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The impact of increasing body mass on peak and mean plantar pressure in asymptomatic adult subjects during walking

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***Introduction*:** The implication of high peak plantar pressure on foot pathology in individuals both with and without diabetes has been recognized. The aim of this study was to investigate and clarify the relationship between increasing body mass and peak and mean plantar pressure in an asymptomatic adult population during walking.

***Methods*:** Thirty adults without any relevant medical history, structural foot deformities or foot posture assessed as highly pronated or supinated, and within a normal body mass index range were included in the study. An experimental, same subjects, repeated measures design was used. Peak and mean plantar pressure were evaluated with the F-Scan in-shoe plantar pressure measurement system under four different loading conditions (0, 5, 10, and 15 kg) simulated with a weighted vest. Pressure data were gathered from three stances utilizing the mid-gait protocol.

***Results*:** There were statistically significant increases in peak pressure between the 10 and 15 kg load conditions compared to the control (0 kg) within the heel and second to fifth metatarsal regions. The first metatarsal and hallux regions only displayed statistically significant increases in peak pressure between 15 kg and the control (0 kg). The midfoot and lesser digits regions did not display any statistically significant differences in peak pressure between any load conditions compared to the control (0 kg). The second to fifth metatarsal region displayed statistically significant increases in mean pressure in the 5, 10 and 15 kg groups compared to the control (0 kg). A statistically significant increase in peak pressure between the 15 kg and control (0 kg) group was evident in all other regions.

***Conclusion*:** The relationship between increasing body mass and peak and mean plantar pressure was dependent upon the plantar region. This study provides more detail outlining the response of peak and mean pressure to different loading conditions than previously reported in the literature. Further research including measurement of temporal parameters is warranted.

Keywords: *plantar pressure*; *body mass index*; *obesity*; *diabetes*; *body weight*; *distribution*

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Measures of body mass in adult subjects have previously been correlated with foot and ankle pathologies such as plantar fasciitis (1) and plantar heel pain (2, 3). In particular, dynamic peak plantar pressure has been correlated with diabetic foot ulceration in those with peripheral neuropathy and a previous history of foot ulceration (4–6).

Off-loading the plantar foot in individuals with diabetes displaying active plantar ulceration or identified at risk of ulceration is imperative for effective management (7). This becomes even more important in the presence of peripheral sensory neuropathy (8, 9). Prevention of cyclic tissue hypoxia during ambulation and direct trauma are factors underlying this approach (7). Debridement of hyperkeratotic and non-viable tissue, padding, insoles/orthoses, removable cast walkers, and total contact casting are all modalities intended to decrease the amount of force and pressure at sites of ulceration and surrounding tissue on the plantar foot. Despite the variable success of these modalities, other alternative management strategies such as weight loss initiatives seem to attract less attention. This is unsurprising due to an immediate need

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for aggressive off-loading in cases of active plantar ulceration. If body mass is correlated with plantar pressure variables and patterns of plantar pressure distribution, this information may aid the identification of areas that may be potentially affected by increases or reductions in body mass. Reducing peak plantar pressures in individuals at risk of ulceration via a reduction in body mass has previously been advocated (10). However, despite evidence linking peak plantar pressure to foot pathology, the evidence linking regional peak plantar pressure increase in response to increasing body mass in healthy adult subjects during walking has been reported to be inconclusive (11). This is also reflected in the array of articles investigating this relationship in both symptomatic and asymptomatic subjects.

Studies investigating the impact of either obesity (12, 13), different load carrying conditions (14, 15), simulated changes in body mass (10, 16), or body mass as a correlate to peak plantar pressure (17–25) have reported disparities in the regional areas affected by body mass when peak plantar pressure has been measured. Although the impact of increasing body mass on regional peak plantar pressure at particular intervals (9.1 and 18 kg) has been established, a need exists to investigate what impact a range of increases in body mass has on peak plantar pressure during walking. This information would be particularly valuable for individuals with diabetes. However, as the type of relationship between increasing body mass and dynamic peak plantar pressure in different regions remains inconclusive, investigation in an asymptomatic population is important. The aim of this study was to investigate and clarify regional peak and mean plantar pressure distribution in response to different levels of body mass increase in asymptomatic adult subjects during walking.

Method

An experimental, same subjects, repeated measures design was employed for this study. Ethics approval was granted from the University of South Australia Human Research Ethics Committee. An a priori sample size calculation revealed 24 subjects were required to achieve 80% statistical power to detect a small effect size (0.25) with an $\alpha = 0.05$. Inclusion criteria stated that subjects must be aged between 18–35 years, have a Foot Posture Index (FPI-6) score of between –4 and +9 for both feet and own sports shoes to wear for the data collection. Subjects did not meet eligibility for the study if they (a) had a history of trauma resulting in structural deformity of the foot or ankle, (b) had a body mass index (BMI) < 18.50 or > 30.0 kg/m^2, (c) foot pain at the time of recruitment, or were (d) using foot orthoses at the time of recruitment or data collection. All subjects gave written informed consent prior to their screening for study eligibility.

Prior to the pressure data collection phase, subjects were screened for eligibility relating to their physical characteristics, including BMI (assessed by calculation after measurement of weight and height and reported in kg/m^2) and foot posture (measured by the FPI-6 and reported as a score between –12 and +12 for each foot). The FPI-6 is a valid and reliable measure of static foot posture (26, 27) that was used as an attempt to limit the influence of foot posture on plantar pressure (28, 29) by excluding subjects with feet displaying pronated or supinated characteristics at the extremes of the scoring continuum. Recruitment via a sample of convenience method yielded 30 subjects that met all inclusion criteria (Table 1).

Plantar pressure data was collected using the F-Scan in-shoe plantar pressure measurement system (TEKSCAN, Boston, MA) version 6.3x. Insoles comprised a 0.18 mm insole with a resolution of four sensors per centimeter squared. Each subject was assigned their own insole that was used for the pressure data collection period. The F-Scan pressure data have been reported to be highly correlated with calibrated force platform measures ($r^2 =$ 0.85–0.96) (30, 31). A high level of reliability between measurements has also been reported (ICC = 0.94) (31). A coin toss determined that only data from the right foot would be collected, to avoid sample size inflation that may impact upon the likelihood of Type 1 error (32). Data was collected at a sampling rate of 50 Hz.

The pressure data collection protocol consisted of measurement under four separate loading conditions (0, 5, 10, and 15 kg). Each subject acted as their own control. Loading conditions to simulate an increase in body mass were achieved with the application of a weighted vest (XLR8 weighted vest, Speed, Power & Stability Systems Ltd, New Zealand). Insole calibration was performed at the subjects' own body weight at the beginning of data collection according to the manufacturer's instructions. Subjects completed each walking trial on a 10 m walkway. Pressure data were collected from three steps/stances, utilizing a modified method of the mid-gait protocol already described in the literature (33). It has previously been reported that pressure data

Table 1. Subject characteristics

Gender	*n* =	Age (years) ± SD	Weight (kg) ± SD	Height (m) ± SD	Body mass index (kg/m^2) ± SD
Male	15	22.66 ± 2.84	77.29 ± 9.03	1.81 ± 0.05	23.45 ± 2.35
Female	15	21.73 ± 3.36	61.92 ± 14.14	1.63 ± 0.07	22.97 ± 3.79

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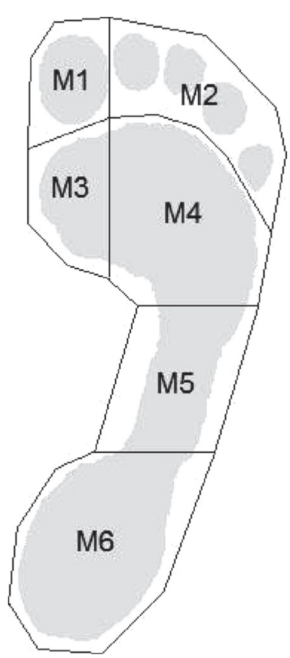
collected from three steps/stances provides an adequate level of reliability for peak pressure output with intraclass correlation coefficients ranging from 0.77–0.97 (33, 34). Walking trials for each subject under the different loading conditions were randomized to decrease the influence of ordering effects. Each subject wore the insole in their shoe for a 10 minute 'bedding in' period to allow insole acclimatization and potentially increase the reliability of measurement (35, 36). The weighted vest was added to subjects shortly before each walking trial to limit fatigue. Subjects were instructed to walk at a self-selected comfortable walking speed for each of the four walking trials in order to gain pressure data representative of each subject's normal walking condition.

Peak and mean plantar pressure (N/cm^2) were recorded for each plantar region (Fig. 1) and contact times (seconds) were measured with the TEKSCAN Research Program version 6.3x (TEKSCAN, Boston, MA). Identification of anatomical landmarks served as reference points for creation of the masks for each of the plantar regions. Pressure data for each subject was analyzed using their own individual template, which was used for the data from each of the four loading conditions. Contact times for each step/stance were recorded as a surrogate measure of subject walking speed and were compared to evaluate any differences between subjects, as walking speed has been shown to impact the magnitude of peak plantar pressure recorded during walking trials (37, 38). Data was extracted and analyzed with SPSS v. 17 (SPSS, Chicago, IL). A random effects mixed model with post-hoc comparisons (paired *t*-tests) were used for data analysis to investigate the differences in peak and mean pressure between the loading conditions and identify if body mass is a significant determinant of peak and mean pressure in this study. Bonferroni adjustments were applied for the post-hoc comparisons to account for multiple comparison testing. The coefficient of variations was calculated as a measure of the variability of the data relative to the mean for the contact times as a surrogate measure of walking speed.

Results

All regions displayed a mean increase in peak pressure with each load condition, except for the heel and lesser digits regions that showed a mean decrease in peak pressure between the 10 and 15 kg load conditions. There were statistically significant increases in peak pressure between the 10 and 15 kg load conditions compared to the control (0 kg) within the heel and second to fifth metatarsal regions ($p \leq 0.01$). The first metatarsal and hallux regions only displayed statistically significant increases in peak pressure between the 15 kg and control condition ($p \leq 0.05$, ≤ 0.01, respectively). The midfoot and lesser digits regions did not display any statistically significant differences in peak pressure between any load condition compared to the control (0 kg) (Table 2 and Fig. 2).

For the mean plantar pressure variable, all regions displayed a mean increase in mean pressure over the four loading conditions except the first metatarsal region, in which mean pressure fluctuated between the load conditions and failed to show a consistent positive increase in pressure. The second to fifth metatarsal region displayed highly statistically significant increases in mean pressure in the 10 and 15 kg groups compared to the



Mask	Region
M1	Hallux
M2	Lesser Digits
M3	First Metatarsal
M4	Second to Fifth Metatarsals
M5	Midfoot
M6	Heel

Fig. 1. Plantar regions analyzed and masking configuration.

Table 2. Regional peak plantar pressure with increasing body weight

	Heel				Midfoot				Metatarsals 2–5			
	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg
Mean	37.33	44.61	48.34	47.09	18.58	18.80	19.15	19.95	40.14	44.73	47.52	51.96
SD	13.24	20.31	22.59	16.00	15.51	11.55	8.93	11.63	18.06	19.12	21.48	21.13
p-Value	N/A	0.059	0.002**	0.006**	N/A	1.000	1.000	1.000	N/A	0.067	0.001**	0.000**

	Metatarsal 1				Lesser digits				Hallux			
	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg
Mean	30.43	32.15	32.35	34.26	18.33	20.14	23.64	22.67	25.50	27.82	28.76	33.44
SD	12.49	12.86	11.30	12.28	19.06	14.85	22.57	12.04	13.51	15.67	14.79	16.91
p-Value	N/A	0.758	0.606	0.036*	N/A	1.000	0.395	0.649	N/A	0.634	0.242	0.000**

*Significant at $p < 0.05$.
**Significant at $p < 0.01$.

control (0 kg) ($p \leq 0.01$). A statistically significant increase in mean pressure between the 15 kg and control (0 kg) group was evident in all other plantar regions ($p \leq 0.05$), with differences in the first metatarsal, lesser digits, and hallux region being assessed as highly significant ($p \leq 0.01$) (Tables 3 and 4, Fig. 3).

Plantar contact times for the stances during each loading condition displayed similar values and minimal intergroup variation, with a greatest mean difference of 0.015 seconds (15 kg group vs. 5 kg group). Contact times from all four load groups displayed similar coefficient of variations, with a maximum difference of 2.52%, representing minimal intragroup variation (Table 5).

Discussion

The relationship between body mass and dynamic peak and mean plantar pressure has been described in the literature. However, inconclusive results between studies and the need to further clarify this relationship were the focus of this study.

The measurement of peak pressure within this study revealed both similarities and differences to previous results reported in the literature. Vela et al. (10) found statistically significant increases ($p \leq 0.05$) in peak pressure underneath the heel, midfoot, first metatarsal, and lesser metatarsals when 9.1 and 18.2 kg of additional load was added to subjects. However, in the present study

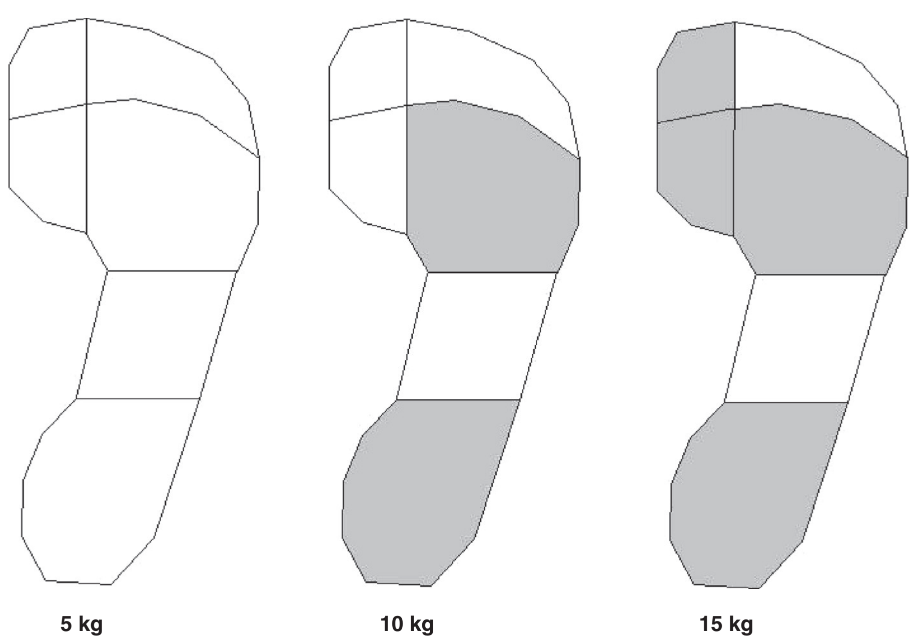


Fig. 2. Regions displaying statistically significant increases in peak pressure for load conditions compared to the control condition (0 kg).

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Table 3. Regional mean plantar pressure with increasing body weight

	Heel				Midfoot				Metatarsals 2–5			
	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg
Mean	18.68	20.84	22.92	25.91	8.71	9.09	9.96	10.11	15.68	18.69	18.96	20.56
SD	9.50	9.63	10.48	19.67	5.23	4.49	4.66	4.78	6.53	7.31	7.68	6.87
p-Value	N/A	1.000	0.303	0.017*	N/A	1.000	0.074	0.036*	N/A	0.001	0.000**	0.006**

	Metatarsal 1				Lesser digits				Hallux			
	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg	0 kg	5 kg	10 kg	15 kg
Mean	11.31	12.06	11.81	13.07	5.56	5.69	6.71	7.31	7.24	7.73	7.80	9.86
SD	4.44	5.43	4.41	5.09	4.75	3.16	4.70	3.67	4.76	5.20	4.44	5.90
p-Value	N/A	0.556	1.000	0.007**	N/A	1.000	1.000	0.007**	N/A	1.000	1.000	0.000**

*Significant at $p < 0.05$.
**Significant at $p < 0.01$.

it was observed that statistically significant increases in peak pressure only occurred in the heel, the second to fifth metatarsal regions (10 and 15 kg conditions vs. control), and first metatarsal and hallux regions (15 kg vs. control).

The study by Vela et al. (10) utilized 9.1 kg as the lightest load, substantially heavier than the 5 kg load used in the present study. Therefore, the presence of statistically significant increases in peak pressure over plantar regions in the study by Vela et al. (10) may be a function of the increased mass alone. It would seem more likely for a difference in peak pressure to occur due to the larger load condition. This may also explain the absence of statistically significant differences in peak pressure in the present study between all load conditions underneath the midfoot and lesser digits regions, and between the control and 5 and 10 kg loads for the first metatarsal and hallux regions.

The heel region displayed differences in peak pressure for the 10 and 15 kg conditions compared to the control and thus appeared sensitive to smaller changes in body mass than the forefoot regions. It is commonly observed that during normal human ambulation the first region of the foot to make contact with the supporting surface post swing phase is the calcaneus. As the initial contact phase of the gait cycle involves only the calcaneus contacting the supporting surface before subsequent midfoot and forefoot loading, the lower limb would seem to be less functionally capable of adapting to increased loads at this point. This would possibly explain the increased sensitivity of the heel region to increasing body mass that was observed.

Table 4. Statistically significant results for overall factor testing of mass as a determinant of peak and mean plantar pressure

Region	Peak pressure ($p =$)	Mean pressure ($p =$)
Heel	0.002**	0.039*
Midfoot	0.810	0.032*
Metatarsals 2–5	0.000**	0.000**
Metatarsal 1	0.093	0.018*
Lesser digits	0.417	0.026*
Hallux	0.000**	0.001**

*Significant at $p < 0.05$.
**Significant at $p < 0.01$.

In the present study no statistically significant increases were found in peak pressure during walking within the midfoot region when an additional load was added. This is in contrast to Birtane and Tuna (13), who reported that out of six plantar regions only the midfoot area recorded a statistically significant increase in peak plantar pressure when obese subjects (BMI 30.0–34.99 kg/m^2) were compared to non-obese controls. The authors also present the explanation of this phenomenon as previously stated in the literature (39); that excessive impact forces limit the ability of the medial longitudinal arch to attenuate such change, and thus adaptation occurs in the form of increased plantar contact area within the region of the midfoot. As the present study only investigated smaller increases in load (up to 15 kg), it is possible that the changes proposed above did not occur because the ability of the foot to adapt to such loads overcame any excessive impact force created by an increase in body mass.

Hills et al. (12) also reported that the greatest increase in peak pressure between non-obese and obese subjects occurred within the midfoot region. Large differences in body mass were evident between non-obese and obese subject groups, with a mean difference of 36.0 kg for

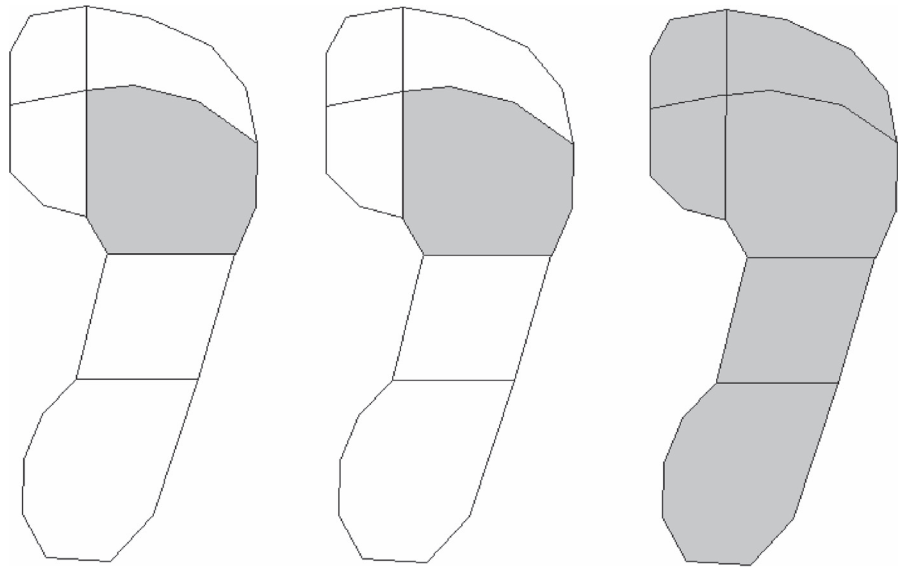

Fig. 3. Regions displaying statistically significant increases in mean pressure for load conditions compared to the control condition (0 kg).

females and 43.6 kg for males. These large differences may provide an explanation for the increased midfoot peak pressures during walking due to the above suggested pattern of increased plantar contact and pressures due to excessive loading. Changes observed due to obesity in the lower limb that may impact upon distribution of plantar pressure, such as genu valgum (40) would not be a significant factor in the present study due to the inclusion criteria regarding subject BMI. The instantaneous increase in body mass from the weighted vest does not truly represent the typical increase in body mass observed in an obese individual that occurs over a longer period of time. This is due to differences in the distribution of body mass in individuals who gain weight, in comparison to the abdominal distribution created with a weighted vest. The increase in mean pressure within all six plantar regions when 15 kg of load was introduced possibly shows the body's limited ability to adapt to a large increase in mass. The 15 kg of additional load possibly overcame the body's ability to regulate the mean or average amount of pressure subjected to the plantar foot.

The foot posture of subjects in this study may have been more supinated than intended, potentially decreasing the probability of midfoot loading. A score for each foot of between –4 and +9 was required for eligibility for this study. Retrospective analysis of large data sets that have utilized the FPI-6 to score foot posture concluded that a slightly pronated (+4) foot posture was normal during relaxed bipedal stance (41). By definition the inclusion criteria in the present study introduced a bias toward recruiting individuals with a slightly supinated foot posture. This may have impacted upon the distribution of plantar pressure measurements as previously demonstrated (28).

Table 5. Plantar contact times

	0 kg	5 kg	10 kg	15 kg
Mean (seconds)	0.636	0.622	0.635	0.637
SD	0.053	0.058	0.043	0.050
CV (%)	8.316	9.319	6.797	7.862

The results of the present study regarding mean plantar pressure as a response to different levels of body mass provide more detail than previously reported in the literature. Martinez-Nova, Huerta, and Sánchez-Rodríguez (25) measured plantar pressure within the forefoot (metatarsals, lesser digits, and hallux) regions and used multivariate regression analysis to identify variables as significant predictors of mean plantar pressure. Stronger explanative relationships were evident between body mass and mean plantar pressure within the metatarsals 1–4 region during walking, with 13–24% of the variance attributable to body weight (25). The study by Martinez-Nova et al. (25) did not identify body mass as a statistically significant predictor of mean pressure within the lesser digits and hallux regions. Although the present study found no differences in mean pressure within the lesser digits and hallux regions between the 5 and 10 kg load conditions compared to the control (0 kg), body mass was identified as a significant predictor of mean pressure within these regions. Despite this, intracluster correlations revealed that 80.1 and 82.5% of variance in mean plantar pressure was attributable to individual subject variation (rather than body weight exclusively) within the metatarsal 1 and second to fifth metatarsal regions, respectively.

The response of peak and mean plantar pressure to an increase in body mass up to 15 kg has been described in this study. Due to the relatively consistent increase in peak and mean pressure across most plantar regions with the introduction of increased body mass, it would be logical to assume on a basic level that a decrease in body mass may result in decreased peak and mean plantar pressures during walking when regional analysis is considered. If this can be demonstrated in diabetic populations, it may provide a platform and possibly highlight the importance of reducing body mass in the management and prevention of diabetic plantar ulceration, particularly in those with peripheral neuropathy. This has been demonstrated with the utilization of a supporting harness during treadmill walking in asymptomatic adult subjects (16). Despite this, there exists a need to investigate in more detail the response of plantar pressure variables to a reduction in body mass during unsupported walking in asymptomatic subjects. This may describe the relationship between body mass reduction and plantar pressure variables in a healthy population, before investigation into other populations is undertaken.

Walking velocity has previously been shown to impact upon the magnitude of peak and mean plantar pressure measured during walking (36, 37). As the walking velocity of subjects in the present study was not controlled, the differences in walking speed compared to previous studies may have affected the distribution of plantar pressure. If the walking velocity of subjects was significantly lower than previous studies, it may explain a decreased level of midfoot loading (as represented by midfoot contact area) due to a decreased pronation moment that has been observed in subjects at faster walking velocities (42). The contact times measured in this study revealed the largest intergroup mean difference was 0.015 seconds (15 kg group vs. 5 kg group) and the greatest difference in the coefficient of variations of 2.52%, indicating good consistency of walking speed between subjects and between trials under the four different loading conditions.

It has previously been demonstrated that the application of multiple masking templates when analyzing plantar pressure data decreases the reliability of data extraction (43). In the present study, plantar pressure for the six regions was extracted using a masking template for each subject. As plantar pressure is dictated by the applied force divided by the size of the region, application of individual masks essentially scales the results between subjects enabling comparison between individuals. However, it should be noted that the decrease in reliability experienced with custom masking templates is a limitation of this study.

Conclusion

This study investigated the effect of increasing body mass added at known intervals on peak and mean plantar pressure variables in healthy adult subjects during walking. Although there was a positive relationship between increasing body mass and peak and mean plantar pressure variables for most plantar regions, the relationship was highly dependent upon the region of interest. The lesser metatarsals and heel region displayed a higher level of sensitivity to increases in body mass compared to other plantar regions when peak pressure was measured. For the mean pressure variable, the second to fifth metatarsal region was most sensitive to smaller changes in body mass, with 15 kg of additional body mass required before all plantar regions displayed significantly higher values compared to the control group. This study provides insight into the degree and location of change in regional peak and mean plantar pressure variables when body mass is increased at known intervals within a young asymptomatic adult population. Investigation of other temporal parameters is needed, as these also provide valuable information regarding the loading characteristics of the plantar foot. As small increases in body mass impact upon the magnitude of regional peak and mean plantar pressure in asymptomatic individuals, it would seem plausible that this relationship may also be seen in pathological populations, such as those with diabetes. The results of this study suggest further research into other populations may be warranted.

Conflict of interest and funding

The author has not received any funding or benefits from industry or elsewhere to conduct this study.

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