



# The effect of shoe and floor characteristics on walking kinematics

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## ABSTRACT

It is common sense that walking on sand poses challenges to postural control. However, there are no studies quantifying the kinematics of sand walking compared to other types of postural perturbations such as unstable shoes. The aim of the study was to investigate differences in walking kinematics during walking on solid ground, in unstable shoes and on unstable surfaces. Nineteen healthy young adults ( $23.5 \pm 1.5$  years) performed three different walking tasks: 1) walking at preferred speed while wearing regular shoes; 2) Walking at preferred speed wearing Masai Barefoot Technology shoes and 3) barefoot walking at preferred speed on a large sand grave. Full-body kinematics were recorded during all conditions using an inertial motion capture system. Basic gait parameters (walking speed, stride length and duration), relative vertical center-of-mass position (rvCOM), and ankle, knee and hip joint angles in the sagittal plane were compared across the tasks through statistical parametric mapping over the course of full walking cycles. Participants presented similar walking speed, as well as stride length and duration across different conditions ( $p > 0.05$ ). However, walking on sand reduced the rvCOM ( $p < 0.05$ ), while also requiring greater ankle plantarflexion during stance phase ( $p < 0.05$ ), as well as greater knee and hip flexion during leg swing and initial contact when compared to the other conditions ( $p < 0.05$ ). It was concluded that walking on sand substantially changes walking kinematics, and may cause greater postural instability than unstable shoes. Therefore, walking on sand can be an alternative to improve postural control in patients undergoing walking rehabilitation.

## 1. Introduction

Unstable shoes such as Masai Barefoot Technology have become increasingly popular as a medical training device (Nigg, Emery, & Hiemstra, 2006). The rocker sole deliberately reduce postural stability, eliciting increased lower limb muscle activation and potentially strengthening lower limb and lower back muscles (Nigg et al., 2006; Price, Smith, Graham-Smith, & Jones, 2013). The unsystematic perturbations induced by unstable shoes has been characterized similar to walking barefoot on uneven surfaces. However, walking on sand may be even more challenging, as the floor characteristics change constantly due to the applied forces during stance (Apps, Sterzing, O'Brien, Ding, & Lake, 2017; MacLellan & Patla, 2006) (Fig. 1).

Irregular and compliant surfaces require active postural adjustments through somatosensory mechanisms to detect body orientation with respect to the surface. Adapting to such environmental changes may require self-organization to define the most stable walking pattern, which has been widely investigated through dynamic systems theory (Austin, 2001; Harbourne & Stergiou, 2009). It is shown that highly variable movement patterns may indicate low stability, which may suggest that the biological system is seeking

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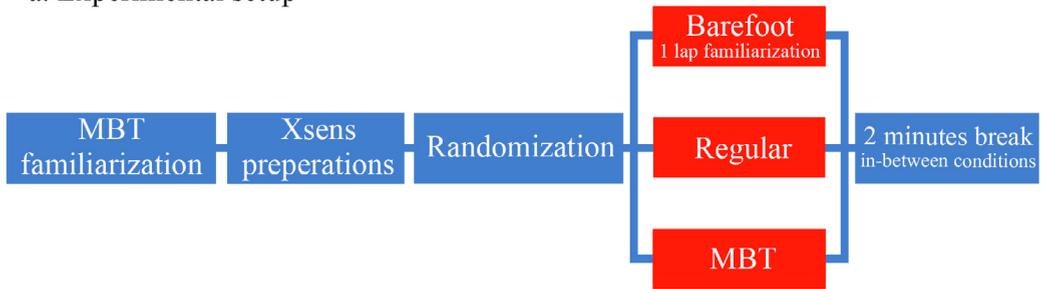
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## a. Experimental setup



## b. Regular, MBT and barefoot conditions

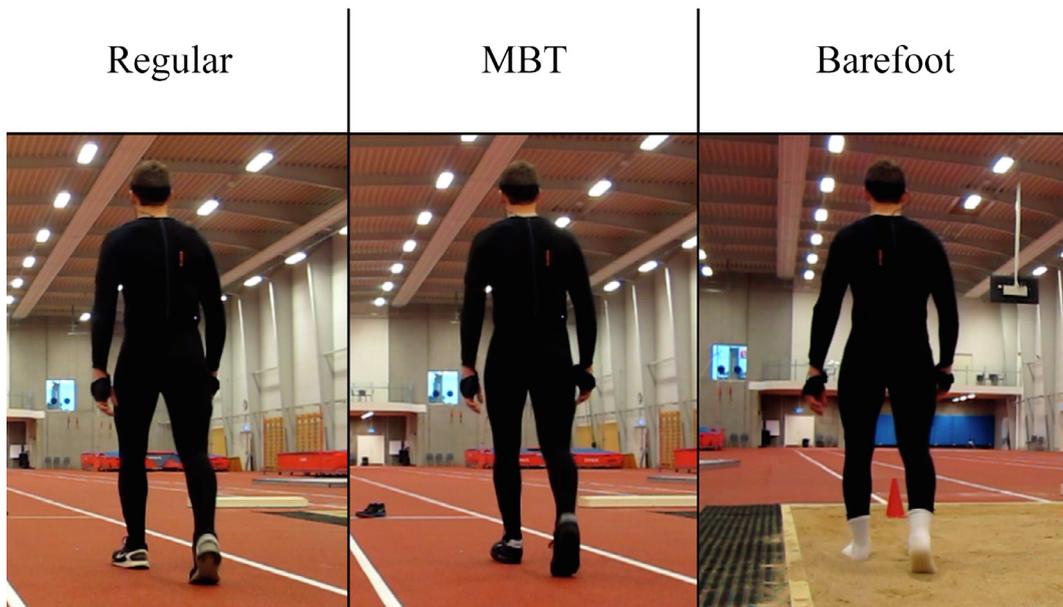


Fig. 1. Experimental setup (a) and illustrative subject walking using regular shoes, MBT shoes and walking barefoot on sand (b).

for optimal solutions to generate stability (Harbourne & Stergiou, 2009; Nessler et al., 2013; Oliveira, Farina, & Kersting, 2012). Considering that the stance phase of walking can be described as an inverted pendulum, postural control during gait is achieved through the interaction of the hip and foot musculature with the gravitational component (Austin, 2001). Therefore, manipulations of the walking surface and/or footwear can introduce perturbations to the trivial optimal control of gait. Such perturbations may increase the complexity of the gait control, which has been shown to be beneficial in gait rehabilitation (Harbourne & Stergiou, 2009).

Previous studies have shown that healthy adults use several strategies to adapt to changes on walking surface and/or footwear. Some strategies involve changes in step length and width to enlarge base of support (MacLellan & Patla, 2006), larger mediolateral center-of-pressure variability (Xu, Wang, Greenland, Bloswick, & Merryweather, 2015), lowered vertical center-of-mass (Chang, Sejdić, Wright, & Chau, 2010; MacLellan & Patla, 2006; Marigold, 2005), and increased hip and knee flexion (van den Berg, Barr, McLoughlin, & Crotty, 2017), producing a greater toe clearance during the swing phase (Gates, Wilken, Scott, Sinitski, & Dingwell, 2012). Walking wearing unstable shoes show similar kinematic trends by increasing knee and hip flexion angles (Demura & Demura, 2012; Taniguchi, Tateuchi, Takeoka, & Ichihashi, 2012), and lowering the center-of-mass position (Choi et al., 2015). However, there are no studies investigating how changes in kinematics from unsystematic perturbations differ between unstable shoes and walking in sand and how kinematic adaptations to promptly counteract surface instability could be used as a functional training modality (van den Berg et al., 2017). In addition, understanding intra-subject variability is highly relevant to describe walking patterns and movement disorders (Lacquaniti, Ivanenko, & Zago, 2012; Oliveira, Gizzi, Farina, & Kersting, 2014; Oliveira, Gizzi, Kersting, & Farina, 2012). Variability becomes important when comparing walking patterns across different surfaces and/or footwear, in which adaptations to better control posture may require greater changes in specific phases of the gait cycle. Previous studies have explored variability in different phases of the gait cycle in barefoot walking (De Cock, De Clercq, Willems, & Witvrouw, 2005) and in the presence of neural disorders (Mari et al., 2014). However, literature still lacks evidence regarding intra-subject variability caused by footwear and/or surface in specific phases of the gait cycle.

The aim of the present study was to describe kinematic differences related to walking on solid grounds using regular shoes (REG) in comparison to walking wearing MBT shoes (MBT) or walking barefoot on sand (SND). We hypothesized that SND walking would induce lower vertical center-of-mass position to maximize stability by creating a larger base of support. Moreover, it was hypothesized that SND walking would induce a more flexed lower limb joint positioning during stance compared to both REG and MBT walking to produce a greater toe clearance during the swing phase on the moving surface that deforms. Lastly, it was hypothesized that SND walking would increase the intra-subject variability for lower limb joint angles in different phases of the gait cycle, due to the unpredictable sand shaping at every step.

## 2. Methods

### 2.1. Participants

Nineteen healthy and physically active college sports students (15 male, 4 female,  $23.5 \pm 1.5$  years, height  $178.3 \pm 9.6$  cm, weight  $77.6 \pm 10.2$  kg) volunteered for the experiment. Exclusion criteria included previous usage of unstable shoes or history of lower extremity injury. All participants provided written informed consent before participation and the procedures were in accordance with the ethical committee of Northern Jutland practices.

### 2.2. Experimental design

In a single session, participants performed three different walking tasks in randomized order: 1) Barefoot walking – walking clockwise at self-selected speed in a rectangular sand grave ( $6.5 \times 1.5$  m) wearing socks; 2) Regular walking – walking at self-selected speed using a pair of their own regular shoes with a flat midsole in a  $6.5 \times 1.5$  m rectangular path marked on the floor with cones on an athletics track; 3) MBT walking – walking at self-selected speed using unstable shoes (MBT 1997) in the same  $6.5 \times 1.5$  m rectangular path. Participants walked five course laps in each condition, separated by a 2-minute rest period.

Anthropometric measurements taken prior to data recordings were used to calibrate the motion capture system. In addition, the height of the shoes was determined by subtracting the ankle height barefoot from the ankle height while wearing shoes. This value was inserted as a parameter in the calibration process. The height for the REG shoe was specified for each participant individually, whereas the height for the MBT shoe was fixed at 3 cm, and the height for SND condition was set as zero. Subsequently, participants were instructed on the basics of walking while wearing MBT shoes, based on guidelines provided by the manufacturer. Participants were instructed to look ahead, keep the head upright and maintain a straight position while walking. Familiarization to the MBT shoes was finished when participants could comfortably maintain straight posture to counteract pronation of the foot and consistently achieve rolling foot movement from heel to toe. One familiarization lap was also provided for the REG and SND conditions.

Participants walked at self-selected speed in all walking conditions. During familiarization to each condition, participants were asked to report their perceived exertion using Borg's RPE scale, which ranged from 6 ("no exertion at all") to 20 ("maximal exertion", Borg, 1970). The target rating was 7–11, which would represent an exertion interval between "extremely light" to "light" effort equivalent to a comfortable walking speed with minimal exertion between  $1.0$  and  $1.4 \text{ m}\cdot\text{s}^{-1}$  (Bohannon, Andrews, & Thomas, 1996; Oliveira et al., 2018; Oliveira, Arguissain, & Andersen, 2018).

### 2.3. Inertial motion capture system

An inertial motion capture system (Xsens MVN Link, Xsens Technologies BV, Enschede, The Netherlands) and its respective software (Xsens MVN Studio version 4.2.4, Xsens Technologies BV, Enschede, The Netherlands) were used to record full-body kinematics (240 Hz sampling rate). The system consist of 17 inertial measurements units (IMU) mounted on a tight-fitting Lycra suit (Fig. 2). Data quality was assured by following the manufacturer's recommendations regarding calibration and distance from sources of electromagnetic fields.

### 2.4. Data analysis

The orientation of each body segment was obtained by fusing accelerometer, gyroscope and magnetometer signals using an extended Kalman filter (Roetenberg, Luinge, Baten, & Veltink, 2005), which is implemented in the MVN studio software. Relevant kinematic variables were extracted from the motion capture recording using the build-in Xsens whole-body model. The right foot position was estimated from its origin at the ankle joint. In addition, tri-dimensional whole-body center-of-mass position, as well as right ankle, knee and hip joint angles were extracted.

A post-recording analysis revealed that the vertical foot position fluctuated between 1 and 5 cm across conditions, despite the use of specific foot height settings during the recordings. This fact is particularly relevant for the SND condition, in which the softness of the sand might allow the feet to move below the floor level. A validation analysis was performed to compare the peak vertical center-of-mass position in relation to the foot position during mid-stance (20–50% gait cycle). The relative peak vertical center-of-mass position was defined as the subtraction of the minimum foot height between 20 and 50% gait cycle from the peak vertical center-of-mass position within the same time interval. The results were non-significant and highly similar across conditions (REG:  $0.982 \pm 0.059$  m; MBT:  $0.979 \pm 0.062$  m; SND:  $0.982 \pm 0.061$  m,  $p > 0.05$ ). These results suggest that the center-of-mass height, relative to the foot position, was not influenced by the type of shoe/floor characteristic. An offset procedure was used to minimize the

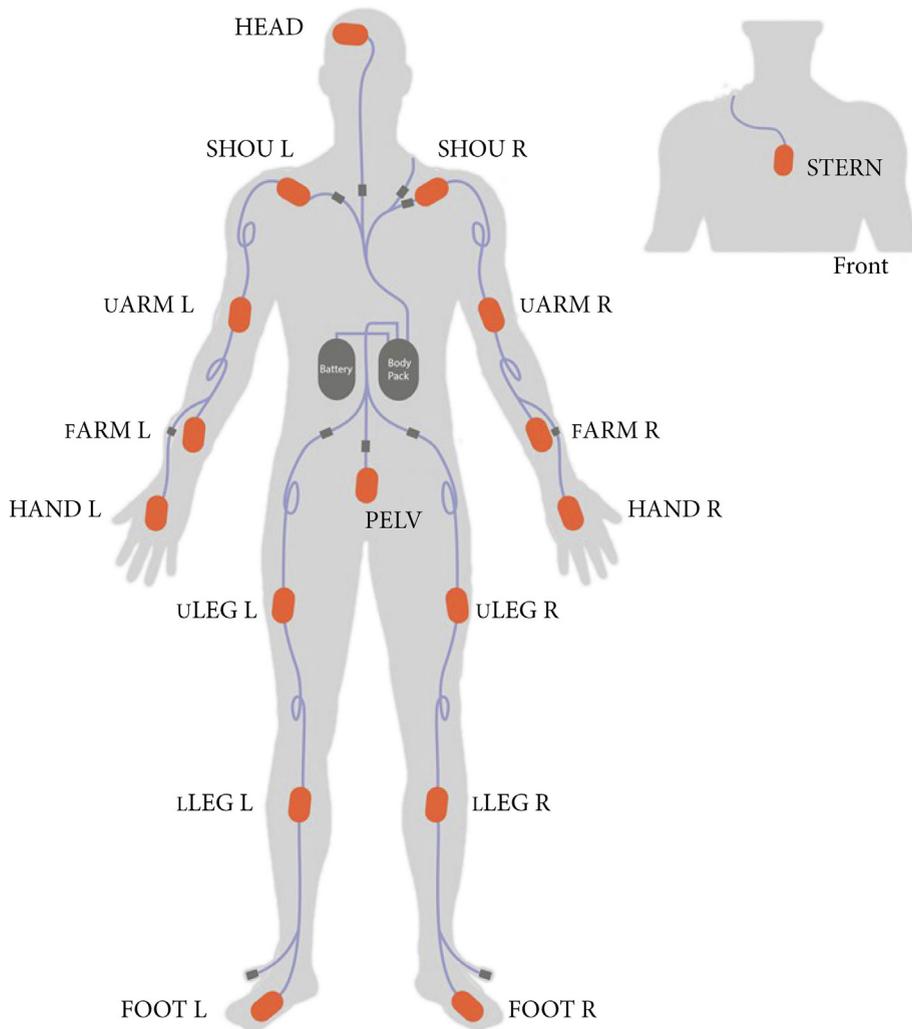


Fig. 2. The definition of the 17 IMUs mounted on each of the 17 segments on the kinematic model of Xsens MVN. From Xsens (2017).

influence of foot vertical position on the vertical center-of-mass position. The vertical center-of-mass position data across a full gait cycle was normalized by its own averaged center-of-mass position. This procedure was conducted for each gait cycle in all conditions. Therefore, further data analysis of the vertical center-of-mass position were performed in relative values (relative vertical center-of-mass position [rvCOM]). All data vectors were low-pass filtered (6 Hz, second-order Butterworth zero-phase).

Custom scripts programmed in MATLAB® (R2015b, Mathworks Inc., Natick, MA USA) were used for data analysis. Data were segmented in relation to the right lower limb gait cycle, which was defined from a peak knee extension on the right lower limb (prior to foot contact to the floor) until the subsequent peak knee extension. This method was chosen due to difficulties in defining the gait cycle using shank vertical acceleration in the SND condition. The stride duration was computed as the time between the beginning of one gait cycle to the next. The stride length was defined as the distance between the beginning of one gait cycle to the next using the right foot horizontal position. Subsequently, all gait cycles were time-normalized to 200 points (Oliveira et al., 2014, 2012). In order to avoid the influence of acceleration, deceleration and turning on the walking paths, only the gait cycles recorded during the long lines (6.5 m) were used in the analysis (Floron, Ubbesen, Battistella, Dejtiar, & Oliveira, 2018). In addition, the first and the last cycle for each run along these long lines were excluded, remaining  $33.6 \pm 6.7$ ,  $31.3 \pm 6.1$  and  $33.4 \pm 6.2$  cycles for analysis for the regular, MBT and SND walking conditions respectively. For each participant, the data from all gait cycles were averaged for each variable for further statistical analysis. In addition, the range of the averaged rvCOM was computed for each condition.

An additional analysis of data variability has been conducted using the rvCOM and the lower limb joint angles. For each participant and condition, the gait cycle was divided into three sectors: early stance (0–20% gait cycle), mid stance (21–60% gait cycle) and swing phase of walking (61–100% gait cycle). The standard deviation of the ankle, knee and hip angles, as well from the rvCOM, was computed across all cycles for each of these three gait cycle sectors in each condition.

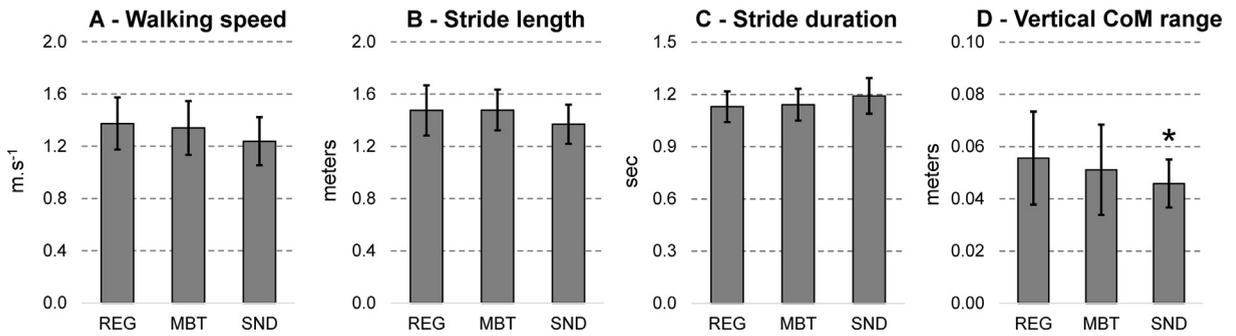


Fig. 3. Mean (SD) walking speed, stride length, stride duration and relative vertical center-of-mass (CoM) range throughout the gait cycle for the regular shoes (REG), MBT shoes (MBT) and walking on sand (SND). \* Denotes significant difference in relation to the REG shoes ( $p < 0.01$ ).

### 2.5. Statistical analysis

The differences between REG, MBT and SND on Borg scale, walking speed, stride duration, rvCOM range and data variability (ankle, knee and hip angles, as well as rvCOM in three gait cycle sectors) were assessed using one-way ANOVA with repeated measures. The rvCOM and lower limb joint angles were analyzed using a curve analysis, one-dimensional statistical parametric mapping (SPM) (De Ridder et al., 2015; Pataky, 2010). SPM has been highly relevant for researchers in the field of human biomechanics as an alternative method to highlight differences related to lower limb kinematics (De Ridder et al., 2015; Liew, Morris, & Netto, 2016). SPM is a statistical method allowing the comparison of continuous time series, providing more intuitive information of differences over time (Pataky, 2010). Therefore, SPM can be useful to underpin differences in kinematic parameters between normal walking and challenging walking conditions throughout entire gait cycles. SPM allows the calculation of the traditional F and t statistics, subsequently referred to as SPM{F} or SPM{t} over the length of the time series. The first step on the statistical analysis was to perform an SPM ANOVA with repeated measures to establish the effect of different conditions (REG vs MBT vs SND) on the dependent variables. When applicable, the post-hoc analysis were conducted as pairwise comparison with the p value adjusted for multiple comparison using the Bonferroni correction. Details regarding the analysis procedure are described elsewhere (Friston, Ashburner, Kiebel, & Nichols, 2007; Pataky, 2010).

## 3. Results

There were no significant differences in the Borg scale reported by the participants across conditions (REG:  $8.7 \pm 0.7$ ; MBT:  $8.9 \pm 0.9$ ; SND:  $8.9 \pm 1.1$ ,  $p > 0.05$ ). Regarding gait kinematics, the different conditions did not influence the walking speed, stride length and stride duration (Fig. 3A–C).

### 3.1. Center-of-mass position

There was a significant main effect of conditions for the range of the rvCOM ( $F(2,36) = 8.66$ ;  $p < 0.01$ ; Fig. 3D). Post-hoc analysis revealed that the range of the rvCOM during REG was significantly greater in comparison to SND ( $p < 0.05$ ).

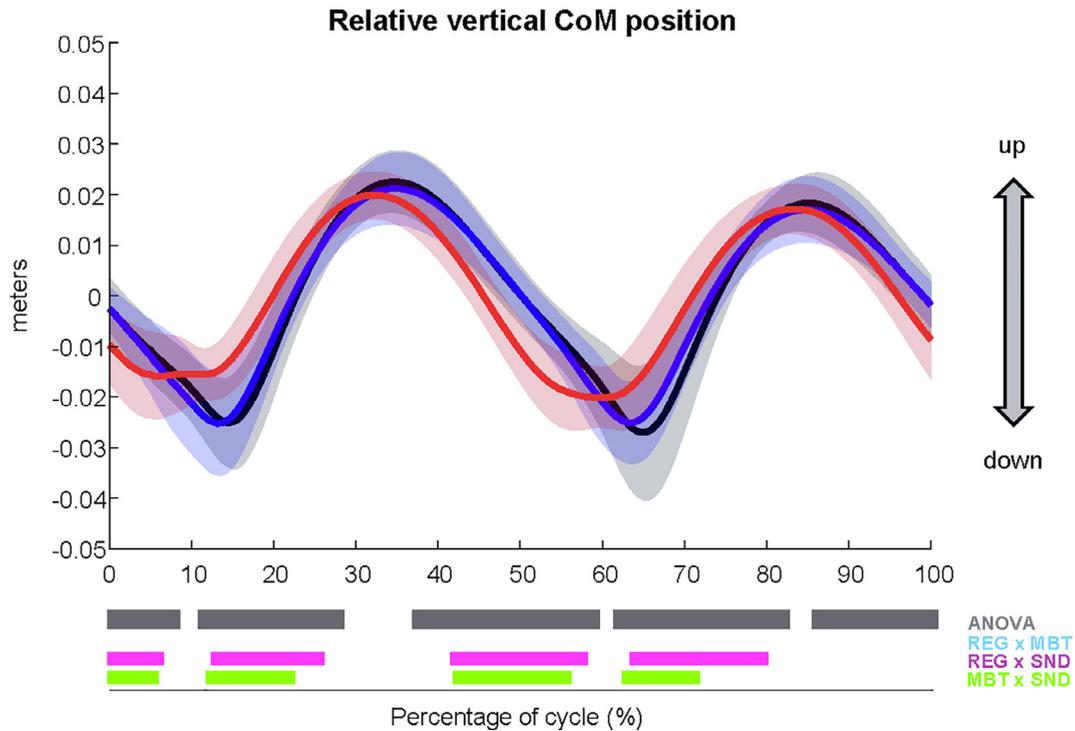
There was a significant main effect of condition for the rvCOM using the SPM analysis for the majority of the gait cycle ( $F(2,36) = 3.229$ ,  $p < 0.05$ , Fig. 4). Post-hoc analysis revealed differences in the rvCOM between SND in relation to REG and MBT during stance and early swing phases ( $p < 0.005$ ).

### 3.2. Ankle, knee and hip joint angles – sagittal plane

There were significant main effects of condition for ankle, knee and hip angles in the sagittal plane ( $F(2,36) = 3.230$ ,  $p < 0.05$ , Fig. 5A–C). For the ankle joint (Fig. 5A), post-hoc analysis revealed increased dorsiflexion for MBT in comparison to REG during early stance and late swing phases ( $p < 0.005$ ). Moreover, SND induced greater dorsiflexion throughout the stance phase in comparison to REG and MBT ( $p < 0.001$ ). No differences were observed between MBT-SND throughout the swing phase, whereas both SND and MBT showed increased dorsiflexion in comparison to REG ( $p < 0.001$ ). For the knee joint (Fig. 5C), post-hoc analysis revealed that SND induced more flexed knee angles in comparison to REG and MBT throughout the swing phase and the subsequent transition to stance ( $p < 0.001$ ). Moreover, the knee was more extended during SND in comparison to REG and MBT during late stance phase ( $p < 0.01$ ). With respect to the hip joint (Fig. 5C), post-hoc analysis revealed that SND induced more flexed hip angles in comparison to REG and MBT throughout the swing phase and the subsequent transition to stance ( $p < 0.001$ ).

### 3.3. Movement variability

There were significant main effects of condition for the intra-subject variability calculated from the ankle, knee and hip joint



**Fig. 4.** Relative center-of-mass (CoM) position in the medial-lateral (A) and vertical direction (B) during gait cycles (defined between two sequential peak knee extensions). The solid lines represent averaged values and shaded areas represent  $\pm 1$  standard deviation for the regular shoes (REG, black), MBT shoes (MBT, blue) and walking on sand (SND, red). The solid line traces below the data correspond to the SPM results. The grey traces correspond to the F values meeting the threshold for significance ( $p < 0.05$ ) from the 1-way ANOVA with repeated measures. The light blue, cyan and green traces correspond to the post-hoc tests p values meeting the threshold for significance ( $p < 0.05$ ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

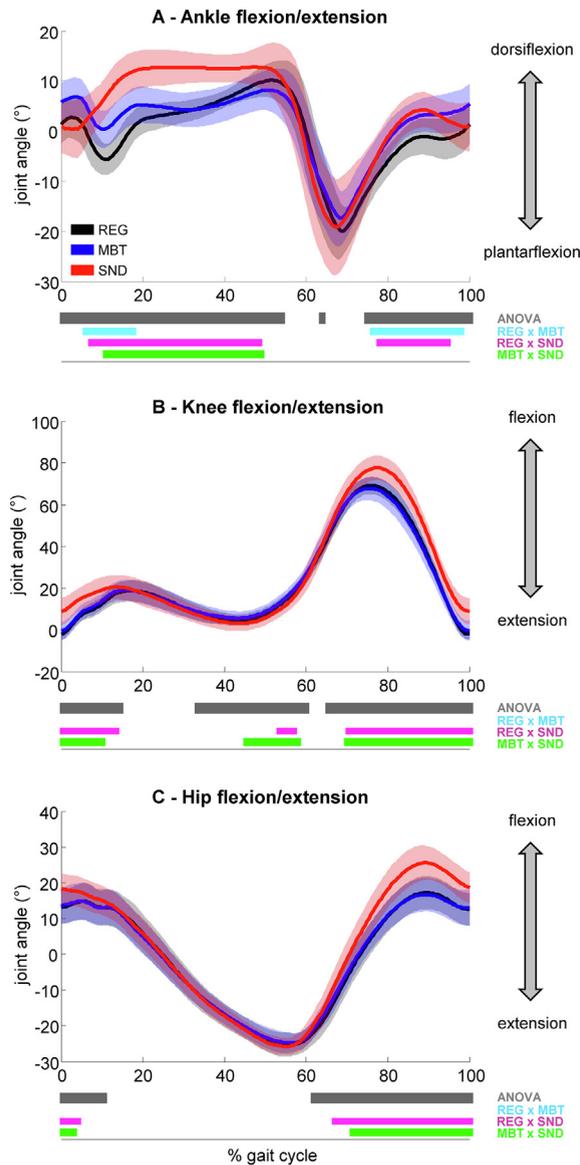
angles during early stance ( $p < 0.001$ ,  $F(2,36) = 21.748$ , Fig. 6, left column). Post-hoc analysis revealed that the variability was greater for SND compared to both REG and MBT for the ankle and hip joints ( $p < 0.0001$ ), whereas the variability was smaller for SND compared to REG and MBT for the knee joint ( $p < 0.0005$ ). During mid-stance, there were also significant effects of condition for all lower limb joints during mid-stance ( $p < 0.05$ ,  $F(2,36) = 3.665$ , Fig. 6, central column). Post-hoc analysis revealed smaller variability for MBT in comparison to both REG and SND for the ankle joint ( $p < 0.01$ ), as well as in comparison to REG for the hip joint ( $p < 0.05$ ). With respect to the swing phase, there were significant main effects of condition for the hip joint ( $p < 0.001$ ,  $F(2,36) = 59.919$ ) and rvCOM ( $p < 0.01$ ,  $F(2,36) = 6.294$ , Fig. 6, right column). Post-hoc analysis revealed greater variability for SND in comparison to both REG and MBT for the hip joint ( $p < 0.001$ ). In addition, there was a greater variability for SND in comparison to REG for the rvCOM ( $p < 0.05$ ).

#### 4. Discussion

Our results showed that walking on sand reduced vertical motion of the center-of-mass and required greater ankle plantarflexion throughout the stance phase, along with more flexed knee and hip joints during leg swing and initial contact. Moreover, it was found that walking on sand increased intra-subject variability of the ankle and hip joint angles during early stance, whereas this variability was reduced for the knee joint. These substantial changes in walking kinematics on sand suggest an increased complexity to perform locomotion, requiring increased need for postural control to achieve dynamic stability. Therefore, it is possible that managing posture in such conditions may be a beneficial stimulus to improve postural control.

##### 4.1. Changes in the center-of-mass position

The center-of-mass overall range and relative position throughout the gait cycle were smaller for SND when compared to REG and MBT. This result corroborates a previous study that measured the center-of-mass position from participants walking on a soft mattress (MacLellan & Patla, 2006). The central nervous system may reduce height of the center-of-mass to increase stability. It has been shown that a lowered center-of-mass decreases the moment arm between the ground reaction force and the center-of-mass, increasing walking dynamic stability and reducing chances of falls (MacLellan & Patla, 2006; Marigold & Patla, 2002). Increased step width and shorter step length are mechanical ways to improve walking dynamic stability (MacLellan & Patla, 2006; Winter, 1995), while also

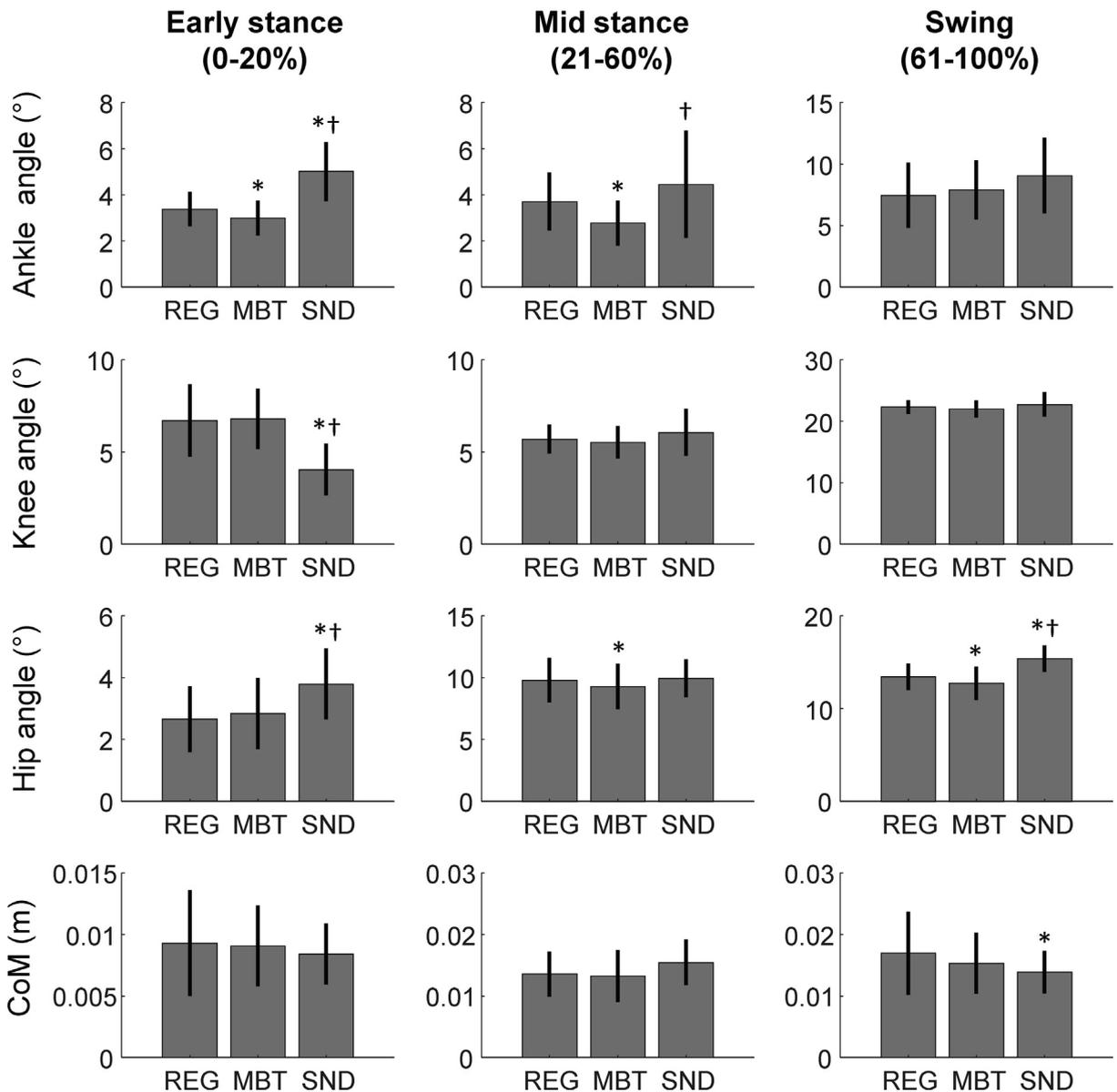


**Fig. 5.** Ankle (A), knee (B) and hip (C) joint angles during a gait cycle (defined between two sequential peak knee extensions). The solid lines represent averaged values and shaded areas represent  $\pm 1$  standard deviation for the regular shoes (REG, black), MBT shoes (MBT, blue) and walking on sand (SND, red). The solid line traces below the data correspond to the SPM results. The grey traces correspond to the F values meeting the threshold for significance ( $p < 0.05$ ) from the 1-way ANOVA with repeated measures. The light blue, cyan and green traces correspond to the post-hoc tests p values meeting the threshold for significance ( $p < 0.05$ ). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lowering the whole-body center-of-mass position. Conversely, the lack of differences in center-of-mass position between MBT and REG does not corroborate previous literature that found smaller center-of-mass position for unstable shoes when compared to REG Choi et al. (Choi et al., 2015). Differences in experimental protocols and especially potential differences in overall kinematics outcomes when comparing optical and inertial motion capture measurements (Fleron et al., 2018) might explain the contradictory results.

#### 4.2. Changes in ankle joint angles

The larger ankle dorsiflexion during the stance phase for SND, in comparison to MBT and REG, may suggest that the compliant sand structure requires larger and somewhat unpredictable ankle movements to stabilize body positioning. In addition, a rearfoot strike on SND may sink the heel and consequently the forefoot rests on a pile of sand that forces dorsiflexion. Additionally, MacLellan and Patla (2006) reported that toe trajectory was increased during walking on unstable surface, to avoid unexpected impact with



**Fig. 6.** Mean (SD) ankle angle (*first row*), knee angle (*second row*), hip angle (*third row*) and vertical center-of-mass (COM) position (*fourth row*) variability (e.g., averaged standard deviation) during early stance (0–21% gait cycle, *left column*), mid stance (21–60% gait cycle, *central column*) and swing phase of walking (61–100% gait cycle, *right column*). Variability was computed for the regular shoes (REG), MBT shoes (MBT) and walking on sand (SND). \* Denotes significant difference in relation to the REG shoes ( $p < 0.01$ ). † Denotes significant difference in relation to the MBT shoes ( $p < 0.01$ ).

deformities in the surface by increasing foot clearance. Sand varies and forms in small piles of different dimensions, making it difficult to predict whether there is a risk of collisions – and subsequent loss of balance – during the swing phase. The increased dorsiflexion while walking on sand may also be related to participants assuming a more stooping posture, in which forward trunk leaning and greater hip/knee flexions may require adjustments on foot kinematics during stance phase of walking. Such foot adjustments are also necessary to provide optimal foot positioning to generate effective propulsion on this soft surface.

Walking wearing MBT shoes induced greater dorsiflexion from 8 to 19% of stance and during the swing phase when compared to REG (Fig. 5). Roberts and co-workers (Roberts, Birch, & Otter, 2011) found that ankle and subtalar joint had a greater range of motion for MBT in the sagittal plane when compared to barefoot walking on normal surface. Although it is difficult to compare results due to different data analyses, our finding seems to corroborate those from Roberts et al. (2011), as MBT induced greater dorsiflexion and similar peak plantarflexion throughout the gait cycle in comparison to REG. No difference was observed during swing phase between MBT-SND, suggesting a similar strategy in the preparation of heel-contact with respectively a soft sole and yielding sand. MBT shoes are constructed with a soft elliptical sole part underneath the heel region that transitions to a firmer and lower sole underneath the

forefoot area (Roberts et al., 2011; Romkes, Rudmann, & Brunner, 2006). Walking in sand will cause the heel to sink into the sand, leaving a pile of sand that the forefoot rests on. Therefore, both MBT and SND conditions would allow the heel to sink while prevent the forefoot from plantarflexing at initial contact.

#### 4.3. Changes in knee and hip joint angles

The higher flexion during take-off and swing phase could be a compensation to the loss of momentum during stance phase. Lejeune, Willems, and Heglund (1998) and Davies and Mackinnon (2006) suggested that walking on the yielding sand structure results in increased energy consumption, due to energy spent to deform the sand. Our results suggest that the central nervous system actively coordinates lower limb joints towards flexion to allow for adequate foot clearance (Schulz, 2011). Furthermore, the higher hip flexion during SND, could also be caused by a more stooping posture during walking on the yielding sand structure. Such stooping posture causes a forward trunk center-of-mass motion, which must be counteracted to avoid exacerbated forward leaning and subsequent risks of falls (Marigold, 2005). The greater knee and hip flexion found during SND corroborate a previous study that compared the kinematics of walking on sand and regular floor in patients with multiple sclerosis (van den Berg et al., 2017). The higher flexion during take-off and swing phase could be a compensation to the loss of momentum during stance phase. Lejeune et al. (1998) and Davies and Mackinnon (2006) suggested that walking on the yielding sand structure results in increased energy consumption, due to energy spent to ambulate the sand.

#### 4.4. Movement variability

In this study we calculated the intra-subject variability in different gait phases and across the difference walking conditions to provide an estimation of consistency in performing the walking tasks. The greater variability for the ankle joint during SND throughout the stance phase may remarkably represent the instability caused by the soft sand. Interestingly, both ankle and hip joints presented greater variability during early stance, whereas there was a reduced variability for the knee joint during this gait phase. These results strongly agree with previous descriptions of the interaction between foot and hip muscles to control gait from an inverted pendulum perspective (Austin, 2001; Winter, Patla, & Frank, 1990). The ankle and hip joints must constantly adapt to the environmental changes for every step, whereas the knee joint seems to be constrained to reduce the need for additional factors to be controlled. Similar rationale may be applied to the smaller variability found for the ankle and hip joints during MBT walking compared to REG, where the control of the foot and hip positions may allow optimal postural stability while using shoes with curved soles.

Increased ankle and hip variability during walking on sand may suggest increased complexity of the movement task, which seems to be highly desirable in clinical settings (Harbourne & Stergiou, 2009). A recent study has shown that patients with multiple sclerosis can adapt to walking on sand, but return to baseline kinematic patterns when returning to walking on regular floor (van den Berg et al., 2017). These authors also highlight the need to investigate the potential of walking on sand as a gait retraining strategy. It is possible to speculate that combining a lowered center-of-mass with more flexed knee and hip angles may have contributed to achieving lateral stability in SND condition. Nonetheless, walking on sand required greater variability throughout the task, which may suggest an increased complexity that can provide functional training benefits due to the instability caused in such condition.

A short period of adaptation to walking on sand and on unstable shoes may be a limitation of this study, as the lack of practice could exacerbate the differences in relation to the normal walking condition. A limitation of our study is the lack of data analysis from the medial-lateral center-of-mass position, which could provide relevant insights on postural stability on the frontal plane. However, MacLellan and Patla (2006) found that the medial-lateral center-of-mass trajectory did not differ between normal and compliant surface. The medial-lateral position was avoided in this study due to low consistency on the center-of-mass trajectory across participants. This issue might be caused by different walking trajectories with respect to the global reference on the motion capture recording software, especially when involving walking in a rectangular loop.

In summary, SND condition reduced vertical motion of the center-of-mass and more flexed knee and hip angles in the swing phase. Moreover, some similarities between MBT and SND were observed particularly in ankle movements, as both conditions induced instability during walking. The combination of greater ankle/hip joint angle variability and smaller knee joint angle variability was indicative of increased postural demands to walk on sand. Therefore, walking on sand may be an interesting alternative to conduct exercises in patients undergoing locomotor rehabilitation, as well as patients in need of improvements on postural control in general.

#### Conflict of interest

The authors declare that they have no conflict of interest.

#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.humov.2019.03.014>.

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