In-Shoe Plantar Pressures and Ground Reaction Forces During Overweight Adults' Overground Walking

Marcelo P. de Castro, Sofia C. Abreu, Helena Sousa, Leandro Machado, Rubim Santos, João Paulo Vilas-Boas

Purpose: Because walking is highly recommended for prevention and treatment of obesity and some of its biomechanical aspects are not clearly understood for overweight people, we compared the absolute and normalized ground reaction forces (GRF), plantar pressures, and temporal parameters of normal-weight and overweight participants during overground walking. **Method:** A force plate and an in-shoe pressure system were used to record GRF, plantar pressures (foot divided in 10 regions), and temporal parameters of 17 overweight adults and 17 gender-matched normal-weight adults while walking. **Results:** With high effect sizes, the overweight participants showed higher absolute medial-lateral and vertical GRF and pressure peaks in the central rearfoot, lateral midfoot, and lateral and central forefoot. However, analyzing normalized (scaled to body weight) data, the overweight participants showed lower vertical and anterior-posterior GRF and lower pressure peaks in the medial rearfoot and hallux, but the lateral forefoot peaks continued to be greater compared with normal-weight participants. Time of occurrence of medial-lateral GRF and pressure peaks in the midfoot occurred later in overweight individuals. **Conclusions:** The overweight participants adapted their gait pattern to minimize the consequences of the higher vertical and propulsive GRF in their musculoskeletal system. However, they were not able to improve their balance as indicated by medial-lateral GRF. The overweight participants showed higher absolute pressure peaks in 4 out of 10 foot regions. Furthermore, the normalized data suggest that the lateral forefoot in overweight adults was loaded more than the proportion of their extra weight, while the hallux and medial rearfoot were seemingly protected.

Keywords: biomechanics, gait, locomotion, obesity

Li, & Zhang, 2008). To combat overweight, the most cited approach is to combine exercise and a dietary intervention (Hill & Peters, 1998). Although walking might be critical in terms of biomechanical loading on the musculoskeletal system, this activity is highly recommended and popular for prevention and treatment of overweight (Browning & Kram, 2007). Obesity is associated with a range of disabling musculoskeletal conditions in adults (Anandacoomarasamy, Caterson, Sambrook, Fransen, & March, 2007). The repetitive overload during overweight people's gait has been related to the predisposition to pathological gait patterns, loss of mobility, and subsequent progression of disability (Messier, Ettinger, & Doyle, 1996), as well as to a higher risk for hip and knee osteoarthritis (Felson, 1990; Hochberg et al., 1995; Ko, Stenholm, & Ferrucci, 2010), an increase in the likelihood of foot ulceration (Vela, Lavery, Armstrong, & Anaim, 1998), and heel pain (Prichasuk, 1994). Thus, more attention must be given to the physical/mechanical consequences of repetitive overload, mainly in the lower limbs, to provide support in the areas of prevention, treatment, and control of obesity (Hills, Hennig, Byrne, & Steele, 2002).

The analyses of the three components (horizontals and vertical) of the ground reaction forces (GRF) and plantar pressures can provide useful information about the influence of overweight on the musculoskeletal system (Birtane & Tuna, 2004; Hills et al., 2002; Hills, Hennig, McDonald, & Bar-Or, 2001; Messier et al., 1996). Higher absolute GRF in healthy overweight (no pathology other than overweight) adults compared with normal-weight individuals (Browning & Kram, 2007) and a positive correlation between body mass index (BMI) and absolute GRF components (anterior-posterior, medial-lateral, and vertical) in older overweight adults with osteoarthritis have already been described (Messier et al., 1996). When the mechanical effect of overweight is subtracted from the analyses by scaling data to the body weight (BW), one could expect similar values between overweight and normal-weight individuals. However, a contradiction is observed in these normalized analyses: One article refers to similar horizontal components (anterior-posterior and medial-lateral) and lower vertical GRF (Browning & Kram, 2007), while another observed higher anterior-posterior propulsive force and similar vertical GRF (Lai et al., 2008). Thus, while the absolute GRF values clearly indicate an overall overloading during overweight people's gait, the normalized values suggest some alterations on its pattern, which are not clear. Nevertheless, the temporal characteristics of the foot rollover during walking was shown to be influenced by obesity (Monteiro, Gabriel, Sousa, Castro, & Moreira, 2010), which supports a different temporal gait pattern for overweight individuals.

The assessment of plantar pressure distribution represents an important clinical tool for understanding the structural and functional implications of overweight (Filippin, Barbosa, Sacco, & Lobo da Costa, 2007). The decrease in plantar pressure peaks is considered important for susceptible populations like overweight people to avoid and treat injuries (Pérez-Soriano, Llana-Belloch, Martínez-Nova, Morey-Klapsing, & Encarnación-Martínez, 2011). Significant positive correlations were found between plantar pressures and pain ratings (Hodge, Bach, & Carter, 1999). Two studies addressed the plantar pressure analysis in the overweight adult population. One study (Hills et al., 2001) revealed higher absolute pressure peaks in almost all foot regions, while in the other study (Birtane & Tuna, 2004), overweight individuals showed higher absolute pressure peaks only in the midfoot compared with their normal-weight peers. In both studies (Birtane & Tuna, 2004; Hills et al., 2001), the participants were assessed barefoot, the midfoot and rearfoot were considered as one region, and only absolute data were analyzed. Besides the conflicting results between the studies (Birtane & Tuna, 2004; Hills et al., 2001), there is scarce information regarding plantar pressures during overweight people's walking. Issues such as in-shoe plantar pressures and its analysis as normalized—by BW—values have not been assessed. Assessment of these issues might provide information regarding the behavior of the forces on the interface foot insole, which are not related directly to the excessive BW, and could therefore provide new insights about the adaptations in gait patterns of overweight people. Moreover, because previous studies (Browning & Kram, 2007; Messier et al., 1996) showed differences in the horizontal GRF component when overweight people walked, a more detailed approach—exploring differences in medial and lateral regions—for the midfoot and rearfoot would be interesting to investigate.

A better understanding of the biomechanical features of overweight people during common activities of daily living, such as walking, would be important to identify the characteristics of movement-related difficulties and possible pathogenesis of the musculoskeletal impairments associated to overweight (Wearing, Hennig, Byrne, Steele, & Hills, 2006). Therefore, our aim was to compare the magnitude (absolute values) and pattern (normalized by BW values) of GRF, in-shoe plantar pressure peaks, and temporal parameters between overweight and normal-weight adult participants while walking. We hypothesized that higher absolute GRF and pressure peaks would be observed in the overweight participants compared with their normal-weight peers, that a similar pattern of GRF and plantar pressures would be found between groups, and that there would be differences in the temporal gait parameters between groups.

METHODS

This is a cross-sectional study with a convenience sample. This project was approved by the local ethics committee, and all participants freely signed an informed written consent form based on the Helsinki Declaration.

Participants

We selected two groups of participants: People with BMIs between 20 and 25 were included in the normal-weight group (labeled as NW), and participants with BMIs greater 30 were included in the group of overweight people—labeled as the overweight group (OG). The participants were excluded if they showed any traumatic orthopedic impairment or difficulty with independent gait. The OG included 12 male participants ($M_{\text{age}} = 37.00 \pm 6.06$ years, $M_{\text{height}} = 1.75 \pm 0.04$ m, $M_{\text{body mass}} = 111.20 \pm 10.51$ kg, and $M_{\text{BMI}} = 36.23 \pm 3.54$ kg/m^2) and 5 female participants ($M_{\text{age}} = 36.40 \pm 6.02$ years, $M_{\text{height}} = 1.55 \pm 0.06$ m, $M_{\text{body mass}} = 96.08 \pm 10.52$ kg, and $M_{\text{BMI}} = 40.21 \pm 5.87$ kg/m^2). The NW group also included 12 male participants ($M_{\text{age}} = 27.42 \pm 3.09$ years, $M_{\text{height}} = 1.74 \pm 0.05$ m, $M_{\text{body mass}} = 71.98 \pm 4.68$ kg, and $M_{\text{BMI}} = 23.73 \pm 1.14$ kg/m^2) and 5 female participants ($M_{\text{age}} = 27.4 \pm 1.34$ years, $M_{\text{height}} = 1.60 \pm 0.05$ m, $M_{\text{body mass}} = 52.92 \pm 6.43$ kg, and $M_{\text{BMI}} = 20.67 \pm 1.81$ kg/m^2).

Instruments and Data Acquisition

To record GRF, we used a Bertec force plate (Model 4060-15, Bertec Corporation, Columbus, OH) operating at 1,000 Hz and the Acknowledge software (BIOPAC System, Goleta, CA). To record in-shoe plantar pressures, we used an F-Scan system (TekScan, Boston, MA) operating at 300 Hz with a 0.18-mm thick insole sensor and the F-Scan Research 6.33 software (TekScan, Boston, MA). Three digital video camera recorders, all Sony (Model DCR-HC62E, Sony Corporation, Tokyo, Japan) operating at 50 Hz, and the Dvideo Version 5.0 software (Unicamp, Campinas, São Paulo, Brazil) were used to capture, synchronize, digitalize, and reconstruct the images (Figueroa, Leite, & Barros, 2003). We used an external trigger to start the force plate and in-shoe plantar pressure system simultaneously.

Tasks and Procedures

First, we explained all the procedures of the study to the participants after their weight and height were recorded. We gave each of the participants fitted black shorts, and one reflective marker with a diameter of 1.2 cm was placed with adhesive tape at the right great trochanter of the femur. A cuff unit measuring 98 mm × 64 mm × 29 mm was attached on the lateral malleolus region of both legs of each participant, and a 9.25-mm cable linked the cuff to the VersaTek hub (F-Scan system). The cable did not cause any restriction for walking. Each participant received a pair of thin socks and neutral shoes (ballet sneakers) with sensor insoles inside. Second, the participants familiarized themselves with the trial by walking freely with a comfortable speed (self-selected speed) over a 6-m walkway with the force plate embedded in the middle. One of the researchers identified the starting position for the participants walking at their self-selected speed to hit the force plate without altering their gait pattern. The participants completed three trials in which at least two steps before and after reaching the force plate were performed. We used the third step for further analysis and then we avoided the effects of acceleration (Macfarlane & Looney, 2008).

Data Analysis

We exported the data from the force plate (three GRF components) and in-shoe pressure system (values of each sensor in each frame) to Matlab 7.0 software (MathWorks, Natick, MA) and developed a program to process and calculate the variables. We calculated the following GRF parameters:

- Fz1 (load acceptance peak): first peak from the vertical GRF
- $Fz1_{Imp}$ (load acceptance impulse): the impulse calculated from the beginning of the stance phase to the minimum between the two vertical GRF peaks
- Fz2 (thrust peak): second peak from the vertical GRF
- $Fz2_{Imp}$ (thrust impulse): impulse from the minimum between the vertical GRF peaks to the end of the stance phase
- Fap1 (braking peak): first (negative) peak from the anterior-posterior GRF
- $Fap1_{Imp}$ (braking impulse): impulse calculated from the beginning of the stance phase to the middle zero (negative phase) from the anterior-posterior GRF
- Fap2 (propulsive peak): second peak (positive) of the anterior-posterior GRF
- $Fap2_{Imp}$ (propulsive impulse): impulse from the middle zero to the toe-off from the anterior-posterior GRF
- Fml (medial-lateral peak): positive peak from the medial-lateral GRF
- Fml_{Imp} (medial-lateral impulse): impulse from the beginning to the end of the stance phase of the medial-lateral GRF.

We also calculated the stance phase duration, time of occurrence of the GRF peaks, and the walking speed, which was considered the first time derivative of the great trochanter reflective marker position. For the in-shoe plantar pressure data treatment, first the program divided the foot

TABLE 1
Ground Reaction Forces (GRF) in the Normal-Weight (NW) Group and Overweight Group (OG) During Walking

	Absolute Data				Normalized Data			
Variable	*Unit*	*NW* *M* ± *SD*	*OG* *M* ± *SD*	*p*	*Unit*	*NW* *M* ± *SD*	*OG* *M* ± *SD*	*p*
Fz1	N	684.9 ± 118.3	1,053.0 ± 124.5	< .001	N/BW	1.04 ± 0.04	1.01 ± 0.05	.002
Fz2	N	715.0 ± 100.8	1,098.0 ± 117.2	< .001	N/BW	1.10 ± 0.05	1.05 ± 0.05	< .001
Fap1	N	− 97.0 ± 20.9	− 135.4 ± 33.3	.140	N/BW	− 0.15 ± 0.02	− 0.13 ± 0.03	.141
Fap2	N	120.9 ± 20.3	166.7 ± 25.1	.079	NBW	0.19 ± 0.02	0.16 ± 0.02	.036
Fml	N	66.7 ± 14.5	121.1 ± 21.1	.037	N/BW	0.10 ± 0.02	0.12 ± 0.02	.274
$Fz1_{Imp}$	N.s	165.9 ± 29.3	295.3 ± 48.9	< .001	(N/BW).s	0.26 ± 0.04	0.28 ± 0.03	.300
$Fz2_{Imp}$	N.s	213.7 ± 55.1	340.7 ± 66.2	< .001	(N/BW).s	0.32 ± 0.05	0.33 ± 0.05	.300
$Fap1_{Imp}$	N.s	− 18.2 ± 4.5	− 28.5 ± 5.0	.363	(N/BW).s	− 0.03 ± 0.00	− 0.03 ± 0.00	.300
$Fap2_{Imp}$	N.s	18.2 ± 3.3	28.8 ± 3.9	.353	(NBW).s	0.03 ± 0.00	0.03 ± 0.00	.300
Fml_{Imp}	N.s	29.4 ± 8.0	56.2 ± 12.6	.019	(N/BW).s	0.05 ± 0.01	0.05 ± 0.01	.300

Note. Fz1 = load acceptance peak; $Fz1_{Imp}$ = load acceptance impulse; Fz2 = thrust peak; $Fz2_{Imp}$ = thrust impulse; Fap1 = braking peak; $Fap1_{Imp}$ = braking impulse; Fap2 = propulsive peak; $Fap2_{Imp}$ = propulsive impulse; Fml = medial-lateral peak; Fml_{Imp} = medial-lateral impulse; N = Newton; N.s = Newton times second; N/BW = Newton per body weight; (N/BW).s = Newton per body weight times second. Large effect sizes were observed for the absolute GRF peaks—Fz1, Fz2, Fap1, Fap2, and Fml (partial eta square—$\eta_p^2 = .71$)—for the absolute GRF impulses—$Fz1_{Imp}$, $Fz2_{Imp}$, $Fap1_{Imp}$, $Fap2_{Imp}$, and Fml_{Imp} ($\eta_p^2 = .55$)—and for the normalized GRF peaks ($\eta_p^2 = .16$); and a small effect size was observed for the normalized GRF impulses ($\eta_p^2 = .04$).

into 10 regions: hallux, distal phalanges, medial, central, and lateral forefoot, medial and lateral midfoot, and medial, central, and lateral rearfoot, as used in another study (Castro et al., 2013). The program automatically divided the foot, and the regions were checked by two trained researchers, who, if necessary, manually corrected this procedure. The program calculated the plantar pressure peaks, which were considered the highest pressure sensor value during the third step, and their time of occurrence for each region. We used the vertical GRF to calibrate the plantar pressure data trial by trial, as suggested by Castro et al. (2013). All data (GRF and pressure peaks) were showed as absolute and normalized (scaled to BW) values. The time of occurrence of the peak events was normalized by the stance phase.

Statistical Analysis

We arbitrarily chose some variables to verify the intraindividual repeatability of the three trials. For this, we calculated the intraclass correlation coefficient (ICC) to the stance phase duration, Fz1, time of occurrence of Fz1, $Fz1_{Imp}$, and for the pressure peaks in three regions (hallux, central forefoot, and central rearfoot). We computed the mean of the three repetitions of each participant, and all statistical procedures were performed with these mean values. We used four independent-sample *t* tests to compare the age, weight, height, and BMI between the NW group and the OG. We used eight multivariate analyses of covariance (MANCOVAs) with the groups (NW and OG) as the between-subjects factor, the participants' age as the covariate, and the following as dependent measures: (a) absolute and (b) normalized GRF peak parameters (Fz1, Fz2, Fap1, Fap2, and Fml), (c) absolute and (d) normalized GRF impulse parameters ($Fz1_{Imp}$, $Fz2_{Imp}$, $Fap1_{Imp}$, $Fap2_{Imp}$, and Fml_{Imp}), (e) temporal parameters (stance phase duration, speed, time of occurrence of Fz1, Fz2, Fap1, Fap2, and Fml), (f) absolute and (g) normalized pressure peaks (10 foot regions), and (h) their time of occurrence as dependent measures. Because the covariate (age) was not significant (see the Results section) in any of the analyses, we used eight multivariate analyses of variance (MANOVAs). Whenever a statistically significant difference was found, the Fisher's Least Significant Difference was calculated. Considering MANOVA assumptions, the data were found to be normal as indicated by the Shapiro-Wilk test ($p > .05$), and the sphericity verified by the Mauchly's test was held. We used the partial eta squared (η_p^2) to measure the effect sizes (ESs) considering an η_p^2 of .01 as small, of .06 as medium, and higher than .14 as large (Stevens, 2002). We used the Statistica Version 8 software (Statfoft, Tulsa, OK) and an α value set at .05 to perform the statistical analyses.

RESULTS

We found excellent data repeatability. The GRF parameters of stance phase duration, Fz1, $Fz1_{Time}$, and $Fz1_{Imp}$ displayed ICCs between .94 and .99, while the pressure peaks in the hallux, central forefoot, and central rearfoot regions showed ICCs of .93, .96, and .91, respectively. There were differences between OG and the NW group in age, $t(32) = 6.030$, $p < .001$, weight, $t(32) = 10.334$, $p < .001$, and BMI, $t(32) = 12.135$, $p < .001$, whereas no differences were found in height, $t(32) = 0.196$, $p < .846$. In the MANCOVA, the covariate age was not statistically significant in any of the analyses ($p > .05$). Thus, the

TABLE 2
Temporal Variables

Variable	*Normal-Weight Group* *M* ± *SD*	*Overweight Group* *M* ± *SD*	*p*
Stance phase duration (s)	0.76 ± 0.06	0.82 ± 0.08	.980
Speed (m/s)	1.13 ± 0.10	0.98 ± 0.14	.950
$Fz1_{Time}$ (% Stance Phase)	24.59 ± 2.76	28.63 ± 3.71	.102
$Fz2_{Time}$ (% Stance Phase)	74.64 ± 2.06	73.69 ± 5.15	.700
$Fap1_{Time}$ (% Stance Phase)	18.01 ± 2.84	20.46 ± 2.66	.319
$Fap2_{Time}$ (% Stance Phase)	83.65 ± 1.23	85.17 ± 1.95	.538
Fml_{Time} (% Stance Phase)	50.95 ± 24.94	74.13 ± 5.13	< .001

Note. Fz1 = load acceptance peak; Fz2 = thrust peak; Fap1 = braking peak; Fap2 = propulsive peak; Fml = medial-lateral peak; i_{Time} = time of occurrence of Fz1, Fz2, Fap1, Fap2, and Fml. A large effect size was observed for the temporal parameters—stance phase duration, speed, $Fz1_{Time}$, $Fz2_{Time}$, $Fap1_{Time}$, $Fap2_{Time}$, and Fml_{Time} (partial eta square = .27).

different age between groups did not seem to cause any confounding effects in the dependent measures.

Differences between OG and the NW group were found in absolute GRF peaks, $F(4, 128) = 79.637$, $p < .001$, $\eta_p^2 = .71$, and absolute GRF impulses, $F(4, 128) = 38.465$, $p < .001$, $\eta_p^2 = .55$, and large ESs were found. The OG showed higher values for both vertical and medial-lateral peaks (Fz1, Fz2, and Fml) and impulses ($Fz1_{Imp}$, $Fz2_{Imp}$, and Fml_{Imp}), whereas for the anterior-posterior GRF (Fap1, Fap2, $Fap1_{Imp}$, $Fap2_{Imp}$), similar values were found (Table 1 and Figures 1a, 1b, and 1c). For the normalized GRF, statistically significant differences were found between OG and the NW group for the GRF peaks, $F(4, 128) = 6.03$, $p < .001$, $\eta^2 = .16$, while for the normalized GRF impulses,

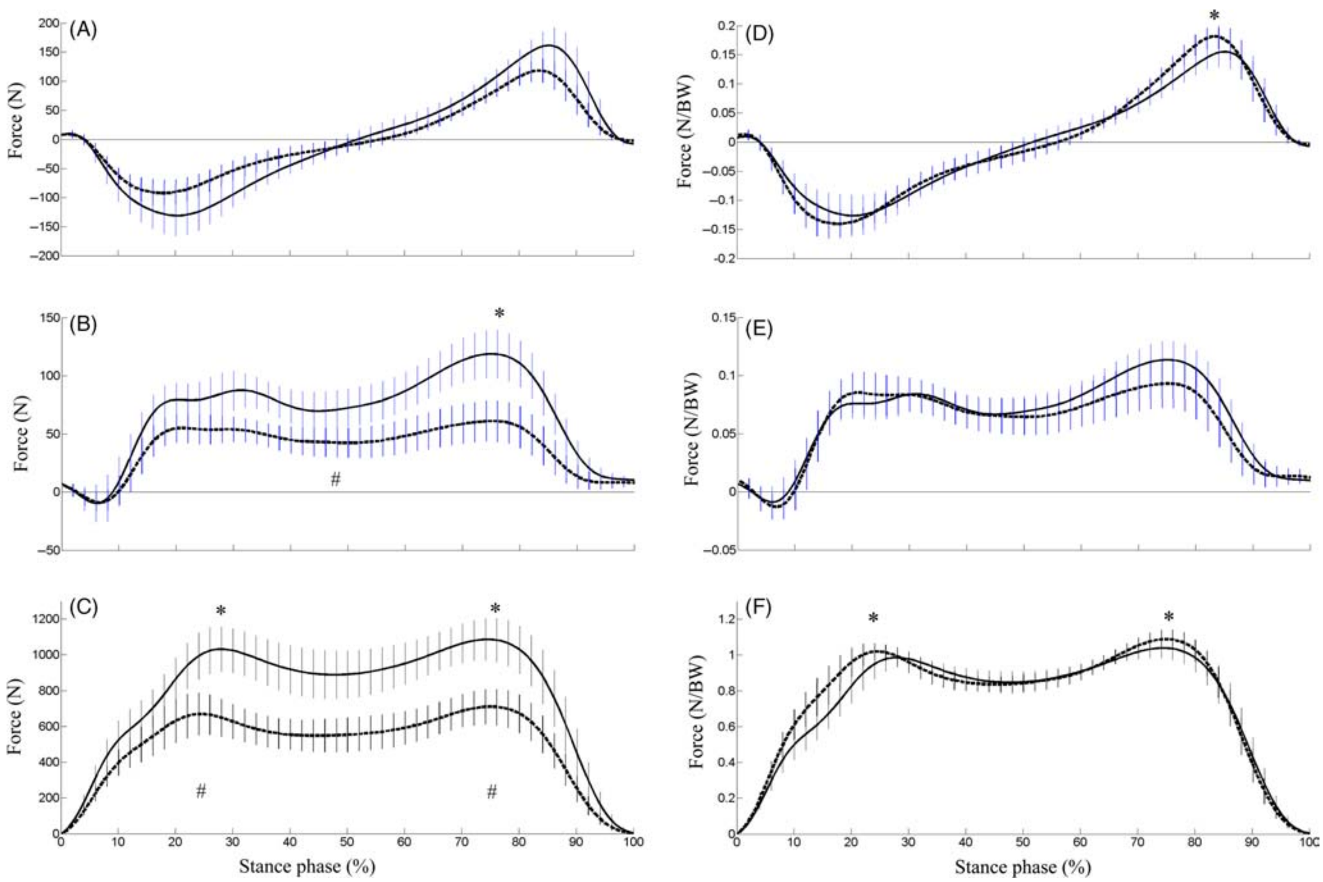

FIGURE 1 Comparison of ground reaction forces (GRF) parameters between normal-weight and overweight participants: (A) absolute mean anterior-posterior GRF, (B) absolute mean medial-lateral GRF, (C) absolute mean vertical GRF, (D) normalized mean anterior-posterior GRF, (E) normalized mean medial-lateral GRF, and (F) normalized mean vertical GRF. Bold lines represent the overweight group and dotted lines represent the normal-weight group. Error bars represent the standard deviation (color figure available online). * $p < .05$ for peak variables. # $p < .05$ for impulse variables.

similar values were found, $F(4,\ 128) = 1.232$, $p = .30$, $\eta^2 = .04$; large and small ESs were observed, respectively. The OG presented lower values for both vertical GRF peaks (Fz1 and Fz2) and for the Fap2 compared with the NW group (Table 1 and Figures 1d, 1e, and 1f).

Statistically significant differences between groups were also found in the plantar pressure peaks for both absolute, $F(9,\ 288) = 10.040$, $p < .001$, $\eta_p^2 = .24$, and normalized, $F(4,\ 288) = 8.222$, $p < .001$, $\eta_p^2 = .20$, values (Figure 2). Large ESs were also observed. The absolute pressure peaks were higher for the OG in the central and lateral forefoot, medial midfoot, and central rearfoot regions, while they were lower in the hallux compared with the NW group (Figure 2a). The normalized pressure peaks were higher in the lateral forefoot and lower for the hallux ($p < .001$) and medial rearfoot ($p = .001$) regions for the OG compared with the NW group (Figure 2b).

Statistically significant differences were found in the time of occurrence of GRF peaks, $F(6,\ 192) = 12.090$, $p < .001$, $\eta_p^2 = .27$, and time of occurrence of pressure

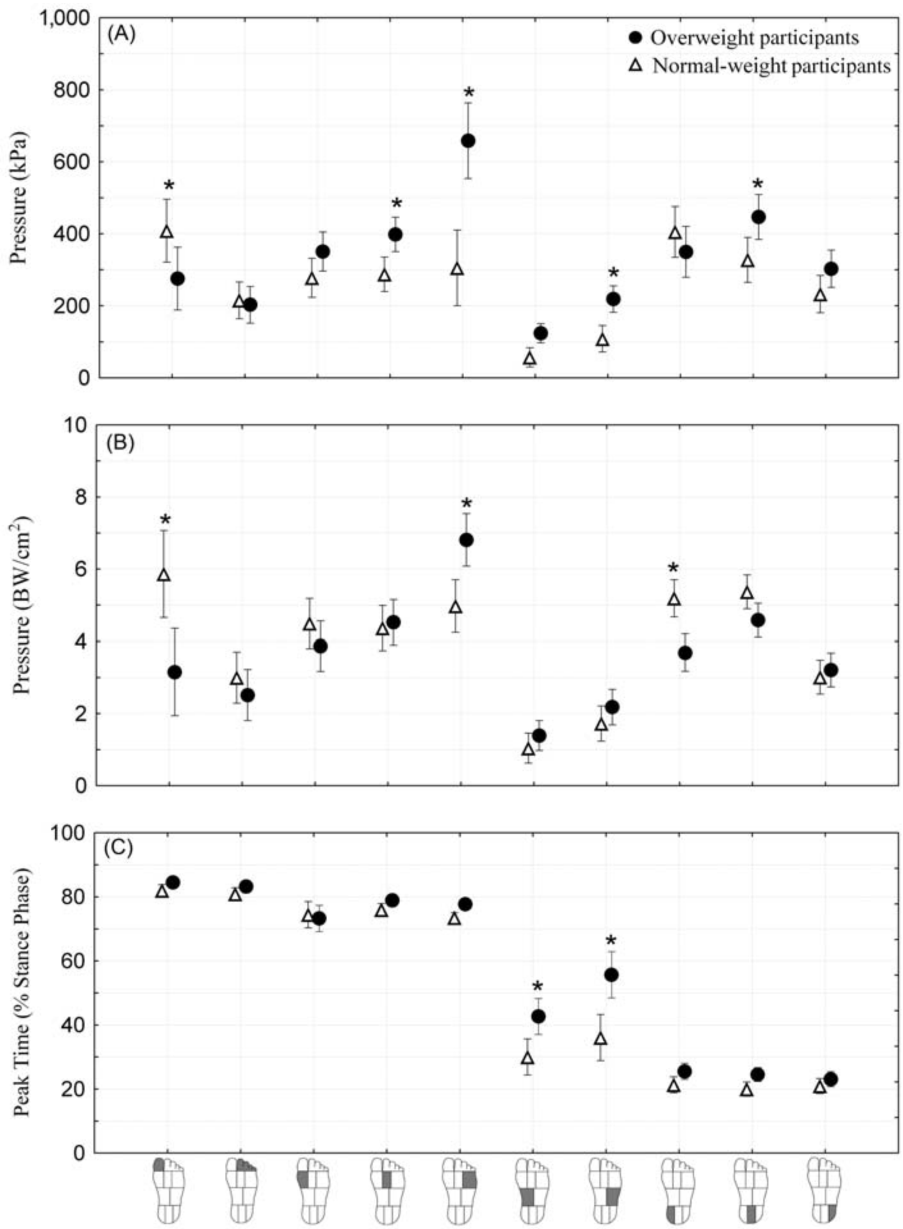

FIGURE 2 Comparison of pressure parameters between normal-weight and overweight participants as a function of foot region: (A) absolute mean pressure peaks, (B) normalized mean pressure peaks, and (C) mean time of occurrence for the pressure peaks. Large effect sizes were observed for the absolute plantar pressure peaks (partial eta squared— $\eta_p^2 = .24$), normalized plantar pressure peaks ($\eta_p^2 = .20$), and time of occurrence for the plantar pressure peaks ($\eta_p^2 = .17$). Error bars represent the 95% confidence interval. * $p < .05$.

peaks, $F(9, 288) = 6.566$, $p < .001$, $\eta_p^2 = .17$, with both displaying large ESs. The time of occurrence for the Fml and pressure peaks in the medial and lateral midfoot regions were larger for the OG than for the NW group. The stance phase duration, speed and time of occurrence for the GRF peaks (Fz1, Fz2, Fap1, and Fap2), and pressure peaks in the medial, central, and lateral rearfoot, medial, central, and lateral forefoot, hallux, and distal phalanges were similar between groups (Table 2 and Figure 2c).

DISCUSSION

We compared the absolute and normalized GRF and plantar pressure peaks and some temporal parameters between normal-weight and overweight participants during self-selected overground-level walking. To our knowledge, the current study was the first to evaluate overweight people with an in-shoe plantar pressure system, assess the plantar pressure values relatively to the BW (normalized data), and divide the rearfoot and midfoot for analyses. We partially satisfied our first hypothesis as higher absolute GRF (medial-lateral and vertical components) and absolute pressure peaks in 4 out of the 10 foot regions were observed in the overweight participants; however, we did not expect similar absolute anterior-posterior GRF and pressure peaks in five regions between groups, as well as higher pressure peaks in the hallux for the normal-weight participants. Our second hypothesis was to some extent not confirmed as in the normalized GRF (anterior-posterior and vertical components), and in 3 foot regions, we observed differences between the groups. We partially confirmed our third hypothesis: The medial-lateral GRF peaks and the pressure peaks in the midfoot were different between groups; on the other hand, 14 out of 17 temporal variables were similar between the OG and NW group. The aforementioned differences between groups were not only statistically significant, but also provide relevant information about the influence of overweight on the magnitude and pattern of GRF, plantar pressure, and temporal parameters, as large ESs were observed.

At the beginning of the stance phase (first 30% of stance time), the overweight participants showed a different behavior in the vertical GRF compared with their normal-weight peers. Corroborating our data, higher absolute Fz1 (Browning & Kram, 2007, 1080 ± 65 N vs. 676 ± 32 N; Messier et al., 1996, 968 ± 21 N vs. 756 ± 17 N) and lower normalized Fz1 (1.00 ± 0.01 N/BW vs. 1.03 ± 0.01 N/BW) for overweight compared with normal-weight individuals (Browning & Kram, 2007) have already been demonstrated. This behavior suggests an adaptation in the overweight GRF pattern to relieve the consequences of their extra BW on the musculoskeletal system. Thus, the overweight people did present higher vertical loads as expected, which reflects their increased BW. However, and interestingly, they showed lower normalized vertical GRF peaks. Because higher values of mechanical stress are related to development of osteoarthritis (Piscoya, Fermor, Kraus, Stabler, & Guilak, 2005) and the vertical GRF is related to the joint contact forces, the overweight participants seemingly altered their vertical GRF pattern to decrease the effect of this overload (excessive body mass) on their bodies. We did not find differences between groups in terms of absolute and normalized braking forces (Fap1 and $\mathrm{Fap}_{\mathrm{Imp}}$). Contrary to our results, higher values of absolute Fap1 (152 ± 10 N vs. 91 ± 5 N) were already reported (Browning & Kram, 2007), whereas data regarding the normalized values corroborated our findings (Browning & Kram, 2007). These contradictions observed in some variables between the studies might have occurred as a consequence of the different protocols adopted: walking overground at a self-selected speed (present study) versus walking on a treadmill at a controlled speed of 1 m/s (Browning & Kram, 2007). Messier et al. (1996) found a significant positive correlation between BMI and absolute Fap1 and $\mathrm{Fap1}_{\mathrm{Imp}}$ in overweight participants with osteoarthritis. Our data suggest, for people without musculoskeletal impairment, no differences in braking forces between the NW group and OG. Thus, the braking forces may play a relevant role in discriminating the gait of overweight people with or without physical impairment.

As expected, the pressure events occurring at the beginning of the stance were the rearfoot pressure peaks. Hills et al. (2001) found higher values for male overweight participants compared with normal-weight participants (391 kPa vs. 335 kPa) and found similar values for female participants (375 kPa vs. 358 kPa). In contrast, Birtane and Tuna (2004) found no differences in rearfoot pressure peaks between overweight and lean people (210 kPa vs. 193 kPa). Differently from the previous studies (Birtane & Tuna, 2004; Hills et al., 2001), we divided the rearfoot into three regions. In the medial and lateral rearfoot, similar absolute pressure peaks were displayed between the groups, while in the central region, the OG showed higher values than those of the NW group (447 kPa vs. 328 kPa). The normalized data indicated similar pressure in the central and lateral rearfoot and lower values in the medial rearfoot region for overweight compared with normal-weight participants. Plantar fasciitis is a common musculoskeletal disorder that is observed in 11% to 15% of adults and is characterized by pain in the inferomedial aspect of the heel (Mendonça, Provenza, & Appenzeller, 2013; Thomas et al., 2010). Obesity is considered a risk factor for such a disorder and mechanical overload is believed to be its most common cause (Thomas et al., 2010). Therefore, we suppose that the decreased normalized medial rearfoot peaks found in the OG from this study might have occurred as a protective adaptation of the gait pattern to avoid overloading this region, which is considered the most susceptible region in the rearfoot (Thomas et al., 2010).

Previous studies have described higher pressure peaks in the midfoot for overweight (141 kPa vs. 99 kPa and 135 kPa

vs. 46 kPa) compared with normal-weight people (Birtane & Tuna, 2004; Hills et al., 2001). In these studies, the midfoot was analyzed as one region. Therefore, a direct comparison with our findings is not valid as we divided the midfoot into medial and lateral regions. Nevertheless, our data reveal higher values in the lateral midfoot for the overweight participants compared with the normal-weight participants (218 kPa vs. 108 kPa). However, this behavior was not observed in the medial midfoot region, where similar values were found (125 kPa vs. 57 kPa). These results should be read with caution as a high variability—comparatively to the other regions—in the time of occurrence of the pressure peaks in the medial and lateral midfoot regions was found (Figure 2c).

The medial longitudinal arch in prepubescent obese children is collapsed (Riddiford-Harland, Steele, & Storlien, 2000). This collapse could promote an increased contact area of the medial midfoot region and then compensate for the increased forces resulting in similar pressure values. In this sense, we would expect that the normalized medial midfoot pressures were lower in this region. However, they were not. Nyska, Linge, McCabe, and Klenerman (1997) analyzed the influence that a backpack with 20 kg and 40 kg had on the plantar pressures of normal-weight participants and concluded that the human foot adapts itself under loading condition by maintaining the medial longitudinal arch. These adaptations involved shifting the plantar loads to the central and medial forefoot (Nyska et al., 1997). Our data support this maintenance of the medial longitudinal arch function in adult overweight individuals. Moreover, we observed an adaptation that shifted the plantar pressures to the lateral midfoot and lateral forefoot regions.

Analyzing the end of the stance phase (from 70% to 100% of stance phase), a positive correlation between BMI and absolute Fz2 and lower normalized Fz2 between overweight and normal-weight participants were described (Lai et al., 2008; Messier et al., 1996). These results are in agreement with ours and reinforce the theory of a protective adaptation of the GRF pattern in terms of vertical forces during overweight people's walking. Regarding the medial-lateral forces (Fml and Fml_{Imp}), we found increased absolute values but similar normalized values. These results are in agreement with previous studies (Browning & Kram, 2007; Lai et al., 2008; Messier et al., 1996). As the increase of this component had been linked with a decrease in stability (Birrell, Hooper, & Haslam, 2007), overweight individuals while walking are seemingly more unstable compared with normal-weight people. Differently than the protective adaptation evidenced for the vertical GRF, we observed no adaptation in the GRF medial-lateral component (similar normalized medial-lateral peak and impulse) in overweight individuals to improve their balance.

The end of the stance phase was the period in which the highest pressure peaks and statistically significant differences between groups occurred. The pressure peaks in the lateral forefoot for the OG reached 659 kPa, while in their normal-weight counterparts, they reached 305 kPa. This shift of pressure toward lateral might be a way to keep the skin from chafing in the inner region of the thigh. The OG also showed higher values in the central forefoot. In the medial forefoot and distal phalanges regions, similar values were observed between groups, while lower values in the hallux for OG were found. Birtane and Tuna (2004) found no statistically significant differences for the absolute pressure peaks in the hallux and forefoot regions. In contrast, Hills et al. (2001) found higher absolute values for all regions for overweight individuals. Possibly, these differences among the studies might have occurred as a consequence of the different levels of overweight assessed (Birtane & Tuna, 2004, 32.2 kg/m^2; Hills et al., 2001, approximately 38.8 kg/m^2; our study, 37.4 kg/m^2). Another possible cause of the differences between our study and the mentioned studies (Birtane & Tuna, 2004; Hills et al., 2001) might be the instruments used: an in-shoe pressure system versus pressure plates. In terms of pattern of plantar pressures during walking, we could not compare our findings with others as the aforementioned studies did not show normalized data. We observed that even when escalating the data by BW, the differences in the lateral forefoot and hallux regions between groups continued. These results indicate that the lateral forefoot in the overweight participants was not only the most loaded region, but it also was loaded more than the magnitude of the extra BW; on the other hand, the hallux seemed to be protected.

The times of occurrence were later in the Fml and midfoot (medial and lateral) pressure peaks for the OG compared with the NW group. This can be explained by the increased calcaneal fat pad characteristic in people with high BMI (Mirrashed, Sharp, Krause, Morgan, & Tomanek, 2004), which might have promoted a delay in shifting the forces from the rearfoot to the midfoot. In the current study, no statistically significant differences in the duration of the stance phase and gait speed between groups while walking at their preferred speed were found. Dufek et al. (2012) also found similar self-selected walking speed between normal-weight (1.25 m/s) and overweight adolescents (1.17 m/s). On the other hand, Hulens, Vansant, Claessens, Lysens, and Muls (2003) used the 6-min walk test and verified that normal-weight people (BMI $<$ 26 kg/m^2), people with a BMI between 27.5 kg/m^2 and 35 kg/m^2, and those with a BMI greater than 35 kg/m^2 have statistically significant differences in walking speeds. The authors (Hulens et al., 2003) found a decreased speed as the BMI increased (2.00 m/s vs. 1.64 m/s vs. 1.50 m/s). Spyropoulos, Pisciotta, Pavlou, Cairns, and Simon (1991) found a lower preferred walking speed in overweight men compared with normal-weight men (1.09 m/s vs. 1.64 m/s). The walking speed from both the OG and NW groups was slower in our study compared with the mentioned studies (Hulens et al., 2003; Spyropoulos et al., 1991). One possible explanation might

be that the 6-min walk test is a longer test (Hulens et al., 2003) compared with the test used in the present study, which was performed in a laboratory over a 6-m walkway. Regarding the latter study (Spyropoulos et al., 1991), the main differences were in the walking speed in their normal-weight participants; however, the authors (Spyropoulos et al., 1991) did not provide any information about these participants for comparison with our normal-weight participants. Because walking speed can influence the kinetic parameters of the gait and the natural gait pattern can be altered by a controlled speed (Hennig & Rosenbaum, 1991), we believe that the differences between groups found in our study were neither related to the walking speed nor to alterations on the gait pattern as a consequence of a controlled speed.

A high degree of linear dependence was found among the most common plantar pressure parameters—pressure peak, mean pressure, and the pressure–time integral (Keijsers, Stolwijk, & Pataky, 2010). Therefore, we decided to present just one parameter (pressure peak) to avoid redundant information. Different magnitudes of pressure peaks between studies might occur as a consequence of the plantar pressure peak calculation (Keijsers et al., 2010). Previous studies (Birtane & Tuna, 2004; Hills et al., 2001) did not describe how their plantar pressure peaks were calculated. In our study, we used the sensor peak approach instead of the regional peak approach, as the latter aggregates data from multiple sensors into a single regional value, therefore compromising the individual sensor information (Keijsers et al., 2010). The sensor peak approach provides more reliable information and leverages the high resolution of our in-shoe pressure system by analyzing the sensors individually (Keijsers et al., 2010).

One of the major limitations of this study is that obesity was not measured by a criterion measure such as dual-energy X-ray absorptiometry; future studies should include three groups: normal BMI, high BMI with high fat percentage, and high BMI with low fat percentage (such as athletes). Another limitation of the study is that the distribution between men and women among the participants was not homogenous. However, there are some studies that have shown no statistically significant differences between gender in pressure parameters for normal-weight (Hills et al., 2001; Putti, Arnold, & Abboud, 2010) and overweight people (Hills et al., 2001). Also we did not examine the foot structure and the posture of the participants, and these features could influence the plantar pressure parameters (Razeghi & Batt, 2002).

CONCLUSION

Overweight adults showed in all sets of parameters (GRF, plantar pressure, and temporal parameters) differences in magnitudes (absolute) and pattern (normalized data). The overweight participants displayed an altered anterior-posterior and vertical GRF pattern to minimize the consequences that their increased vertical and medial-lateral forces could have on their musculoskeletal system. However, they were not able to improve their balance, as similar normalized medial-lateral GRF was observed between groups. Higher pressure peaks were found in the central and lateral forefoot, lateral midfoot, and central rearfoot regions. The lateral forefoot was the most loaded region, while the hallux and medial rearfoot regions appeared to be protected during overweight people's walking. It would be interesting if future studies assessed the influence of different approaches, such as therapeutic relief insoles or shoes, training of the intrinsic foot muscles, as well as those conditions such as fatigue or incline levels of ground in the GRF and plantar pressure parameters, on overweight adults' walking.

WHAT DOES THIS ARTICLE ADD?

To our knowledge, this is the first study that simultaneously assessed both magnitude and pattern of GRF and in-shoe plantar pressures during overweight adults' overground walking. We identified not only higher magnitudes of GRF as expected, but also alterations in pattern: The overweight participants showed decreased normalized vertical (load acceptance and trust maximum phases) and horizontal forces (propulsive anterior-posterior). Thus, as a consequence of overweight, there are some strategies in the musculoskeletal system to minimize the joint contact forces and shear stress, as demonstrated while participants walked at a self-selected speed. Regarding the plantar pressures, the overweight participants showed higher magnitudes of pressure peaks in the central (rearfoot and forefoot) and lateral (midfoot and forefoot) plantar foot regions. Therefore, to prescribe safe exercise routines and avoid foot-related injuries, these regions should be carefully and frequently checked. When we analyzed normalized data, the lateral forefoot continued showing higher pressure peaks, whereas the medial rearfoot and hallux appeared to be protected as lower pressure peaks were observed. We found the highest pressure peaks in the lateral forefoot. These values were more than 200 kPa higher than all other regions, indicating that this region needs special care. Clinicians and trainers should pursue pressure-relieving interventions to improve the plantar pressure distribution in overweight adults.

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