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Plantar pressures in people with midfoot osteoarthritis: cross-sectional findings from the Clinical Assessment Study of the Foot

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ABSTRACT

Background: Midfoot osteoarthritis (OA) is a common condition, however its aetiology is not well understood. Understanding how plantar pressures differ between people with and without midfoot OA may provide insight into the aetiology and how best to manage this condition.
Research question: To compare plantar pressures between people with and without symptomatic radiographic midfoot OA.
Methods: This was a cross-sectional study of adults aged $\geq$ 50 years registered with four UK general practices who reported foot pain in the past year. Symptomatic radiographic midfoot OA was defined as midfoot pain in the last four weeks, combined with radiographic OA in one or more midfoot joints. Cases were matched 1:1 for sex and age ($\pm$ 5 years) to controls. Peak plantar pressure and maximum force in 10 regions of the foot were determined using a pressure platform (RSscan International, Olen, Belgium) and compared between the groups using independent samples *t*-tests and effect sizes (Cohen's *d*).
Results: We included 61 midfoot OA cases (mean age 67.0, SD 8.1, 31 males, 30 females) and matched these to 61 controls (mean age 66.0, SD 7.9). Midfoot OA cases displayed greater force (d=0.79, medium effect size, p = <0.001) and pressure at the midfoot (d=0.70, medium effect size, p = <0.001), greater force at the fourth metatarsophalangeal (MTP) joint (d=0.28, small effect size, p = 0.13), and fifth MTP joint (d=0.37, small effect size, p = 0.10) and greater pressure at the fifth MTP joint (d=0.34, small effect size, p = 0.13). They also displayed lower force (d=0.40, small effect size, p = 0.02) and pressure at the hallux (d=0.50, medium effect size, p = <0.001) and lower force (d=0.54, medium effect size, p = <0.001) and pressure at the lesser toes (d=0.48, small effect size, p = <0.001) compared with controls.
Significance: Midfoot OA appears to be associated with lowering of the medial longitudinal arch, greater lateral push off and less propulsion at toe off. Longitudinal studies are needed to establish causal relationships.

1. Introduction

Midfoot osteoarthritis (OA) is a common cause of foot pain affecting one in eight people aged over 50 years [1]. People with midfoot OA experience high levels of disabling pain and impaired physical function [2–4]. Midfoot OA is associated with female sex, older age, obesity, previous injuries, and manual occupations [1]. Foot and lower limb characteristics of people with midfoot OA include a more pronated foot posture, greater first ray mobility, less range of motion in the subtalar joint and first metatarsophalangeal (MTP) joints, decreased foot and leg muscle strength, and altered plantar pressures during walking [4,5].

Plantar foot pressures represent the forces that are exerted on the bottom surface of the foot during gait. The distribution of plantar pressures across different areas of the foot can provide insights regarding foot structure and function. Increased plantar pressures may translate to increased joint reaction forces and moments within the foot,

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and this may lead to abnormal joint stress [6,7]. There is evidence to suggest that increased joint loading is a risk factor for OA at lower limb joints such as the hip and knee [8–10]. Therefore, it is plausible that altered loading patterns of the foot could also be linked to the development of midfoot OA.

A recent systematic review examining the lower limb function of people with midfoot OA demonstrated that people with midfoot OA have altered plantar pressures [5]. This was only investigated in two studies, which found that people with midfoot OA had increased average pressure and pressure time integrals in the heel, midfoot, and medial forefoot and increased mean maximum force in the midfoot [3,11]. They also found reduced mean maximum forces at the second MTP joint [11]. The limitations of these studies were that they were conducted in clinical populations rather than representative samples, which increases the chance of selection bias. They also had stricter exclusion criteria which limits the ability to generalise findings to the broader midfoot OA population [12]. Further, the studies used different definitions to define midfoot OA, making it difficult to compare findings.

Therefore, the objective of this cross-sectional study was to compare plantar pressures between people with and without symptomatic radiographic midfoot OA, using clear case definitions in a population-based cohort.

2. Methods

2.1. Study design

This study utilised baseline data from a population-based prospective observational cohort study, the Clinical Assessment Study of the Foot. The study protocol is described in detail elsewhere [13,14]. Adults aged ≥ 50 years registered with four general practices in Staffordshire, UK, were mailed a Health Survey questionnaire to gather information on demographic and social characteristics and general health. In the UK, over 95% of people are registered with general practices, thus providing a convenient general population sample [15]. Those who responded, reported pain in and around the foot in the past 12 months, which was scored on a 0–10 numerical rating scale, where 10 equalled pain as bad as it could be. They then provided written consent to further contact and were invited to attend a research clinic where weightbearing, dorsoplantar, and lateral radiographs of both feet were obtained. The location of foot pain in the last four weeks was ascertained from participants shading a foot manikin (©The University of Manchester 2000. All rights reserved) [16]. Ethical approval was obtained from Coventry Research Ethics Committee (reference number: 10/H1210/5). Participants provided written informed consent to participate and were asked to consent to review of their medical records by the research team.

2.2. Midfoot OA case definition

Symptomatic, radiographic midfoot OA was defined as: (i) pain located in the midfoot region in the last four weeks [1,16,17], combined within the same foot (ii) a radiographic score of two or more for osteophytes or joint space narrowing on either weightbearing dorsoplantar or lateral views in one or more midfoot joints (first cuneometatarsal, second cuneometatarsal, navicular-first cuneiform and talonavicular) using the La Trobe Foot Atlas [18]. For bilateral cases, the index foot was randomly selected. Symptomatic, radiographic midfoot OA cases were then sex- and age-matched to controls with a five-year tolerance for age. Controls had (i) no pain in the midfoot and (ii) no radiographic midfoot OA according to the La Trobe Foot Atlas case definition (i.e., all midfoot joint radiographic scores < 2). The control index foot was matched to the case index foot. For both cases and controls, we excluded those with hallux valgus (measured using a validated line drawing instrument) [19,20] and inflammatory arthritis.

2.3. Force and plantar pressure and assessment

The force and plantar pressures of both feet were recorded using a pressure platform (RSscan International, Olen, Belgium). The RSScan technology has shown good reliability with intraclass correlation coefficients (ICC) > 0.75 with force plate comparisons [21]. The pressure mat was a 12-mm-thick floor mat (578 mm × 418 mm), which incorporated 4096 resistive sensors and sampled at a rate of 300 Hz. At the start of each session, the mat was calibrated and then recalibrated for each participant's shoe size and weight before their assessment. Participants walked barefoot across the mat, using the two-step gait initiation protocol, to ensure the participant's testing foot made contact with the sensor area of the mat with the second step [22]. To familiarise each participant with the procedure, they completed several practice trials across the mat to optimise normal walking, and then three trials were recorded for both feet. Participants completed the assessment in a self-determined timeframe.

2.4. Biomechanical data processing

Data from the plantar pressure measurements were processed by the primary author (MJL) using the Scientific Footscan software (RSscan International, Olen, Belgium). Each foot was automatically divided into 10-foot masks, which represented the hallux, lesser toes (two to five), first MTP joint, second MTP joint, third MTP joint, fourth MTP joint, fifth MTP joint, midfoot, medial heel, and lateral heel. Visual inspection of each masked region was undertaken, and manual adjustments were made to ensure the mask was in the most optimal position to represent the anatomical structure on the plantar aspect of the foot (see Fig. 1). Data were then extracted using a standardised protocol by MJL, who was blinded to the midfoot OA status of each participant. Once the template had been created for each of the three trials for the index foot, the maximum force (N), peak plantar pressures (N/cm^2), and contact time (ms) were calculated and extracted. Contact time was used as a surrogate measure of walking speed. The three trials were imported into Microsoft 365 Excel (Microsoft Corporation, Redmond, WA, USA) and averaged to produce one set of estimates for each participant.

2.5. Statistical analysis

Statistical analysis was undertaken in three stages using IBM SPSS Statistics version 29.0 (IBM Corp, Armonk, NY, USA). First, the case-

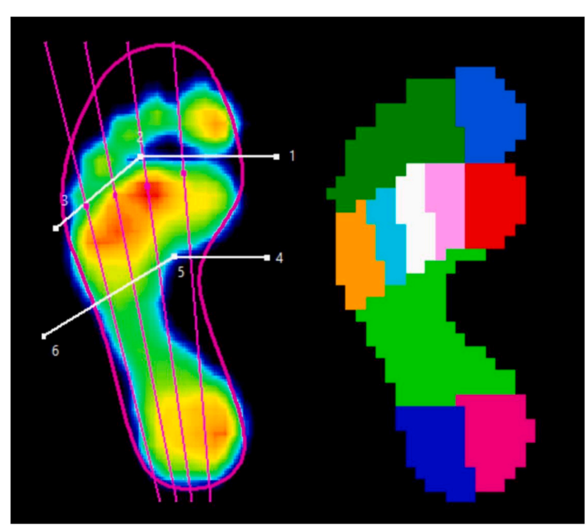

Fig. 1. Output of plantar pressure data from the RScan International system with the 10-foot masks applied, after manual adjustments, to represent the anatomical structures on the plantar foot (hallux, lesser toes, 1, 2, 3, 4 and, 5 MTP joints, midfoot, and medial and lateral heel).

control matching function was used to match symptomatic radiographic midfoot OA cases to controls based on age and sex. Second, the normal distribution of all radiographic variables was confirmed using a combination of graphical outputs (histograms, box plots, P–P plots, Q–Q plots) and statistical tests (Shapiro–Wilk test, Kolmogorov–Smirnov test, skewness, kurtosis). If data were non-normally distributed, the variables were log transformed. Third, differences between midfoot OA cases and controls were calculated using independent samples *t*-tests, and mean differences were calculated with 95% confidence intervals. Adjustments for differences in BMI were conducted using a general linear model with BMI as a covariate. Effect sizes for between-group comparisons were calculated using Cohen's *d* and were interpreted as follows: < 0.1 = tiny, 0.1 to < 0.2 = very small, 0.2 to < 0.5 = small, 0.5 to < 0.8 = medium, 0.8 to < 1.2 = large, 1.2–2 - very large, $d > 2$ = huge [23]. For non-normally distributed data, the *p*-value for the transformed data were reported, but the mean difference and effect sizes were reported on the non-transformed variables.

3. Results

3.1. Study population

As previously reported, 5109 completed health survey questionnaires were received (adjusted response 56%) [24]. Of these, 1635 individuals who reported pain in and around the foot in the past 12 months and provided consent to further contact were invited to the research assessment clinic, and 560 attended. Those with hallux valgus (measured using a validated line drawing instrument) [19,20] (n = 230), inflammatory arthritis (n = 24), incomplete data (n = 11) or corrupt plantar pressure data (n = 2) were excluded, leaving 293 participants (61 with symptomatic radiographic midfoot OA and 232 without). Of the 232 participants without symptomatic radiographic midfoot OA, 110 were excluded due to midfoot pain (with no radiographic OA) (n = 55) or radiographic midfoot OA (with no midfoot symptoms) (n = 55), leaving 122 potential control matches, from which 61 were matched (see Supplementary file 1). The characteristics of participants with symptomatic radiographic midfoot OA and the sex- and age-matched controls are provided in Table 1. The joint-specific prevalence of radiographic OA in the midfoot OA group was as follows: first cuneometatarsal (n = 10, 16.4%), second cuneometatarsal (n = 31, 50.8%), navicular-first cuneiform (n = 13, 22.9%) and talo-navicular (n = 24, 41.0%) joints. The total number of joints affected in the index foot in those with midfoot OA was as follows: one (n = 46, 75.4%), two (n = 13, 22.9%) and three (n = 2, 3.3%). People with midfoot OA had a greater body mass index compared to controls ($p < 0.001$) and were less likely to have completed higher education ($p < 0.001$). The location of other foot pain (not within the midfoot) in the index foot in midfoot OA cases and controls was as follows: toes (cases: n = 19, 31.4%, controls: n = 13, 21.3%), forefoot (cases: n = 22, 36.1%, controls n = 22, 36.1%) and rearfoot (cases: n = 20, 32.8%, controls: n = 13, 21.3%). The severity of foot pain was similar between the groups [midfoot OA = 5.6 (2.2); controls = 5.0 (2.2)]. These observed differences in other foot pain location and severity were not statistically significant.

Table 1
Participant characteristics.

	Midfoot OA (n = 61)	No midfoot OA (n = 61)
Age, years (mean, SD)	67.0 (8.1)	66.0 (7.9)
Sex – n (%) female	30 (49.2)	30 (49.2)
Body mass index, kg/m^2 (mean, SD)	33.2 (5.2)	30.0 (5.4)
Manual occupation – n (%)	18 (29.5)	13 (21.3)
Attended higher education – n (%)	6 (9.8)	20 (32.8)
Foot pain location, index foot – n (%)		
Toes†	19 (31.4)	13 (21.3)
Forefoot‡	22 (36.1)	22 (36.1)
Rearfoot§	20 (32.8)	13 (21.3)
Foot pain severity, (mean, SD)‖	5.6 (2.2)	5.0 (2.2)

†areas 1–5 and 13–17 on manikin
‡areas 6–10 and 18–22 on manikin
§areas 12 and 25 on manikin
‖scored on a 0–10 numerical rating scale, where 10 = as bad as it could be

3.2. Differences in maximum force and peak plantar pressures between midfoot OA cases and controls

Differences in force and plantar pressure measures between midfoot OA cases and controls are shown in Table 2. People with midfoot OA displayed greater force (d=0.79, medium effect size, p = <0.001) and pressure at the midfoot (d=0.70, medium effect size, p = <0.001), greater force at the fourth MTP joint (d=0.28, small effect size, p = 0.13), and fifth MTP joint (d=0.37, small effect size, p = 0.10) and greater pressure at the fifth MTP joint (d=0.34, small effect size, p = 0.13) compared with controls. They also had lower force (d=0.40, small effect size, p = 0.02) and pressure at the hallux (d=0.50, medium effect size, p = <0.001) and lower force (d=0.54, medium effect size, p = <0.001) and pressure at the lesser toes (d=0.48, small effect size, p = <0.001) compared with controls. There were no significant differences in contact time between cases and controls (d=0.08, tiny effect size, p = 0.66). Adjusting for body mass index slightly attenuated these differences, but the effect size categories for these variables remained largely unchanged (see Supplementary file 2). See Fig. 2 for a graphical depiction of the results.

4. Discussion

The objective of this study was to compare plantar pressures between people with and without symptomatic radiographic midfoot OA, using clear case definitions in a population-based cohort. In this study, people with midfoot OA displayed significantly greater forces and pressures within the midfoot during walking. They also displayed greater forces and pressure in the lateral forefoot and lower forces and pressures in the hallux and lesser toes. There was no difference in walking speed between cases and controls.

We investigated the maximum force and the peak plantar pressures within 10 regions of the plantar aspect of the foot. Both outcomes represent foot function and the mechanical stress applied during walking. Maximum force was the highest sensor measurement in each mask and represents the magnitude of the vertical ground reaction forces acting on the foot [25]. Peak plantar pressure was force divided by the area of each mask and represents load over a specific area [26]. Both outcomes represent the motion of the lower limb during walking and the mechanical stress underlying each corresponding region.

The most significant finding from this study was that people with midfoot OA had higher forces and pressure in the midfoot compared with controls. Our findings are consistent with Menz et al. [11], who reported greater mean maximum force in the midfoot in older people with medial midfoot OA, and Rao et al. [3] who also reported greater pressure time integrals and average pressure in the medial midfoot in people with midfoot OA. The relationship between increased midfoot loading and the development of midfoot OA is unclear. The increased external forces in the midfoot may be directly linked to joint loading and the development of midfoot OA. However, it is also plausible that the increased forces in the midfoot are a consequence of the lowering of the medial arch during gait [7,27,28]. As flattening of the arch is associated with increased joint moments and contact pressures within the midfoot joints [29–31], this may then lead to increased joint compressive forces in the midfoot joints and subsequent development of pathology.

We also found that people with midfoot OA have greater forces and pressure in the lateral forefoot. The finding of an increased loading in the fourth and fifth MTP joint in our study suggests a more lateral propulsion. This finding can potentially be explained by the low-gear

Table 2
Maximum force and peak plantar pressure in participants with and without midfoot OA. Values are mean (SD) unless otherwise indicated.

	Midfoot OA (n = 61)	No Midfoot OA (n = 61)	Mean difference (95% CI)	*p*-value	Effect size*	
Maximum force (N)						
Hallux †	157.4 (85.8)	196.7 (111.5)	-39.3 (−3.6 to −75.0)	0.02	0.40	Small
Lesser toes †	67.4 (43.6)	98.6 (70.2)	-31.2 (−10.2 to −52.1)	<0.001	0.54	Medium
1st MTP joint	214.8 (95.6)	217.7 (109.3)	-2.9 (34.1 to −39.8)	0.88	0.03	Tiny
2nd MTP joint	237.0 (88.7)	235.8 (97.9)	1.2 (34.7 to −32.3)	0.94	0.01	Tiny
3rd MTP joint †	236.7 (108.3)	218.3 (89.9)	18.4 (54.1 to −17.2)	0.34	0.19	Very small
4th MTP joint	167.2 (81.5)	146.1 (71.9)	21.1 (48.7 to −6.4)	0.13	0.28	Small
5th MTP joint †	126.3 (82.1)	100.4 (54.9)	25.9 (50.9–0.9)	0.10	0.37	Small
Midfoot †	297.8 (156.6)	188.1 (120.0)	109.7 (159.8–59.7)	<0.001	0.79	Medium
Medial heel †	379.9 (160.4)	369.2 (154.7)	10.7 (67.2 to −45.8)	0.69	0.07	Tiny
Lateral heel †	304.8 (126.9)	320.2 (144.2)	-15.4 (33.3 to −64.1)	0.68	0.11	Very small
Peak pressure (N/cm^2)						
Hallux †	10.5 (5.2)	13.5 (6.7)	-3.0 (−0.8 to −5.1)	<0.001	0.50	Medium
Lesser toes †	2.8 (1.7)	3.8 (2.5)	-1.0 (−0.3 to −1.8)	<0.001	0.48	Small
1st MTP joint	13.6 (5.8)	14.2 (6.6)	-0.6 (1.6 to - 2.8)	0.59	0.10	Very small
2nd MTP joint	23.4 (8.3)	24.5 (9.5)	-1.0 (2.2 to −4.2)	0.52	0.12	Very small
3rd MTP joint	25.1 (10.5)	24.9 (9.1)	0.3 (3.8 to −3.2)	0.88	0.03	Tiny
4th MTP joint	18.7 (8.1)	17.7 (7.5)	1.0 (3.8 to −1.8)	0.47	0.13	Very small
5th MTP joint †	10.5 (6.3)	8.7 (4.3)	1.8 (3.7 to −0.1)	0.13	0.34	Small
Midfoot	6.3 (2.9)	4.6 (1.9)	1.7 (2.6–0.8)	<0.001	0.70	Medium
Medial heel	20.6 (7.8)	20.3 (7.4)	0.37 (3.1 to −2.4)	0.79	0.05	Tiny
Lateral heel	16.9 (6.7)	16.9 (6.1)	-0.1 (2.2 to −2.4)	0.96	0.01	Tiny
Total contact time (ms)	1057.8 (248.1)	1040.4 (177.5)	17.5 (95.0 to −60.1)	0.66	0.08	Tiny

† Non normally distributed data, *p*-values reported as log transformed data, mean differences and effect sizes reported on non-transformed data.
MTP: metatarsophalangeal
* Cohen's *d*. Interpretation: < 0.1 = tiny, 0.1 to < 0.2 = very small, 0.2 to < 0.5 = small, 0.5 to < 0.8 = medium, 0.8 to < 1.2 = large, 1.2–2 - very large, d > 2 = huge [23].

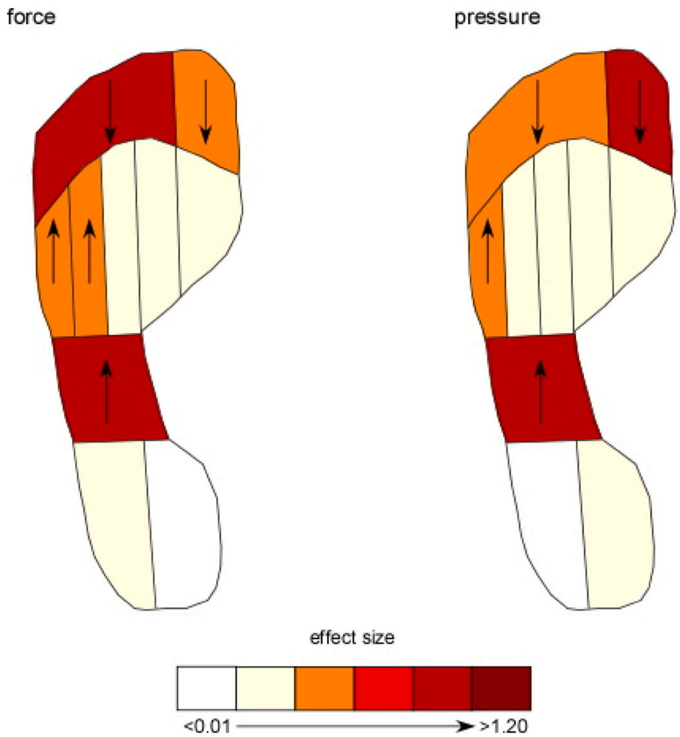

Fig. 2. Differences between midfoot OA cases and controls for force (left) and pressure (right). Shading indicates effect size; arrows indicate effect sizes of small to medium. Midfoot OA cases demonstrated lower force at the toes but greater force at the midfoot, 4th and 5th MTP joint, and lower pressure at the toes but greater pressure at the midfoot and 5th MTP joint.

versus high-gear theory of propulsion, which was first introduced by Bojson-Moller [32] who describes two metatarsal axes through which propulsion can occur. A high-gear style of propulsion uses a transverse axis through the first and second MTP joints, compared with low-gear which uses an oblique axis through the second to fifth MTP joints. In high-gear propulsion, the centre of pressure line has been described as starting at the lateral hindfoot and then moving medially after the cuboid-cuneiform joint, ending at the hallux and resulting in an efficient propulsion. Although we did not investigate the centre of pressure in this study, as people with midfoot OA have more load under the fourth and fifth MTP joint compared with controls, this could suggest a more low-gear style of propulsion that is less efficient.

A recent study by Hosokawa et al. [33] found that people with midfoot OA (second and third cuneometatarsal OA) and hallux valgus were more likely to have incongruity of the first cuneometatarsal joint, supporting the lateral gear propulsion theory. The authors suggested that instability and hypermobility through the first cuneometatarsal joint resulted in the load not being transferred to the first ray (high-gear propulsion) and being shifted laterally (low-gear propulsion). This lateral shift may overload the second and third cuneometatarsal joints and lead to degeneration of the midfoot joints and OA. While Hosokawa et al.'s study [33] suggested that hallux valgus and incongruity of the first cuneometatarsal joint could be a contributing factor to midfoot OA, our study specifically excluded participants with hallux valgus. As people with midfoot OA often have incongruity of the first cuneometatarsal joint, this is a potential theory in the development of the condition. However, there may be other explanations for a lateral loading pattern, such as a pain avoidance strategy [34]. Additionally, as foot OA tends to affect multiple joints simultaneously [2], it is possible that people with midfoot OA have a reduced range of movement in the first MTP joint [35], which may contribute to this loading pattern [36].

We also found that people with midfoot OA had lower forces and pressures at the hallux and lesser toe regions. This has been described as a 'pull off' rather than 'push-off' strategy to generate forward momentum when walking [37] and may indicate an apropulsive gait pattern in people with midfoot OA during propulsion. The mechanisms for this pattern are not clear. It is plausible that this reflects a process of 'guarding' to minimise foot loading during propulsion and subsequent pain [38]. However, people with midfoot OA are more likely to have OA in other joints [2], reduced foot and leg strength [4], and reduced range of movements within other joints of the foot and ankle [35,39]. These are all factors that could contribute to a less propulsive gait pattern during propulsion.

The clinical implications of the findings of this study are that altered plantar pressure is associated with midfoot OA. Reducing midfoot joint loading may be an important strategy for the management of this condition. For example, interventions such as footwear and foot orthoses, which influence foot posture and reduce loading within the foot, may be effective interventions for this condition [40]. In small trials, arch contouring foot orthoses have been shown to alter plantar foot pressures and improve symptoms in midfoot OA [40]. However, rigorous trials are required to establish the effectiveness of interventions designed to influence foot mechanics in midfoot OA. In addition, prospective studies are required to understand if the altered plantar pressures are a result or consequence of the condition.

There are several strengths of this study. First, in contrast to previous studies which relied on relatively small clinical samples, we analysed data from a large, representative population-based study. This makes the results more representative of the midfoot OA population and reduces bias that can occur in clinical populations. Second, the definition of cases was undertaken using a standardised foot manikin to identify the location of pain [16]. This ensures consistency between participants and increases the reliability of the data. Finally, we used a reliable atlas for documenting radiographic OA, which improves the consistency and comparability of findings [18].

Nevertheless, several limitations of this study warrant consideration. First, the study was cross-sectional in design, which does not allow us to establish causal relationships. We are unable to confirm whether the increase in midfoot force and pressure is a cause or a result of midfoot OA. Second, the observed differences could be due to a pain avoidance strategy [35] or changes in the function of the lower limb and foot, such as a reduction in the range of movement of the first MTP joint [35]. Third, the force data was gathered solely through a pressure platform, which only captures the vertical component of force. A force platform would provide more comprehensive data on other aspects of force, such as shear. Furthermore, the collected data only relates to external forces under the foot, and joint moments were not measured. Joint moments offer a more accurate estimate of joint forces and loading. Fourth, as all participants had some foot pain, this meant that the controls were not completely pain free, even though they did not have any pain in the midfoot. However, there were no significant differences in pain severity or foot pain location outside of the midfoot. Finally, people with midfoot OA had a greater body mass index compared to controls. Having a greater body mass index is a common finding in people with midfoot OA [1]. However, after adjusting for this in the statistical analysis, the effect sizes remained largely unchanged.

5. Conclusions

People with midfoot OA have greater forces and plantar pressures at the midfoot and lateral forefoot and lower forces and pressures at the hallux and lesser toes during walking. These findings are in line with established theoretical models of foot function, suggesting that people with midfoot OA may have increased lowering of the medial longitudinal arch, a more lateral push off, and less propulsion at toe off. Even when controlling for body mass index, the effect sizes remained largely unchanged. Future studies should assess whether interventions designed to normalise foot loading, such as foot orthoses and footwear, are effective in managing midfoot OA. In addition, prospective studies are needed to determine the temporal relationships between foot function and the development of midfoot OA.

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CRediT authorship contribution statement

All authors were involved in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be submitted for publication. Study conception and design: Roddy, Peat, Marshall, Thomas, Menz, Munteanu, Buldt, Lithgow. Acquisition of data: Marshall, Thomas, Lithgow. Analysis and interpretation of data: Roddy, Peat, Marshall, Thomas, Menz, Munteanu, Buldt, Lithgow.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Edward Roddy, Martin J. Thomas, Michelle Marshall, George Peat reports financial support for the study was provided by Arthritis Research UK (Programme Grant 18174). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2023.12.008.

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