Previous studies have evaluated lower limb kinematics and kinetics of FW and time-reserved BW. This is the first study using a clinical multi-segment foot model to compare foot inter-segment kinematics of FW and time-reversed BW while walking with and without shoes.

In BW, since the absence of peripheral visual feedback and visual flow, the walking speed generally decreased compared to FW. Therefore, the spatiotemporal parameters showed a significant decrease during BW except for stride length, which was consistent with previous studies(Choi & Bastian, 2007). Walking speed showed no significant difference between BF and SH conditions during both FW and BW walking. A reduction in gait speed was found when barefoot participants walking with their own habitual shoes in a previous study(Lythgo, Wilson, & Galea, 2009). While a standardized flexible shoe was employed in this study, the familiarity of the shoes may potentially have a significant influence on gait biomechanics such as walking speed. Significantly lower stride length and higher stride frequency can be found under BF condition compared to SH condition in BW walking. Lower stride length and higher stride frequency could be reflected as a more stable BW walking strategy in maintaining balance(Elboim-Gabyzon & Rotchild, 2017). The underlying mechanism of better walking stability and performance during BW-BF walking could be explained by the extra signal input from the foot sole tactile system. Hallemans et al.,(Hallemans, Ortibus, Meire, & Aerts, 2010) also reported a shorter stride length and less trunk flexion gait pattern in subjects with visual impairment or blindfolded subjects with normal vision. The reduced visual input is suggested in a more cautious walking strategy with the foot contact the ground for haptic exploration. BW-BF walking may receive more information from the available sensory system which compensates for the decline in input from the visual system. The increased stride frequency and decreased stride length in BW-BF compared with BW-SH walking may also demonstrate an additional strategy for receiving more information from the foot sole with higher frequency to feeling the ground.

In general, the foot motions (HF/TB, FF/HF and HX/FF) observed in FW-BF and FW-SH walking was consistent with previous studies(Damavandi, Dixon, & Pearsall, 2010)(Nicholson et al., 2018). In this study, the characteristics of HF/TB, FF/HF and HX/FF angular displacement patterns were also found similar in FW and time-reversed BW walking patterns under SH and BF conditions. While the selected crucial points of foot inter-segment angles during the stance phase were significantly different between FW and time-reversed BW. For the HF/TB angles, only BF/SH conditions effects were observed in the HF/TB maximum plantarflexion angle. Which indicates a flatter foot placement at initial contact under BF condition compared to SH(Lohman, Balan Sackiriyas, & Swen, 2011). Footwear has been shown to hinder the kinesthesia while barefoot locomotion observed a greater awareness of foot position. Maximum HF/TB and FF/HF dorsiflexion angles were found significantly increased in BW compared to FW. Lee et al.,(Lee, Kim, Son, & Kim, 2013) also reported an increased peak ankle dorsiflexion angle in time-reversed BW (17.9°±2.0) compared with FW (14.8°±2.3). For a normal barefoot walking gait, the calcaneus inverted about 2° in an inverted position when the heel struck (HS) the ground, which showed slightly lateral of center(Hunt, M. Smith, Torode, & Keenan, 2001). While at heel off (HO) in BW, the HF/TB were more everted. For the frontal plane of FF/HF angles, BW was also found more pronated at toe contact (TC) and higher maximum pronation angles under both BF and SH conditions. An everted foot position was demonstrated from the HF/TB and FF/HF frontal plane angle patterns during BW walking. During BW, the participants' anticipation of an increased challenge to medial-lateral balance and lack of visual information may have manifested. Initial corrective backward walking FF/HF pronated toe contact posture and HF/TB everted heel off posture indicate a more cautious stepping pattern compared to FW(Powell, Long, Milner, & Zhang, 2011). This inference has been verified with larger foot contact area in the medial side in BW. These differences in the FF/HF frontal plane angles correspond to conformational changes inside the foot to permit the maximum forefoot plantar surface contact with the ground during BW. Restriction in the transverse plane ROM of the HF/TB and FF/HF due to reduced foot flexibility, which may compensate for medial-lateral body balance and comfortable locomotion in BW. The junction of the hallux/forefoot (HX/FF) is also a major component of the multi-segment foot model, which showed the kinematics of the first metatarsophalangeal (MTP) joint. The sagittal plane HX/FF angles differed for FW and BW at HC/HO correspond to the toe clear need for FW walking. Toe clearance was regarded as a subtle but effective behavior adaption to support foot clearance during FW walking(Mills, Barrett, & Morrison, 2008). Different muscle activation patterns between FW and BW may be the intrinsic factor inducing different foot motion patterns. Decreased HX/FF dorsiflexion angle was observed under SH conditions. The windlass mechanism of the foot is dependent on dorsiflexion of the MTP joint at initial contact to increase plantar aponeurosis tension and in turn inverts the hindfoot. Wolf et al.,(Wolf et al., 2008) observed significantly reduced medial longitudinal arch length in shod walking compared to barefoot walking, which suggested that the shoes inhibit the windlass mechanism. While this study failed to find any difference in foot torsion ROM between BF/SH conditions. Morio et al.,(Morio et al., 2009) suggested that more flexible shoes do not change foot motion as much as conventional shoes. In summary, by using the Oxford multi-segment foot model, small yet consistent variations in foot inter-segment angle patterns were distinguishable between FW and BW walking patterns under BF and SH conditions. Main changes in the HF/TB and FF/HF patterns were observed most conspicuous in the frontal and transverse planes, respectively. Increased pronation of FF/HF and eversion of HF/TB sequentially during BW walking ensure sufficient plantar/outsole to ground contact area to maintain balance without disturbing the upper body movements. Restriction in HX/FF dorsiflexion at HO in BW walking induce less plantar aponeurosis tension, which implies inhibition of the windlass mechanism in BW walking. The foot torsion was not disturbed under shod conditions in this current study. Therefore, more flexible shoes or barefooted should be recommended for BW locomotion in general.

The plantar pressure distribution has been previously utilized to analyze foot function. In this study, an obvious FF/HF pronation in the first half stance and HF/TB eversion in the late stance was observed when walking backward resulting in pronated foot placement. Therefore, this increase in pronation when walking backward could be explained by increased contact area in the big toe (BT) and medial forefoot (MFF) while decreased contact area in the lateral forefoot (LFF) and midfoot (MF). The increased surface area of the foot at contact in BW reducing the risk of a slip. Walking barefoot displaying higher plantar pressure in the central forefoot (CFF), and lateral forefoot (LFF) and H regions in both FW and BW walking. Peak plantar pressure in habitually barefoot subjects was observed to be lower in the heel and metatarsal regions compared to shod walking. An increased peak plantar pressure were observed when walking barefoot compared with shoes under the metatarsal heads and calcaneus for habitually shod walkers(Zhang, Paquette, & Zhang, 2013). This suggested that an acute transfer to barefoot walking for habitually shod walkers would correspond to increased plantar pressures in some plantar sub-regions especially in the forefoot and heel regions in both FW and BW walking.

Several limitations concerning this study should not be ignored. Firstly, all subjects were males, which was originally for the purpose of alleviating gender-related locomotion functional differences. Secondly, foot inter-segment kinetics were not included in this study, as the OFM foot model is a kinematic only model. Thirdly, electromyography (EMG) of the lower extremity muscles were not included in this study for BW walking analysis. Future studies should focus on foot inter-segment kinetics and EMG during BW walking with shoes and barefoot. The longitudinal training effect from backward and barefoot walking need to be considered.

Conclusion

In conclusion, the present study shows differences in spatiotemporal parameters, foot inter-segment kinematics, plantar sub-sections peak pressures and contact areas between FW and BW under BF and SH conditions. The increased stride frequency and decreased stride length may be a strategy for BW-BF walking receiving more information from the plantar sensory system which compensates for the decline in visual cue input. The foot inter-segment motion analysis of BW has rarely been studied previously. In the current study, increased pronation of FF/HF in loading response and eversion of HF/TB sequentially in BW-BF walking combined with medially distributed plantar pressure ensure sufficient contact area between plantar and ground to maintain balance. Decreased HX/FF dorsiflexion at HO in BW induces less plantar aponeurosis tension which may inhibit the windlass mechanism compared to FW walking. Based on the findings of this study, BW rehabilitation or training under the barefoot condition is highly recommended for better proprioception with the ground.

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Figure Legends

Figure 1. Experimental set-up (not on scale)

Figure 2. Foot inter-segment kinematics during FW and time-reversed BW under barefoot and shod conditions.

Figure 3. Effect of walking patterns (FW vs. BW) and shoe conditions (BF vs. SH) on peak pressure. Notes. “P” means main effect of walking pattern; “C” means main effect of shoe condition; P×C means interaction.

Figure 4. Effect of walking patterns (FW vs. BW) and shoe conditions (BF vs. SH) on plantar contact area. Notes. “P” means main effect of walking pattern, “C” means main effect of shoe condition.

Table Legends

Table 1. Means ± SD of the Spatial-temporal parameters of FW and BW under BF and SH conditions (N=16).

Variables				ANOVA		
	Pattern	BF	SH	Pattern	Condition	Pattern × Condition
Speed (m/s)	FW	1.34±0.05	1.37±0.06	**F=48.032**	F=2.984	F=0.652
	BW	1.08±0.07	1.12±0.11	**P<0.001**	P=0.088	P=0.440
SL (m)	FW	1.30±0.08	1.33±0.05	**F=8.573**	**F=26.552**	F=0.962
	BW	1.40±0.13	1.44±0.11	**P=0.004**	**P<0.001**	P=0.331
SF (steps/min)	FW	108.9±6.6	105.1±7.5	**F=87.181**	**F=23.382**	F=2.982
	BW	96.7±8.1	93.2±7.2	**P<0.001**	**P<0.001**	P=0.088
ST (s)	FW	0.69±0.02	0.71±0.03	**F=34.042**	F=1.442	F=0.014
	BW	0.80±0.04	0.79±0.06	**P<0.001**	P=0.234	P=0.909

Notes. “SL” represents stride length; “SF” represents stride frequency; “ST” represents stance time.

Table 2. Means ± SD of the hindfoot relative to tibia angles (HF/TB) (°) during stance phase of FW and time-reversed BW under BF and SH conditions (N=16).

Variables					ANOVA		
Planes	Event	Pattern	BF	SH	Pattern	Condition	Pattern × Condition
Sagittal	HC/HO	FW	-1.2±6.0	2.2±5.3	**F=24.651**	F=0.962	F=0.482
		BW	-4.8±7.4	-5.6±8.8	**P<0.001**	P=0.331	P=0.489
	Max DF	FW	12.4±7.1	14.9±8.9	**F=23.014**	**F=17.682**	F=0.591
		BW	18.6±9.8	21.0±11.4	**P<0.001**	**P<0.001**	P=0.462
	Max PF	FW	-9.2±6.0	-6.1±5.3	F=2.692	**F=24.832**	F=2.753
		BW	-7.8±7.4	-5.8±6.8	P=0.105	**P<0.001**	P=0.102
	TO/TC	FW	6.2±5.2	7.2±4.9	F=0.841	F=3.980	F=1.062
		BW	9.4±6.3	8.8±5.5	P=0.362	P=0.077	P=0.303
	ROM (DF/PF)	FW	21.5±7.5	21.0±9.3	**F=18.805**	F=4.693	F=1.073
		BW	25.7±10.4	26.8±8.7	**P<0.001**	P=0.058	P=0.305
Frontal	HC/HO	FW	3.9±5.3	2.0±4.6	**F=26.842**	**F=37.442**	**F=7.593**
		BW	-1.8±4.3	-3.0±5.1	**P<0.001**	**P<0.001**	**P=0.022**
	Max IV	FW	5.6±4.6	4.5±5.5	**F=13.963**	F=2.982	F=0.758
		BW	8.7±4.6	7.1±6.2	**P<0.001**	P=0.124	P=0.407
	Max EV	FW	-4.8±4.4	-6.8±5.1	**F=5.645**	F=0.047	F=0.281
		BW	-4.3±4.9	-6.0±5.5	**P=0.042**	P=0.264	P=0.602
	ROM (IV/EV)	FW	10.4±7.7	11.3±8.4	F=0.813	F=0.101	F=3.399
		BW	13.0±7.2	13.1±6.8	P=0.128	P=0.753	P=0.098
Transverse	HC/HO	FW	2.5±3.6	1.2±3.4	**F=26.093**	F=0.164	F=0.384
		BW	-4.6±5.1	-3.1±6.7	**P<0.001**	P=0.697	P=0.539
	Max IR	FW	10.2±4.4	7.9±4.8	**F=94.215**	F=1.613	F=3.402
		BW	6.8±5.1	4.7±6.7	**P<0.001**	P=0.212	P=0.098
	Max ER	FW	-10.2±2.9	-10.8±3.1	**F=35.055**	F=4.563	F=0.212
		BW	-5.8±4.6	-6.1±4.2	**P<0.001**	P=0.064	P=0.656
	ROM (IR/ER)	FW	20.4±9.5	18.7±6.9	**F=38.365**	F=0.362	F=2.414
		BW	12.6±5.8	10.8±6.3	**P<0.001**	P=0.561	P=0.161

Notes. HC=FW heel contact; HO=BW heel-off; TO=FW toe-off; TC=BW toe contact; DF=dorsiflexion; PF=plantarflexion; IV=inversion; EV=eversion; IR=internal rotation; ER=external rotation; SP=supination; PR=pronation; ROM=range of motion.

Table 3. Means ± SD of the forefoot with respect to hindfoot angles (FF/HF) (°) during stance phase of FW and time-reversed BW under BF and SH conditions (N=16).

Variables					ANOVA		
Planes	Event	Pattern	BF	SH	Pattern	Condition	Pattern × Condition
Sagittal	HC/HO	FW	-7.1±4.6	-5.6±3.8	F=0.175	F=3.063	F=1.226
		BW	-6.4±4.3	-4.5±3.5	P=0.678	P=0.195	P=0.297
	Max DF	FW	5.8±3.5	7.1±4.4	F=0.813	F=0.644	F=0.361
		BW	7.5±4.7	9.1±5.1	P=0.128	P=0.428	P=0.563
	TO/TC	FW	-0.7±3.5	3.6±5.6	**F=79.806**	**F=55.564**	**F=9.164**
		BW	7.5±4.7	9.1±5.1	**P<0.001**	**P<0.001**	**P=0.014**
	ROM (DF/PF)	FW	12.9±4.2	13.1±4.9	F=1.193	F=1.579	F=4.024
		BW	13.6±3.8	13.5±5.5	P=0.305	P=0.244	P=0.076
Frontal	Max SP	FW	6.3±3.4	4.1±5.1	**F=21.392**	F=0.818	F=0.194
		BW	2.8±3.8	2.7±3.7	**P<0.001**	P=0.128	P=0.662
	Max PR	FW	-1.3±3.7	-2.9±4.3	**F=25.813**	F=0.494	F=0.502
		BW	-5.8±4.8	-4.1±5.2	**P<0.001**	P=0.482	P=0.484
	TO/TC	FW	0.6±2.5	0.3±3.1	**F=18.732**	F=0.642	F=0.844
		BW	-5.2±3.6	-3.1±5.2	**P<0.001**	P=0.428	P=0.362
	ROM (SP/PR)	FW	7.6±4.5	7.0±5.2	F=2.672	F=2.023	F=1.043
		BW	8.6±4.1	6.8±3.7	P=0.105	P=0.191	P=0.345
Transverse	HC/HO	FW	0.6±6.9	-2.1±5.3	**F=58.952**	**F=33.288**	F=0.997
		BW	3.2±4.9	0.5±5.5	**P<0.001**	**P<0.001**	P=0.344
	Max ABD	FW	-3.2±4.0	-4.9±4.2	F=3.626	F=2.564	F=1.287
		BW	-3.9±3.8	-4.8±4.6	P=0.089	P=0.143	P=0.286
	Max ADD	FW	6.7±6.9	3.6±5.3	**F=73.388**	**F=87.207**	F=3.688
		BW	3.2±4.9	0.5±5.5	**P<0.001**	**P<0.001**	P=0.087
	ROM (ADD/ABD)	FW	9.9±6.8	8.5±6.2	**F=19.159**	F=0.957	**F=28.261**
		BW	7.1±4.1	5.3±5.8	**P<0.001**	P=0.353	**P<0.001**

Notes. HC=FW heel contact; HO=BW heel-off; TO=FW toe-off; TC=BW toe contact; DF=dorsiflexion; PF=plantarflexion; SP=supination; PR=pronation; ABD=abduction; ADD=adduction; ROM=range of motion.

Table 4. Means ± SD of the hallux relative to forefoot (HX/FF) angles (°) during stance phase of FW and time-reversed BW under BF and SH conditions (N=16).

Variables				ANOVA		
Events	Pattern	BF	SH	Pattern	Condition	Pattern × Condition
HC/HO	FW	22.4±11.5	16.9±10.3	**F=25.990**	**F=28.483**	F=1.584
	BW	7.4±8.9	4.7±5.6	**P<0.001**	**P<0.001**	P=0.212
Max DF	FW	29.8±9.2	23.8±10.3	**F=39.938**	**F=26.941**	F=1.262
	BW	24.4±8.6	24.8±7.9	**P<0.001**	**P<0.001**	P=0.290
Max PF	FW	2.4±6.0	2.7±5.5	**F=33.973**	F=0.703	F=1.225
	BW	4.5±4.9	1.2±5.2	**P<0.001**	P=0.404	P=0.274
ROM (DF/PF)	FW	27.4±8.1	21.1±9.5	**F=26.554**	**F=7.177**	**F=24.643**
	BW	19.9±7.6	23.6±8.4	**P<0.001**	**P=0.009**	**P<0.001**

Notes: HC=FW heel contact; HO=BW heel-off; TO=FW toe-off; TC=BW toe contact; DF=dorsiflexion; PF=plantarflexion; ROM=range of motion.