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Influence of gait cadence on plantar pressures and ground reaction forces during obese adults' walking

KEY WORDS:

Cadence. Locomotion. Overweight.
 Physical activity. Speed.

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ABSTRACT

To prescribe safer exercise routines for obese people it is important to understand the effects of changing gait cadence on biomechanical gait parameters. The aim of this study was to verify if changes in gait cadence during overground walking affect the ground reaction forces and in-shoe plantar pressures of normal-weight and obese participants differently. As a secondary aim, the ground reaction forces and plantar pressures between normal-weight and obese participants were compared during both low and high gait cadences. We assessed ground reaction forces and in-shoe plantar pressures in 10 foot regions during low (70 steps/ minute) and high (120 steps/ minute) gait cadences in 17 obese adults and 17 gender-matched normal-weight participants during walking. Changes in gait cadence similarly affect ground reaction forces ($p = .21$) and plantar pressures ($p = .47$) of normal-weight and obese adults. Similar ground reaction force peaks were observed between groups in both gait cadences ($p = .59$). Statistically significant differences in plantar pressures ($p < .001$) were found between groups in both gait cadences. In conclusion, higher vertical and anterior-posterior ground reaction forces associated with higher plantar pressure peaks in the rearfoot and toe regions in obese individuals suggest that walking at high gait cadences demands more to the musculoskeletal system compared to low gait cadences.

Influência da cadência de caminhada nas pressões plantares e forças de reação do solo em pessoas obesas

RESUMO

Para prescrever exercícios mais seguros para pessoas obesas é importante entender como alterações na cadência de caminhada influenciam parâmetros biomecânicos do andar. O objetivo deste estudo foi verificar se mudanças na cadência de caminhada afetam as forças de reação do solo e as pressões plantares em pessoas com peso corporal normal e pessoas obesas de maneira diferente. Os parâmetros biomecânicos do andar também foram comparados entre os participantes com obesidade e com peso corporal normal durante o andar com alta e baixa cadência de caminhada. Dezesete participantes com obesidade e 17 participantes pareados por sexo com peso corporal normal foram envolvidos no presente estudo. As forças de reação do solo e as pressões plantares em 10 regiões do pé foram registradas enquanto os participantes andaram com uma cadência de caminhada baixa (70 passos/ minuto) e alta (120 passos/ minuto). A cadência do andar influenciou de maneira similar as forças de reação do solo ($p = .21$) e pressões plantares ($p = .47$) em pessoas com obesidade e com peso corporal normal. Similares forças de reação do solo foram encontradas entre os grupos em ambas as cadências de caminhada ($p = .59$), e diferenças estatisticamente significativas foram encontradas entre os grupos quando as pressões plantares foram analisadas ($p < .001$). Maiores forças de reação do solo ântero-posterior e vertical associadas a maiores picos de pressões plantares no retro-pé e na região dos dedos sugere que pessoas obesas quando caminham em altas cadências exigem mais do sistema músculo-esquelético do que quando caminham com baixas cadências.

PALAVRAS CHAVE:

Cadência. Locomoção. Sobrepeso.
 Atividade física. Velocidade.

INTRODUCTION

Obesity is considered as a global epidemic disease ⁽¹¹⁾. This condition can endanger the integrity of the lower limbs and feet as it causes higher weight-bearing forces ⁽¹⁸⁾. Obese individuals show higher risk of having knee and hip osteoarthritis ⁽¹⁶⁾, plantar foot ulceration ⁽²²⁾ and heel pain ⁽²⁸⁾ than normal-weight people. Physical activity, such as walking is highly recommended as an exercise to prevent, control and lose weight ⁽¹⁰⁾. The intensity of walking prescribed in exercise programs is uniquely based on cardiorespiratory parameters ⁽⁹⁾, and brisk walking is the dose of exercise most commonly reported ⁽²⁶⁾. Although cardiorespiratory parameters are indubitably important, they do not consider the musculoskeletal demands imposed by activity. Biomechanical parameters could provide the profile of loads imposed to the musculoskeletal system, and add value for exercise prescription.

Evaluating the plantar pressures is useful for enhancing the comprehension of foot structure and function, as well as to identify overloaded foot regions, and thus to prevent foot-related injuries ⁽⁸⁾. High in-shoe plantar pressure peaks have been correlated to plantar foot pain ⁽¹⁾. Plantar pressure systems inform the magnitude of the vertical ground reaction force (GRF) applied on each foot region. Force plates provide both global vertical and horizontal GRF components, but force plates do not inform the foot regions where the forces are being applied ⁽⁵⁾. The vertical GRF provides information of mechanical stress ⁽²¹⁾ and its increase might be linked to high joint contact forces, and therefore related to conditions such as knee or hip osteoarthritis. Anterior-posterior GRF (shear force) play an important role in developing foot-related injuries such as blister and ulceration ⁽¹⁵⁾. Thus, the simultaneous analysis of GRF and in-shoe plantar pressures would make clearer how the musculoskeletal system is affected by different factors, such as obesity or gait cadence.

Changing walking cadence or speed – the relationship between cadence and speed tends to be linear during non-impaired gait ⁽²⁰⁾ – influences the GRFs ^(6, 13) and plantar pressures ⁽²⁴⁾ in normal-weight subjects. Based on previous studies assessing normal-weight subjects ^(6, 13, 24), one could expect increases in GRF and plantar pressure peaks when obese people changed their gait cadence from low to high cadences. However, differences in gait pattern between obese and normal-weight people were previously described ^(4, 17). Therefore, it is currently unclear how changing gait cadence affects the magnitude of these biomechanical gait parameters in obese subjects, and which foot regions are more or less loaded. This information could be used to prevent lower limb injuries and to prescribe safer exercises for obese populations.

The aim of this study was to verify if changes in gait cadence during overground walking affect the GRFs and in-shoe plantar pressures of normal-weight and obese participants differently. As a secondary aim, the GRFs and plantar pressures between normal-weight and obese participants were compared during both low and high gait cadences. We hypothesized that both normal-weight and obese participants will present higher GRF and plantar

pressure magnitudes during high gait cadences compared to low gait cadences; however, the rate of change in the GRF and plantar pressure peaks will be different between groups. We also hypothesized that the GRF and plantar pressure peaks, when scaled to body mass, will be different between obese and normal-weight participants in both gait cadences.

METHODS

This is a repeated measure 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

Healthy participants with body mass indexes either between 20 and 25 (normal-weight group), or higher than 30 (obese group) were recruited for this study. Participants with any musculoskeletal impairment were excluded. Musculoskeletal impairment was assessed by asking the participants whether they felt any pain at the time of the evaluation, or whether they suffered any musculoskeletal injury that could affect their ability of walking during the last six months, or whether they felt any difficulty of independent walking at the time of the evaluation.

Seventeen obese participants (12 males and five females – mean age of 36.8 ± 5.8 years old; height of 169.3 ± 11.6 cm; body mass of 106.8 ± 12.4 kg; and body mass index of 37.4 ± 4.6 kg/m²) and 17 gender-matched participants (mean age of 27.4 ± 2.7 years old; height of 170.0 ± 8.7 cm; body mass of 69.2 ± 10.1 kg; and body mass index of 22.8 ± 1.7 kg/m²) were enrolled in this research.

MEASURES

To record GRFs, we used a Bertec force plate (model 4060-15, Bertec Corporation, Columbus, OH, USA), operating at 1000 Hz, and the Acknowledge software (BIOPAC System, Goleta, CA, USA). We recorded plantar pressures using an F-Scan in-shoe pressure system (TekScan, South Boston, USA) operating at 300 Hz with 960 pressure cells with 0.18 mm thick insole sensor, and the F-Scan Research 6.33 software (TekScan, South Boston, USA). To control the gait cadence, we used a metronome (Wittner Maelzel Metronome, Germany). We used videogrammetry to record gait speed: three digital video camera recorders and the Dvideo v.5.0 system (Unicamp, Campinas, Brazil) to capture, synchronize, digitalize and reconstruct the images ⁽⁷⁾. Finally, we used an external trigger to synchronize the systems by starting them simultaneously.

PROCEDURES

First, we explained all procedures of the study to the participants and then we recorded their weight and height. We provided participants with fitted black shorts and one reflective marker with a diameter of 1.2 cm, which was placed with adhesive tape at the right great trochanter of the femur. We placed the F-Scan system on the participants without causing any restriction to the walking. The sensor insoles were trimmed to perfectly suit to the participants' shoes. All participants received neutral shoes with flat sole and with the sensor insoles inside.

Second, the participants familiarized themselves with the test by walking freely over a 6 m walkway. The force plate was embedded in the middle of the walkway. Afterwards, they became familiar with walking at 70 steps per minute (labeled as low gait cadence) and 120 steps per minute (labeled as high gait cadence). We adopted these gait cadences because in preliminary tests we observed they were the most adopted cadences when obese subjects were asked to walk slow and brisk, respectively. Finally, the participants performed three valid trials for each condition in which they took, at least, two steps before and after reaching the force plate, avoiding thus acceleration effects ⁽¹⁹⁾.

DATA ANALYSIS

Data from the force plate (three components of the GRFs), videogrammetry and in-shoe plantar pressure system (values of each sensor in each frame) were exported to Matlab 7.0 software (MathWorks, Massachusetts, USA) and a program was developed to compute and process the relevant variables. The gait speed was calculated by the first time derivative of the great trochanter reflective marker horizontal anterior-posterior position. Considering the GRF data, five outcome measures were calculated (FIGURE 1):

- Duration of the stance phase: time spent between the first foot contact and toe off;
- Fz1 (load acceptance peak): the highest vertical GRF value at the first half of the stance phase, i.e. the first peak;
- Fz2 (thrust peak): the highest vertical GRF value at the second half of the stance phase, i.e. the second peak;
- Fy1 (braking peak): the lowest value (negative) at the anterior-posterior GRF;
- Fy2 (propulsive peak): the highest value at the anterior-posterior GRF.

FIGURE 1. Ground reaction force parameters.

Fz1 = load acceptance peak; Fz2 = thrust peak; Fy1 = braking peak; Fy2 = propulsive peak

Regarding the in-shoe pressure system data, the program automatically divided the footprint into 10 plantar foot regions, as previously proposed ⁽³⁾: hallux, distal phalanges, medial, central and lateral forefoot; medial and lateral midfoot; and medial, central and lateral rearfoot. One of the researchers verified this procedure and, eventually, the boundaries between the foot regions were manually corrected. For each of the 10 plantar foot regions the program calculated one outcome measure: the plantar pressure peak, which was considered the highest pressure value shown on the sensor during the stance phase when the participant stepped on the force plate. We used the force plate to calibrate the plantar pressure data as previously proposed ⁽³⁾.

Data were scaled to the participants' body weight. Thus, the unit of the GRF peaks was "Body Weight (BW)" and the unit of the plantar pressure peaks was "BW/cm²".

STATISTICAL ANALYSIS

Statistical analysis was performed using the Statistica® v.8 software (Statsoft®, Tulsa, USA) with a value set at 0.05. The intraclass correlation coefficient (ICC) was used to verify the between-trial repeatability for the variables duration of the stance phase, Fz1, Fz2, and pressure peak (all regions together) for both low and high gait cadences. We computed the mean of each of the participants' three trials and then used these mean values to perform all statistical procedures. Two repeated measures MANOVAs with the gait cadences (low and high) as within-subject factor, group (normal-weight and obese subjects) as between-subject factor, and GRF peaks (Fz1, Fz2, Fy1 and Fy2) and plantar pressure peaks (in the 10 foot regions) as outcome measure, respectively, were conducted. For duration of the stance phase and gait speed variables, two repeated measures ANOVA with the same factors aforementioned were used. We did not use the gait speed as a covariate in the statisti-

cal model because it was not statistically different between groups (see results section). We used the partial Eta square (η^2) to measure the effect sizes considering that an η^2 of 0.01 or less was small, of 0.06 was medium, and of 0.14 or more was large ⁽³⁰⁾.

RESULTS

We found good-to-excellent between-trial repeatability. During low gait cadence the duration of the stance phase, Fz1, Fz2, and pressure peaks showed ICCs of 0.81 ($CI_{95\%}$ 0.57 – 0.92), 0.91 ($CI_{95\%}$ 0.80 – 0.97), 0.91 ($CI_{95\%}$ 0.79 – 0.96) and 0.92 ($CI_{95\%}$ 0.89 – 0.94), respectively; whilst for the high gait cadence they were 0.91 ($CI_{95\%}$ 0.79 – 0.96), 0.81 ($CI_{95\%}$ 0.57 – 0.92), 0.91 ($CI_{95\%}$ 0.79 – 0.96) and 0.95 ($CI_{95\%}$ 0.93 – 0.96), respectively.

Gait speed displayed no statistically significant differences between groups during low gait cadence (obese participants: 0.71 ± 0.08 m/s; normal-weight participants: 0.74 ± 0.05 m/s) and high gait cadence (obese participants: 1.31 ± 0.15 m/s; normal-weight participants: 1.34 ± 0.11 m/s). Gait speed was significantly different between gait cadences for both groups (low vs. high, $p < .001$). Likewise, the duration of the stance phase was similar ($p > .05$) between groups during both low (obese participants: 1.10 ± 0.07 s; normal-weight participants: 1.11 ± 0.06 s) and high (obese participants: 0.70 ± 0.04 s; normal-weight participants: 0.67 ± 0.02 s) gait cadences, and statistically different between low and high gait cadences ($p < .001$).

There were no statistically significant interactions between gait cadence and group in GRF peaks ($F[3, 96] = 1.56, p = .21, \eta^2 = .05$); and there were no statistically significant main effects of group in GRF peaks ($F[3, 96] = 0.64, p = .59, \eta^2 = .02$). Statistically significant main effects of gait cadence were observed in GRF peaks ($F[3, 96] = 105.90, p < .001, \eta^2 = .77$). All GRF peaks (Fz1, Fz2, Fy1 and Fy2) were larger (for Fy1 in modulus) during high compared to low gait cadences (TABLE 1).

TABLE 1. Ground reaction force (GRF) peaks during low and high gait cadences.

VARIABLES (unit BW)	OBESSE PARTICIPANTS		NORMAL-WEIGHT PARTICIPANTS		MAIN Effects (cadence)
	Low cadence	High cadence	High cadence	Low cadence	
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	
Fz1	1.01 (0.03)	1.12 (0.07)	1.00 (0.02)	1.14 (0.09)	$p < .001$
Fz2	1.01 (0.02)	1.11 (0.04)	1.02 (0.01)	1.13 (0.06)	$p < .001$
Fy1	0.10 (0.02)	-0.18 (0.04)	-0.10 (0.02)	-0.19 (0.04)	$p < .001$
Fy2	0.11 (0.02)	0.21 (0.02)	0.13 (0.02)	0.21 (0.03)	$p < .001$

Fz1 = load acceptance peak; Fz2 = thrust peak; Fy1 – braking peak; Fy2 = propulsive peak.

A large effect size was observed for the main effects of gait cadence in GRF peaks (partial Eta square— $\eta^2 = 0.770$)

Gait cadence and group in plantar pressure peaks ($F[9, 288] = 0.958, p = .47, \eta^2 = .03$). Gait cadence ($F[9, 288] = 3.99, p < .001, \eta^2 = .11$), and group ($F[9, 288] = 4.78, p < .001, \eta^2 = .13$) showed statistically significant main effects in plantar pressure peaks during walking (FIGURE 2). During high gait cadences, higher pressure peaks in the medial ($p < .001$) and central rearfoot regions ($p < .001$), hallux ($p = .02$) and distal phalanges ($p = .03$), compared to low gait cadences were observed; while in the other regions similar values ($p > .005$) between gait cadences were found (FIGURE 2A). Normal-weight participants showed statistically higher pressure peaks in the hallux ($p < .001$) and medial rearfoot ($p = .03$) regions compared to obese participants; in the other eight foot regions no statistically significant differences ($p > .05$) were observed (FIGURE 2B).

FIGURE 1. Main effects of (A) gait cadence and (B) group in plantar pressure peaks. Medium effect sizes were observed for main effects of gait cadence (partial Eta square— $\eta^2 = 0.11$) and group ($\eta^2 = 0.13$). Circles and triangles represent group means, and error bars 95 % confidence intervals. * $p < 0.05$ differences between gait cadences (Figure A) or groups (Figure B).

DISCUSSION

This study analyzed if changes in gait cadence during overground walking affect the GRFs and in-shoe plantar pressures of normal-weight and obese participants differently. Differences on these kinetic gait parameters between normal-weight and obese participants during both gait cadences were also analyzed. Our first hypothesis was not confirmed as we did not find statistically significant interactions between gait cadences and groups for both GRF and plantar pressure parameters. Thus, it appears that changes in gait cadence similarly affect the GRFs and in-shoe plantar pressures of normal-weight and obese adults. Our second hypothesis was partially fulfilled as differences in plantar pressure peaks between groups were observed in the hallux and medial rearfoot region, however no differences in the other eight foot regions and in GRF peaks were found between normal-weight and obese subjects. The main effects of gait cadence and groups were not only statistically significant, but also appeared to have practical relevance as medium to large effect sizes were observed.

Browning and Kram ⁽²⁾ found increased GRF peaks in faster speeds (high gait cadences) while walking on a treadmill. They found an increase of 7% in Fz1 and 83% in Fy1 when obese adults changed their gait speed from 0.75 to 1.25 m/s. Similar alterations were found in the present study: in high gait cadences (gait speed of 1.31 m/s), the obese participants showed 11% and 80% higher Fz1 and Fy1, respectively, compared to low gait cadences (gait speed of 0.71 m/s). Our results also suggest similar behavior for GRF propulsion variables (Fz2 and Fy2), which increased 10% and 91%, respectively in high gait cadences. However, comparisons between Browning and Kram ⁽²⁾ findings and ours should be made with caution as differences in GRF peaks between overground and treadmill walking were previously described ⁽²³⁾. High magnitudes of vertical GRF represent a continuous inability to absorb the body load while walking ⁽²⁹⁾, and possibly people become more likely to develop musculoskeletal injuries ⁽²¹⁾. Other variables seemingly related to foot damage (blisters development) are those from anterior-posterior GRF ⁽¹⁴⁾. Therefore, our data support that low gait cadences are the least detrimental to the joint health and least likely to develop foot-related injuries such as blister, callosities and ulceration during overground walking.

Higher pressure peaks were described for the rearfoot (analyzed as one region) when normal-weight individuals walked at high gait speeds ⁽²⁴⁾. Our data partially corroborate with these findings. We have analyzed the rearfoot as three regions (medial, central and lateral). Thus, we do agree that pressure peaks increase in the medial and central rearfoot regions. However, in the lateral rearfoot, no differences were found between low and high gait cadences. One explanation for these results might be that, as previously suggested ⁽²⁴⁾, at higher gait cadences there is an increased eversion of the rearfoot and, as a consequence, the applied load during the load acceptance phase of gait shifts medially. Therefore, medial

and central rearfoot regions are more likely to receive load. Walking cadence did not influence pressure peaks in the midfoot (medial and lateral) for both obese and normal-weight participants. Data from normal-weight people corroborate with these findings ⁽³¹⁾.

Regarding the forefoot region, our data suggest that plantar pressures along the forefoot (medial, central and lateral) are similar between low and high gait cadences, and that there was a similar plantar pressure pattern between normal-weight and obese participants. Burnfield et al. ⁽¹²⁾ compared normal-weight young adults walking at 0.95 m/s and 1.33 m/s and they also did not find differences in the pressure peaks between speeds. On the contrary, Rosenbaum et al. ⁽²⁴⁾ assessed normal-weight participants walking at 0.8 m/s and at 1.7 m/s and found increased pressure peaks in the medial and central forefoot at faster speed. In the present study, normal-weight participants walked at 0.71 m/s and 1.31 m/s. These results suggest that in forefoot regions there are no differences in plantar pressure peaks when gait speed changes less than 0.6 m/s, or gait cadence changes less than 50 steps per minute. After that, significantly higher plantar pressure peaks are likely observed in medial and central forefoot regions. It is important to highlight the lateral forefoot as the region in which the highest in-shoe plantar pressure peaks occurred (≈ 7 BW/cm²) for both normal-weight and obese subjects. Neither gait cadence nor group influenced these values.

To our knowledge, this was the first study assessing how obesity and gait cadence interact on the plantar pressures and GRFs during overground walking. A better comprehension of loads applied on the human body during different modalities of exercise allows prescribing training safer and prevents damaging the lower limbs. This is of fundamental importance for obese individuals as they show higher risk of developing musculoskeletal conditions than their normal-weight counterparts. We identified during the high gait cadences higher shear forces (anterior-posterior GRF), joint contact forces (vertical GRF) and plantar pressures in rearfoot and toes regions compared to low gait cadences. Considering these findings, we would suggest avoiding walking at high gait cadences for obese subjects who show any discomfort in their lower-limb joints or in plantar surface (mainly rearfoot regions). Alternatively, low gait cadences or other modality of exercise such as swimming or cycling would be recommended.

This study presented some limitations. The distribution between men and women among the participants was not homogenous. However, no differences between gender in plantar pressure parameters for normal-weight and obese people was evidenced ⁽²⁵⁾. Only right lower limbs of our participants were assessed; however, similar GRFs have been shown between limbs ⁽²⁷⁾. Finally, we did not control gait speed. We opted to control gait cadence and use a metronome because of its ease of use, and it is more readily interpretable measure of ambulatory activity. Metronomes are also accessible as an application in mobile phones and then, it can be easily used outside the laboratory to monitor gait cadence and, indi-

rectly, to provide a notion about GRFs and plantar pressures during exercises. Furthermore, we observed no differences between groups, and a short and similar 95% confidence interval in gait speeds for both low and high gait cadences. Therefore, when controlling gait cadence similar gait speeds were found between obese and normal-weight subjects.

CONCLUSIONS

No interactions between gait cadence and obesity on GRFs and in-shoe plantar pressures during overground walking were found. However, differences in GRFs and in-shoe plantar pressure peaks when obese participants walked at low compared to high gait cadences, as well as differences in the distribution of plantar pressures between obese and normal-weight participants were observed. The higher vertical and anterior-posterior GRFs associated with higher plantar pressure peaks in the rearfoot and toe regions suggest that walking at high gait cadences demands more to the musculoskeletal system compared to low gait cadences. Joint health and plantar surface profile should be taken into account before prescribing walking at high gait cadences to obese individuals. For those obese subjects who show any discomfort in the plantar surface or lower limb joints, walking at high gait cadences should be avoided in order to prevent high shear stress and joint contact forces. As an alternative, walking at low gait cadences or other modalities of exercise such as swimming or cycling might be more suitable to be prescribed.

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