Obese adults walk differently in shoes than while barefoot

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ABSTRACT

Background: Some comparisons between walking gait of obese and non-obese adults have been made during barefoot conditions, and others while shod. Methodological differences, footwear conditions, and gait speed disparities among the research done on overweight individuals were the factors motivating the present study.

Research question: The present study was designed to compare gait kinematics and kinetics of obese adults between two footwear conditions (barefoot versus shod) at a set walking speed.

Methods: Ten obese (body mass index > 30 kg.m^{-2}), but otherwise healthy adults (age = 26 ± 3 years, height = 1.79 ± 0.10 m, mass = 108.46 ± 13.25 kg) participated in this study. Ground reaction forces and 3D kinematic data were simultaneously collected as participants walked overground at 1.5 m.s^{-1} in barefoot and shod conditions.

Results: Walking barefoot reduced ankle, knee, and hip ranges of motion, and stride length, stance time, and double support time were also reduced. Kinetic outcomes included smaller peak vertical and anterior-posterior ground reaction forces and knee joint moments while barefoot.

Significance: Footwear condition significantly influences key gait variables in obese adults. Conflicting conclusions from previous investigations of gait in obese adults may be a consequence of differing footwear conditions.

1. Introduction

Obesity is a major health issue in the United States. Data from a recent Centers for Disease Control and Prevention report estimates that approximately 36.5% of American adults are obese [1]. Musculoskeletal issues associated with obesity include general pain of the low back and neck [2] and osteoarthritis which could result in knee and hip joint replacements [3]. Increased joint loads during activities of daily living (ADLs) may contribute to the greater prevalence of osteoarthritis in obese individuals [3,4]. Weight loss is suggested as a means to decrease these joint loads [5]; however, ADLs such as walking, which can contribute to weight loss, also produce significant loads on the lower extremity joints. Indeed, walking accounts for a significant portion of ADLs and thus contributes greatly to joint loads.

Increased body mass promotes walking patterns that differ from lean adults. In comparison to non-obese individuals walking at a similar speed, obese individuals use longer stance and double support times [6,7], wider steps [7], and shorter swing times [8]. In terms of joint kinematics, obese individuals generally have a more extended leg at initial foot contact and throughout stance compared to lean adults [8,9]. Increased body mass also leads to different kinetic profiles that accompany changes in the spatiotemporal and kinematic patterns. In absolute terms, peak vertical, anteroposterior, and mediolateral ground reaction forces (GRFs) are greater with obesity, with the increase in vertical and anteroposterior GRFs nearly proportional to the increase in total mass [6]. The impact of obesity on joint kinetics is less clear as some have reported larger joint moment magnitudes at the knee [6], whereas others have reported lower joint moment magnitudes at the knee [8], or no difference compared to non-obese individuals [10]. Differing conclusions may be a result of the BMI ranges recruited. Average body mass index (BMI) in Lai et al. [10] was 33.06 kg m^{-2} compared to the larger average BMI of 42.3 kg m^{-2} in DeVita & Hortobágyi [8]. Likewise, the range of BMI values in Ranavolo et al. [7] was 33.8–44.0 kg m^{-2}.

Besides level of obesity, the contradictory joint kinetic outcomes presented above might be due to whether or not the participants wore shoes. Participants walked barefoot in two of these studies [7,10], and shod in two others [6,8], while McMillan et al. [9] did not report a footwear condition. This makes comparisons of these studies difficult, as the effects of footwear on obese adults is unclear. In lean adults, walking barefoot produces varying spatiotemporal, kinematic, and kinetic patterns compared to shod walking. For example, walking barefoot promotes shorter strides [11,12] and reduced stance [12,13], swing [12], and double support times [12] compared to walking in

shoes at a fixed speed. These patterns are associated with reduced anteroposterior and vertical GRFs [11,13] and reduced lower extremity joint ranges of motion [12,13]. In terms of joint moments, it appears that walking barefoot reduces hip flexor moments and ankle dorsiflexion moments, whereas knee moment outcomes are less consistent [11,13]. Whereas Keenan et al. [11] reported a larger knee flexor moment while barefoot, Zhang et al. [13] found no differences in knee moments. Similar reductions in spatiotemporal, GRF, and joint moment parameters have also been reported for individuals with knee osteoarthritis when walking barefoot compared to shod [14]. Given the high rate of obesity and its association with osteoarthritis, it is of interest to understand the unique effects of footwear on this population.

Other differences in methodology, such as the use of different walking speeds and joint kinetic normalization methods may also have contributed to differing conclusions regarding gait biomechanics in obese adults. For example, Ranavolo et al. [7] did not control walking speed, but instructed the lean adults to walk slowly, while the obese adults were told to walk naturally. No significant difference in speed between groups was reported, but these conflicting instructions may have impacted walking strategies. Finally, Browning and Kram [6] were interested in absolute joint moments and GRFs to understand the loads experienced by the lower extremity while DeVita and Hortobágyi [8] reported moments normalized to mass (but also emphasized the non-normalized data), and others normalized moments to mass and height [9,10].

In summary, contradictory outcomes from previous gait studies of overweight individuals were likely due to methodological differences (e.g., normalization approaches), footwear conditions, and gait speed disparities. These various factors confound comparisons among studies and demonstrate the need to understand their unique effects. The present study was designed to compare gait kinematics and kinetics of obese adults between two footwear conditions (barefoot versus shod) at a set walking speed. It was hypothesized that barefoot walking would lead to reduced range of motion and joint moments at the hip, knee, and ankle, and lower ground reaction forces compared with shod walking. Similarly, it was hypothesized that stride length, stance time, swing time, and double support time would also be lower while barefoot.

2. Methods

2.1. Participants

Ten obese individuals (4 women, 6 men) who had a BMI between 30 and 40 $kg\,m^{-2}$ were recruited for this study. Besides being obese, this group was ostensibly healthy (i.e., no cardiovascular, metabolic, or renal disease). Participant characteristics can be found in Table 1. To differentiate between those who were truly obese vs. those whose muscular build may lead to large BMIs, a waist circumference > 100 cm for men, or > 90 cm for women, provided a secondary inclusion criterion. These circumference criteria place an individual in the High Risk for disease category, based on published guidelines from the American College of Sports Medicine [15]. The university's Institutional Review Board approved this study and all participants provided informed written consent prior to participation.

Table 1
Participant characteristics.

Measure	Mean (SD)
Age (years)	26 (3)
Height (m)	1.79 (0.10)
Mass (kg)	108.46 (13.25)
BMI ($kg\,m^{-2}$)	33.75 (2.91)
Shoe mass (g)	321 (90)

2.2. Data collection

Anthropometric data (including body mass and height) were measured for use in VICON's full body plug-in-gait model. Retroreflective markers were attached to the appropriate anatomical landmarks for the same model using double-sided tape. Participants then performed overground walking trials at 1.5 m s^{-1} ± 5% while barefoot and shod. Two pairs of timing gates (BROWER Timing Systems, Draper, UT) spaced approximately 5 m apart were used to capture walking speed. Participants wore their own athletic shoes for the shod conditions (321 ± 90 g) and the order of conditions was individually randomized. During each trial, 3D motion (100 Hz) (VICON, Englewood, CO) and ground reaction force (GRF) (2000 Hz) data were collected. GRFs were measured using a tandem-belt instrumented treadmill (AMTI, Watertown, MA) embedded in the center of the walkway with 2 individual force plates. Participants completed overground walking trials in each condition until three successful attempts were recorded. Trials included in the data analysis were within the expected velocity range and clean foot contacts were made with the force plates (i.e., a single, whole foot contact on each force plate).

2.3. Data analysis

Markers were labeled with VICON Nexus, but all subsequent processing of data was performed using a custom Visual3D (C-Motion, Germantown, MD) script. Marker data were filtered using a recursive, digital Butterworth lowpass filter (f_c = 6 Hz). This cutoff frequency was confirmed by a residual analysis. GRF data were filtered using a recursive, digital Butterworth lowpass filter (f_c = 50 Hz). Motion and GRF data were combined through inverse dynamics to estimate joint reaction forces and moments for the ankle, knee, and hip in the sagittal plane for a single limb. Joint moment peaks were selected based on the description by Winter [16]. Absolute GRFs and joint moments were selected for analysis in this study due to the within-subject statistical design.

Spatiotemporal and kinematic dependent measures were also identified. Spatiotemporal dependent variables included stride length, stance time, swing time, and double support time. Kinematic variables included angular ranges of motion (ROM) and joint angles at initial contact for the hip, knee, and ankle.

2.4. Statistical analysis

Dependent variables were determined from three successful strides per condition for each participant and then averaged [17]. A series of dependent t-tests were performed using R [18] to compare dependent variables between conditions. An effect size (Cohen's d) was also calculated for each dependent variable. Effect sizes were interpreted as small if d was 0.2–0.49, medium if d was 0.5–0.79, and large if d was greater than 0.8 [19]. The probability associated with a Type I error was set at 0.05 for all tests.

3. Results

A medium footwear effect was observed in stride length, as participants walked with shorter stride lengths (t = −5.17, p < .001) while barefoot. A large footwear effect was observed in stance times (t = −5.54, p < .001) and double support times (t = −5.67, p < .001), where both were smaller while barefoot (Table 2). At initial contact, a significant, large difference in ankle angle was observed (t = −3.90, p = .004, and d = −1.59; Fig. 1). The ankle was plantarflexed at contact while barefoot, but dorsiflexed while shod (Fig. 1). The knee angle at contact did not differ between footwear conditions (t = 1.43, p = .19). A small effect for the hip joint was observed with the hip more flexed at contact while barefoot (t = −2.92, p = .017, and d = −0.30; Fig. 1). ROMs were all smaller while barefoot, with large effects at the

Table 2
Spatiotemporal measures. Mean (SD).

	Barefoot	Shod	Effect Size
Stride Length (m)*	1.55 (0.10)	1.63 (0.11)	−0.76
Stance Time (s)*	0.60 (0.04)	0.65 (0.04)	−1.25
Swing Time (s)	0.40 (0.02)	0.40 (0.03)	0.00
Double Support Time (s)*	0.21 (0.03)	0.25 (0.02)	−1.57

Note: * indicates significant footwear effect. $p < .05$.

Table 3
Joint range of motion in degrees. Mean (SD).

	Barefoot	Shod	Effect Size
Ankle*	27.49 (6.13)	34.02 (4.34)	−1.23
Knee*	52.90 (5.46)	59.56 (4.41)	−1.34
Hip*	47.30 (5.54)	48.66 (5.53)	−0.25

Note: Range of motion = maximum angle – minimum angle of each joint throughout the entire gait cycle. * indicates significant footwear effect. $p < .05$.

ankle (t = −5.65, p < .001) and knee (t = −3.78, p = .004), and a small effect at the hip (t = −4.13, p = .002) (Table 3).

Walking barefoot produced large reductions in peak braking (t = −2.28, p = .048) and propulsive forces (t = −3.77, p = .004) (Fig. 2, Table 4). A small footwear effect was observed in the initial vertical GRF peak, which was smaller while barefoot (t = −2.40, p = .040), but no differences were observed between footwear conditions for the second peak vertical GRF. A medium effect was observed in the minimum vertical GRF (between the peaks), which was larger while barefoot (t = 5.19, p < .001).

The maximum plantar flexor moment was not significantly different between walking conditions (Fig. 1, Table 4). Walking barefoot reduced early stance knee extensor moments (t = −2.69, p = .025). At ˜40% of stride, barefoot walking resulted in knee flexor moments, while in the shod condition the knee moment remained extensor through toe-off (˜60% of stride). This resulted in a significant difference between the knee moments for the two conditions at their minima (˜40% of stride) (t = −2.79, p = .02). Both of these knee moment outcomes had large effect sizes. Hip moments did not differ between footwear conditions.

4. Discussion

The purpose of this study was to investigate the impact of footwear on walking mechanics in obese, but otherwise healthy, adults. While

barefoot, participants reduced stride lengths, GRFs, and knee moments. Notably, the knee moment during mid stance (˜30–40% of stride) was flexor while walking barefoot, whereas in the shod condition the knee moment remained extensor, indicating differing neuromuscular control patterns between footwear conditions. Additionally, with the exception of two dependent variables, all significant differences had large effect sizes.

Walking barefoot produced spatiotemporal responses consistent with the literature [11–14]. We observed shorter strides, stance times, and double support times when walking barefoot compared to shod. Without the cushion of a shoe, the shorter strides and forefoot contact may reduce the impact against the heel at initial contact and lead to the reduced temporal measures. In addition to these spatiotemporal findings and the early stance plantar flexed ankle angle while barefoot, the hip was more flexed at contact without shoes. This ankle position also resulted in a lack of dorsiflexor moment for the barefoot condition (Fig. 1); however, the difference in magnitudes of the early stance ankle moments was not significant. A similar kinematic difference while barefoot at the ankle during weight acceptance has been reported elsewhere in lean adults [13]. Additionally, the initial vertical GRF, and braking and propulsive AP GRFs were reduced while walking barefoot. Collectively, these kinematic and kinetic data suggest participants adopted a lower extremity posture that reduced compressive (vertical) and shear (AP) forces between the foot and ground during stance. In
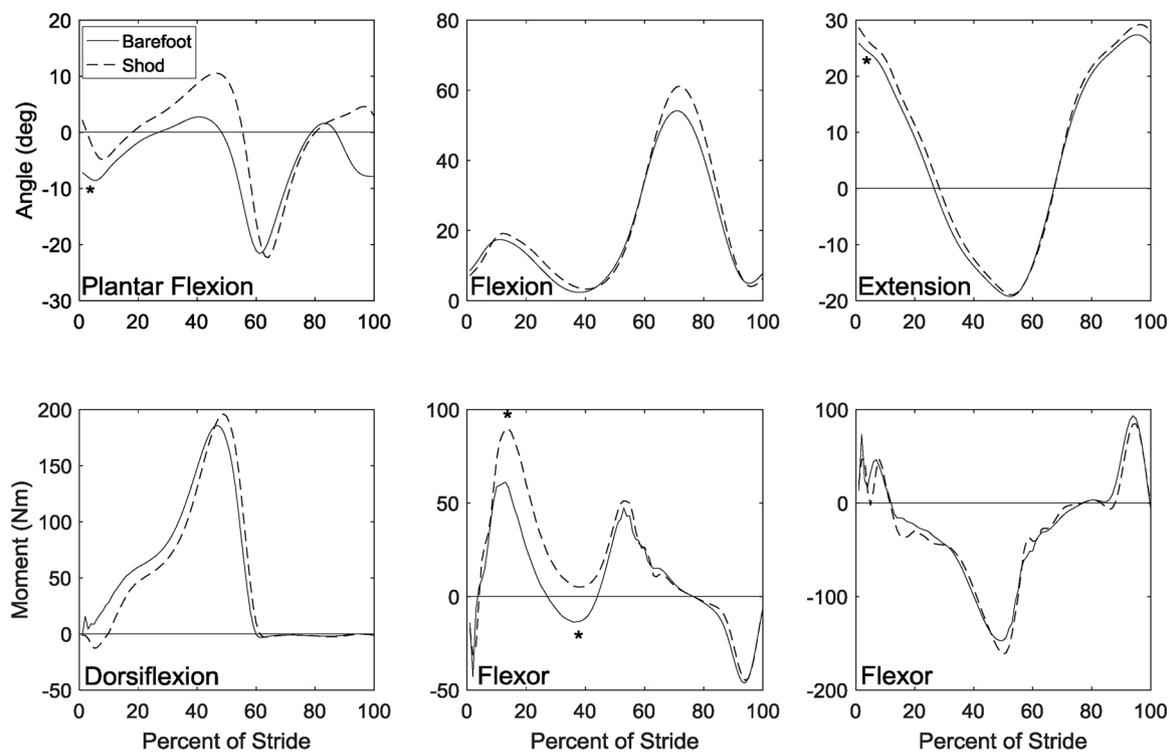

Fig. 1. Group average profiles by condition for sagittal plane ankle (left), knee (middle), and hip (right) angular positions in degrees (top) and joint moments in Nm (bottom).
For joint angles, positive values indicate dorsiflexion and flexion. For joint moments, positive values indicate plantar flexion and extensor. * indicates significant difference between footwear conditions. $p < .05$.
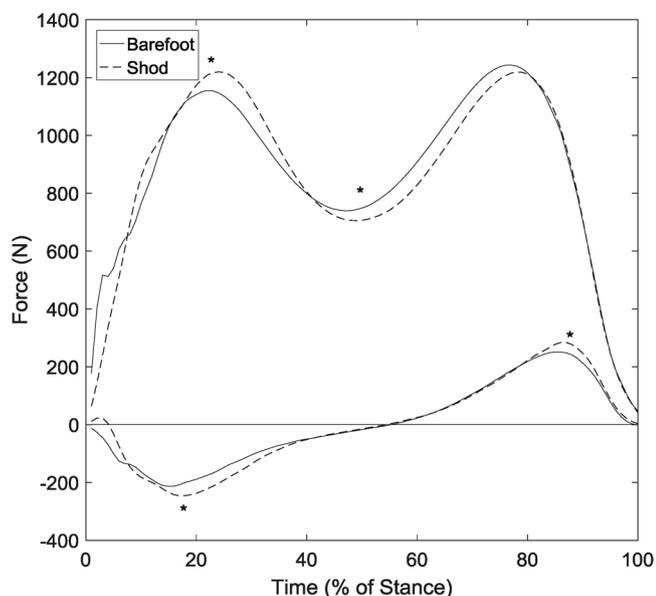
Fig. 2. Group averages by condition for vertical and anterior-posterior ground reaction forces.
* indicates significant difference between footwear conditions. $p < .05$.

Table 4
Kinetic Dependent Variables. Mean (SD).

DV	Barefoot	Shod	Effect Size
GRFs (N)			
VGRF$_1$*	1186.03 (173.18)	1230.09 (153.29)	−0.27
VGRF$_2$	1249.96 (154.46)	1221.64 (153.32)	0.18
VGRF$_{min}$*	918.01 (133.61)	848.31 (109.00)	0.57
Braking*	−227.61 (39.18)	−252.04 (16.11)	0.82
Propulsive*	260.10 (40.67)	287.47 (37.66)	−0.70
Joint Moments (Nm)			
Ankle$_1$	−8.16 (11.31)	−15.22 (7.54)	0.73
Ankle$_2$	187.44 (61.91)	197.51 (25.2)	−0.21
Knee$_1$	−54.68 (23.56)	−38.34 (10.43)	−0.90
Knee$_2$*	59.82 (49.40)	94.92 (41.20)	−0.77
Knee$_3$*	−20.48 (26.46)	3.43 (18.34)	−1.05
Knee$_4$	55.57 (21.07)	55.95 (22.90)	−0.02
Knee$_5$	−48.04 (6.54)	−46.52 (6.79)	−0.23
Hip$_1$	98.04 (30.96)	76.93 (17.27)	0.84
Hip$_2$	−151.11 (47.10)	−160.87 (57.42)	0.19
Hip$_3$	99.60 (22.49)	90.38 (20.50)	0.43

Note: VGRF$_1$ = initial vertical GRF peak, VGRF$_2$ = second vertical GRF peak, VGRF$_{min}$ = minimum between the two peaks, Ankle$_1$ = early stance dorsiflexor peak, Ankle$_2$ = late stance plantar flexor peak (˜50% of stride), Knee$_1$ = knee flexor peak (just after initial contact), Knee$_2$ = early stance knee extensor peak (˜15% of stride), Knee$_3$ = minimum at ˜40% of stride, Knee$_4$ = late stance extensor peak (˜50% of stride), Knee$_5$ = late swing peak (˜90% of stride), Hip$_1$ = early stance extensor peak (just after initial contact), Hip$_2$ = late swing flexor peak (˜50% of stride), and Hip$_3$ = late swing extensor peak (˜95% of stride). $p < .05$.

contrast, others have reported greater propulsive [11,13] and lower braking forces [11] in non-obese adults while walking barefoot at ˜1.3 m s^{-1} compared to when shod. Zhang et al. [13] suggested barefoot walking requires greater propulsive forces due to the lack of heel-toe drop provided by the typical shoe, which may aid in the push-off task. Differing outcomes could be explained by participant characteristic differences among studies. The average BMI in the present study was 33.75 kg m^{-2}, while the average BMIs in Keenan et al. [11] and Zhang et al. [13] were 22.21 and 24.39 kg m^{-2}, respectively. Second, the present study imposed overground walking, while participants in Keenan et al. [11] performed treadmill walking. Differences in the surface-foot interactions may have impacted push-off approach.

Treadmill belts are typically quite rough to prevent foot sliding, which could be uncomfortable for a foot unprotected by a rubber sole.

Walking barefoot reduced knee extensor moments during early stance and promoted a knee flexor moment (instead of extensor) in late stance. Thus, the primary lower extremity joint of interest in obese individuals (i.e., the knee) produced varying outcomes based on footwear condition. The extensor-only profile of the shod condition indicates a different neuromuscular control pattern at the knee which is similar to that seen in knee osteoarthritis gait [20]. Specifically, some individuals with knee osteoarthritis exhibit "stiffened-knee" gait, wherein a consequence of quadriceps weakness is reduced knee flexion coupled with a sustained extensor moment in late stance [21]. An increase in quadriceps strength can alleviate this "stiffened-knee" gait [21]. Whether quadriceps weakness contributed to the extensor-only moment profile of our obese participants during shod walking is unknown, but future research should consider quadriceps strength as a possible mechanism.

Keenan et al. [11] observed similar ankle moment responses between barefoot and shod conditions; however, their data from more proximal joints differ from ours. Keenan et al. [11] reported a reduction in hip extensor and flexor moments and an increase in knee flexor moments. In addition to body composition (obese vs. non-obese) and walking velocity differences (1.5 m s^{-1} vs. ˜1.3 m s^{-1}) among these studies, disagreement in these kinetic outcomes could be due to some participants walking overground, as in the present study and also Zhang et al. [13], versus on a treadmill [11]. Differences in knee and hip moments in particular, but also spatiotemporal parameters, have been reported in lean adults walking on a treadmill compared to overground [22].

Indeed, while to our knowledge there have not been other studies focusing on barefoot vs. shod walking in obese adults, previous investigations have considered footwear approaches to alter gait biomechanics in obese adults. Buchecker, Wagner, Pfusterschmied, Stöggl, & Müller [23] investigated the differences between "conventional street shoes" and Masai Barefoot Technology (MBT) shoes. The latter are intended to reduce joint loading during walking despite their higher mass compared to the standard shoe (650 g vs. 374 g, respectively). In their sample of overweight men (BMI > 25 kg m^{-2}), Buchecker et al. [23] reported a significant decrease in early/late knee adductor moments, but no difference in knee extensor moments, in the MBT shoes. This is in contrast to our results, which did find significant decreases in this measure while barefoot. Additionally, the Masai shoes did not promote late stance flexor moments, as we observed in our participants while walking barefoot. These differences are likely related to the heavier (BMI > 30 kg m^{-2}) individuals recruited for the present study, while only one of their participants fit this criterion. The present study also imposed a slightly challenging, 1.5 m s^{-1} walking speed, while Buchecker et al. [23] allowed individuals to use a preferred walking speed which was not reported.

Removing shoes of the obese adults in the present study promoted reductions in knee extensor moments in early to mid-stance. This adaptation may be associated with reduced joint contact forces and may have beneficial effects, as high joint loads are thought to contribute to joint degradation and development of osteoarthritis [24]. However, obese persons are often encouraged to wear thickly cushioned, heavily supportive shoes for physical activity. Not wearing shoes during low intensity physical activity (e.g., walking) might offset some of the additional load on the knee joint, which over the long term could help reduce the incidence of joint pain that would discourage further physical activity. It should be noted though that the obese adults in our sample did not experience pain with physical activity, so further study would be needed to understand the role of footwear in a cohort of obese adults who do experience pain during walking.

One limitation of this study is the lack of data on the physical activity patterns of these adults. Despite being obese, they were otherwise healthy individuals and may have routinely participated in exercise. An

obese, sedentary individual may respond differently than a physically active obese individual. Future investigations should characterize the physical activity levels of participants to further understand the role of obesity in walking. A second limitation of this study was the lack of control of footwear across participants. Differences in heel-to-toe drop, medial or lateral posting, thickness of cushion, etc. will also influence walking biomechanics.

5. Conclusion

To our knowledge, this is the first study to compare barefoot and shod walking gait in obese adults. Our hypothesis that obese individual would experience smaller peak ground reaction forces, joint moments, spatiotemporal measures, and joint ranges of motion during barefoot walking was supported. Thus, conflicting conclusions regarding the impact of obesity in previous comparisons of obese and non-obese adults may be due to footwear differences between studies (i.e., whether participants were barefoot or shod). Future work should consider the impact of footwear on gait measures and how this may influence comparisons between obese and non-obese adults. Based on the outcomes of this study, obese individuals may benefit from barefoot walking at appropriate times and in appropriate situations and locations. In doing so, and without any weight loss or instruction, obese individuals are able to alter their gait patterns to reduce knee joint moments during barefoot walking.

Conflict of interest statement

The authors do not have any conflicts of interest to declare.

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