

Foot dimensions and morphology in healthy weight, overweight and obese males

Clinical Biomechanics

Carina Price, Christopher Nester

Centre for Health Science Research, University of Salford, Salford, England, United Kingdom

Carina Price,

c.l.price@salford.ac.uk

Room Po33 Brian Blatchford Building

University of Salford

Salford

England

United Kingdom

M6 6PU

Abstract

Background: Overweight and obesity are increasing in prevalence. However, despite reports of poor foot health, the influence of obesity and overweight on adult foot morphology has received limited attention. The objective of this work is to accurately and appropriately quantify the foot morphology of adults who are overweight and obese.

Methods: The foot morphology of 23 healthy weight ($BMI = 22.9 \text{ kg.m}^{-2}$), overweight (27.5 kg.m^{-2}) and obese (32.9 kg.m^{-2}) age (60 years) matched males was quantified using a 3D scanner (all size UK 9). Data analysis computed normalised (to foot length) standard anatomical measures, and widths, heights and circumferences of 31 evenly spaced cross-sections of right feet.

Findings: Anatomical measures of foot, ball and heel width, ball and heel circumference and ball height were all greater in the obese group than the healthy weight ($P < .05$). Cross-sectional measures were significantly wider than the healthy group for the majority of measures from 14-67% ($P = .025$ -1.000) of heel-to-toe length. Also, the obese group had significantly higher midfoot regions ($P = .024$ -.025). This increased foot height was not evident from anatomical measures, which were not sensitive enough to detect dimensional differences in this foot region.

Interpretation: Feet of obese adults differ from healthy and overweight individuals, notably they are wider. Data needs to avoid reliance upon discrete anatomical landmarks to describe foot morphology. In the obese, changes in foot shape do not coincide with traditional anatomical landmarks and more comprehensive foot shape data are required to inform footwear design.

Keywords Morphology, Obesity, Foot, Body Mass Index

1.1 Introduction

The prevalence of adults who are overweight or obese is increasing and figures suggest these adults represent 10-30% of the global population (World Health Organisation, WHO, 2014). It is important that these populations are physically active as part of weight management programmes and to improve cardiovascular health (WHO, 2014), which demands appropriate and comfortable footwear. A high prevalence of disabling foot pain and perceptions of poor foot health have been reported in adults who are overweight or obese (Mickle and Steele, 2015; Mølgaard et al., 2010). A systematic review has also identified relationships between increased body mass index (BMI) and tendonitis and flat foot (Butterworth et al., 2012). Furthermore, obese adults also report reduced satisfaction with retail footwear and that it becomes increasingly difficult to find comfortable and appropriate footwear as BMI increases (Jelinek and Fox, 2009; Park, 2012). This may be attributable to morphological and dimensional discrepancies between the obese foot and the standard and wide-fit retail footwear designed to accommodate it (Price and Nester, 2015).

The foot of an adult who is obese may differ in structure and function compared with the foot of a healthy weight individual due to alterations in morphology, soft tissue properties and functional capability (Dowling et al., 2001; Hills et al., 2002; Riddiford-Harland et al., 2011). Specifically, lower longitudinal arch heights (Gilmour and Burns, 2001; Gravante et al., 2003; Mickle et al., 2006) and greater foot lengths and girths (Mickle et al., 2006; Mickle and Steele, 2015; Park, 2012) are evident in the feet of adults and children who are obese compared with healthy controls. The morphology and function of the feet of adults who are overweight are yet to be widely and thoroughly investigated independently from obese populations as some work does not differentiate overweight and obese individuals (Mauch et al., 2008). Existing research identifies that the ball of the foot is wider, taller and of a larger girth, but this may have also been a function of gender as these were mixed groups with inconsistent proportions

of males and females (Mickle and Steele, 2015). Within-gender differences between obese, overweight and healthy weight groups have not been considered in isolation, but are particularly important because footwear is gender specific.

In order to provide (through retail) or prescribe (via clinic) appropriate footwear to these populations, accurately quantifying the dimensions and morphology of the foot is key. In both retail and clinical contexts measures of foot size and shape are traditionally undertaken with a Brannock device and a tape, which provides simple length, width and girth measures, but may be influenced by human error. Alternatively, measures taken using a 3D scanner have high validity and repeatability and automatically quantify standard measurements required for last manufacture and the definition of footwear (Mits et al., 2009; Telfer and Woodburn, 2010). These methods have been utilised to define feet of specific populations e.g. older adults (Menz et al., 2014; Mickle et al., 2010). However the appropriateness of these automated measures to fully define the anthropometry of specific population's feet has yet to be explored. These measures utilise bony landmarks to define measures, which may not be identifiable in the feet of obese/overweight adults, due to smoothing from additional adipose tissue. The automated measures also, if defined, may not represent the largest dimensions of the foot. Therefore, it is not clear whether manual or 3D scanner measures capture enough data to fully define the dimensions and morphology of the obese foot and therefore the requirements for footwear to meet. Higher resolution foot measures which provide more detailed morphology are more likely to adequately capture differences between groups. This is key for podiatry, footwear design and related researchers to fully define populations.

The current study was undertaken to compare foot dimensions and morphology between healthy, overweight and obese adults. The measurements for comparisons included standard anatomical measures in addition to cross-sections along the length of the foot.

2. Methodology

2.1 Participants

The mean measures from 69 male participants formed three groups of 23 participants categorised by BMI and these defined the healthy weight, overweight and obese foot samples (Table 1). Healthy weight, overweight and obesity are defined by adults having a BMI of 18.5-24.9, 25-29.9 and ≥ 30 kg.m⁻² respectively. Groups were drawn from an existing data set and matched for age ($P = .058$), height ($P = .943$) and shoe size ($P = .196$) (tested via non-parametric comparisons). The sample size was consistent with other similar work in published literature (Birtane and Tuna, 2004; Mickle et al., 2006).

2.2. Data Capture

Scanning of the foot was undertaken using a pre-calibrated 3D scanner with four laser projectors and four cameras (INESCOP, Elda, Spain), of which manufacturers reports, and internal testing, demonstrate an accuracy of ± 1 mm. The within day (Intra class correlation coefficient, ICC=.678-.973) and between day (ICC=.590-.973) repeatability of foot measures are moderate to high and the standard error of the measurement < 1 mm (Price and Nester, 2016), consistent with other researchers using the same technology (Jiménez-Ormeño et al., 2013).

Group	n	Age (years)	Mass (kg)	Height (m)	BMI (kg.m ⁻²)	Shoe Size	Diabetic n
Healthy	23	54 (20-81)	72 (61-90)	1.76 (1.67-1.93)	22.9(20.0-24.7)	9 (7-10)	7
Overweight	23	67 (29-79)	85 (70-96)	1.76 (1.63-1.85)	27.5(25.1-29.7)	9 (7-11)	6
Obese	23	60 (41-78)	96 (80-122)	1.76 (1.66-1.85)	32.9(30.3-38.4)	9 (7-11)	10

Table 1. Participant information for each of the three groups of participants, median (range).

Participants stood in a relaxed bipedal stance and only their right feet were measured to ensure statistical independence within the samples (Menz, 2004).

2.2. Morphology quantification

Foot 3D software (INESCOP, Elda, Spain) was utilised to transform the point clouds to geometry (.stl file). The standard anatomical foot parameters were automatically computed in the program (e.g. instep circumference and foot length). The program utilises automatic landmark identification of the foot and then utilises combinations of planes, intersection points and standard distances to output measures of foot morphology. Measures were visually checked for correctness, all of which were labelling appropriate sites for all participants (Figure 1).

1	Instep Height	Maximum height of the intersection of a vertical cross-section of the foot along the foot axis with the dorsal foot surface.	
2	Instep Distance	Distance between the back most point of the heel and the maximum height of the intersection of a vertical cross-section of the foot along the foot axis with the dorsal foot surface, projected on ground plane.	
3	Heel Width	Distance between the two widest points of the heel at 15% of the foot length from the heel to the toe.	
4	Heel Circumference	Shortest perimeter that contains the back most point of the heel and the maximum height of the intersection of a vertical cross-section of the foot along the foot axis with the dorsal foot surface.	
5	Ball Height	Maximum height of the perimeter of the ball section (joining the most medial and most lateral metatarsal points) from the ground plane.	
6	Ball Width	Distance between the most medial and most lateral metatarsal points, projected on ground plane.	
7	Ball Circumference	Total perimeter of the ball section joining the most medial and most lateral metatarsal points.	
8	Arch Length	Distance between the back most point of the heel and the intersection of the ball circumference with the foot axis, measured along the ground plane.	
9	Lateral Metatarsal Length	Distance between the back most point of the heel and the lateral point of ball of the foot, parallel to the foot axis.	
10	Medial Metatarsal Length	Distance between the back most point of the heel and the medial point of ball of the foot, parallel to the foot axis.	
11	Foot Width	Distance between the medial and lateral points that define the ball of foot measured perpendicular to foot axis.	
12	Foot Length	Distance between the back most point of the heel and the furthest toe point parallel to the foot axis and along the plantar surface plane.	

Figure 1. Definition of standard last/foot measurements and the automatically generated landmarks used to calculate them.

The cross-sectional measures were computed in Rhinoceros 5 (Robert McNeel & Associates, Seattle, USA) where the foot scans were aligned to a longitudinal axis defined by a line from the heel centre to the second metatarsal head. For the purpose of processing the scans were normalised in length to 300 mm, cropped to 100 mm in height and 31 measures along the length of the foot were then computed. For each of these cross-sections the width, height and circumference were computed and presented as percentage of foot length (Figure 2).

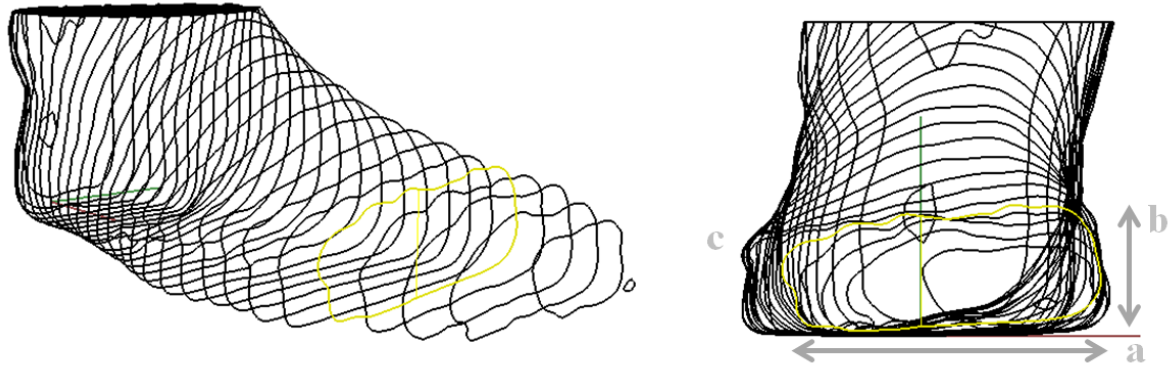


Figure 2. Example of cross-sections of the foot scan in Rhinoceros 5 and the cross-sectional measures taken for each cross-section: a: width, b: height and c: circumference.

2.3. Comparison

The anatomical and cross-sectional measures of the foot were first normalised to participant foot length (raw foot length and 300mm respectively). Data analysis then compared these values between groups for the anatomical and cross-section measures (raw foot length was also compared). Statistical analysis was undertaken in SPSS (Version 20, IBM, U.S.A) using independent samples ANOVA with Bonferroni correction for multiple comparisons. For height and circumference, comparisons were undertaken from 40% of the foot length so as not to include the ankle morphology within the analysis.

3. Results

3.1. Anatomical measures

Measures of absolute foot length did not differ between the groups (healthy weight mean 266.2, SD 10.9 mm; overweight mean 267.6, SD 9.0 mm; obese mean 265.4, SD 10.8 mm, $P = .751$). The anatomical measures of foot, ball and heel width increased with each increase in group BMI however significant differences were only evident between the healthy weight and obese groups ($P = .001-.006$; Figure 3). The height and circumference of the ball of the foot followed the same pattern. For heel circumference the obese group had a significantly larger measure than the overweight group (mean difference = .068 normalised to foot length, $P = .016$; Figure 3). The healthy weight and overweight groups did not differ significantly for any anatomical measure.

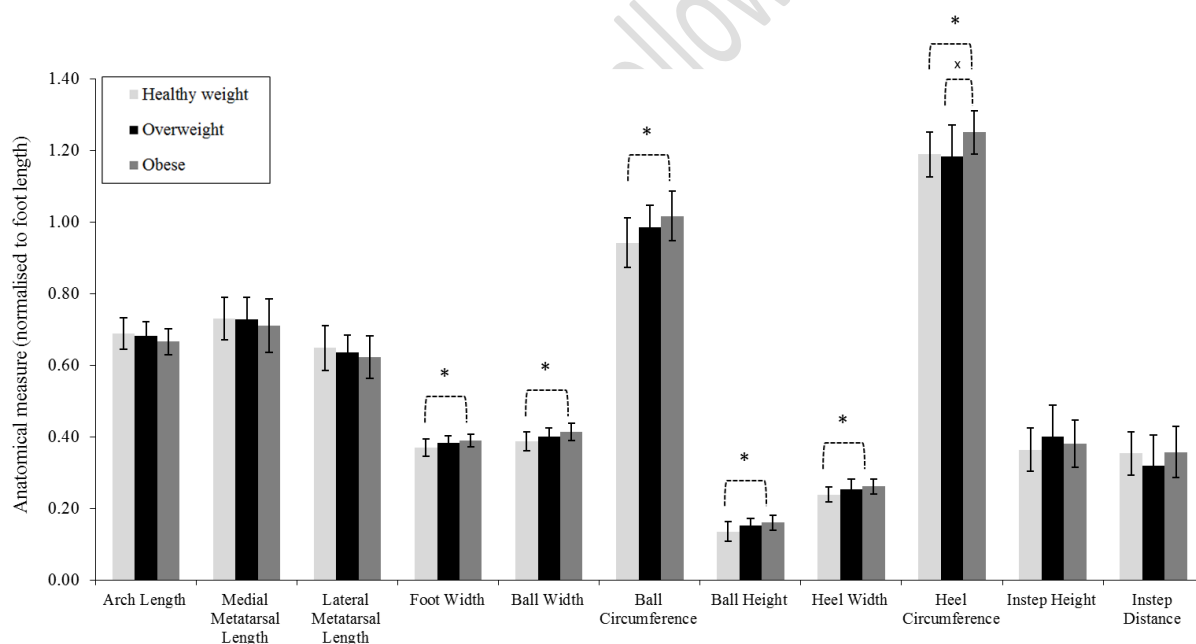
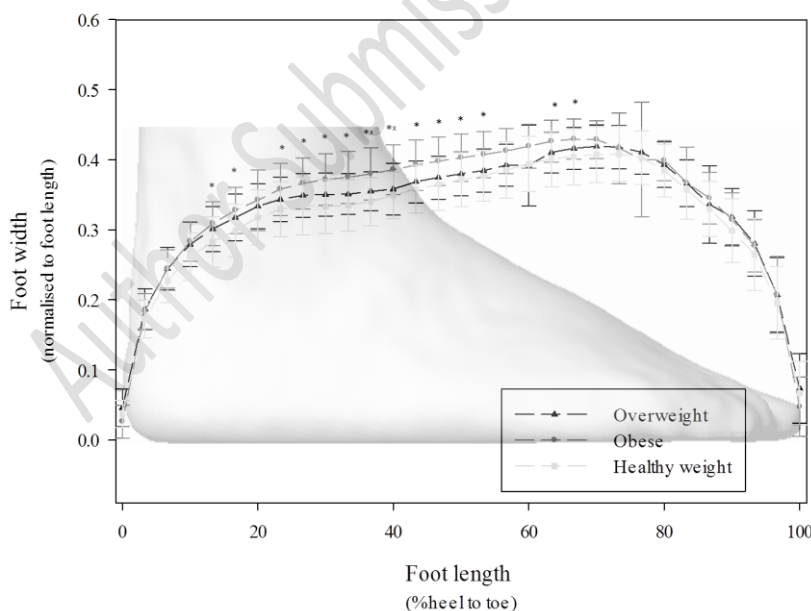


Figure 3. Mean anatomical measures normalised to foot length for the population groups where error bars denote standard deviation: *significant difference between healthy and obese, x*significant difference between overweight and obese.

3.2. Cross-sectional measures

Foot width was significantly larger in the obese foot compared to the healthy weight foot for 23-53% of the foot length (mean difference = .029-.040, $P = .000-.026$; Figure 4a). For 37-40% of foot length, the obese foot was also wider than the overweight foot (mean difference = .025-.028, $P = .032-.040$). Foot height was more consistent between the populations and the overweight group did not differ from either group. In the midfoot the foot height of the obese adults was significantly larger than the foot of the healthy weight adults (mean difference = .021-.025, $P = .024-.025$), this was mirrored in the area that would be at the ball of the foot (mean difference = .015-.017, $P = .024-.044$; Figure 4b). The circumference of the foot was larger in the obese population than the healthy and overweight for 40-47% of foot length (mean difference = .071-.101, $P = .001-.042$; Figure 4c). Further from the heel (50-57% of the foot length) the obese foot circumference was greater than the healthy population (mean difference = .069-.085, $P = .011-.043$), but not the overweight.



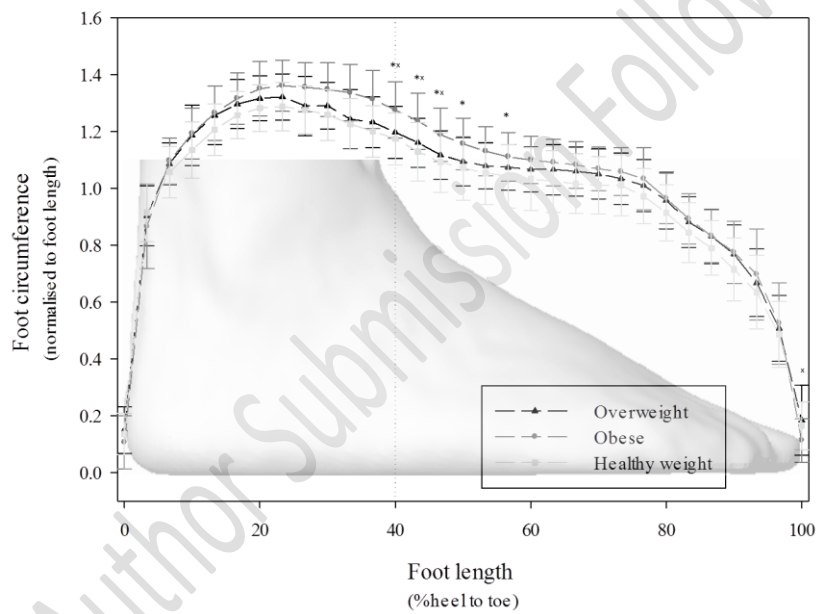
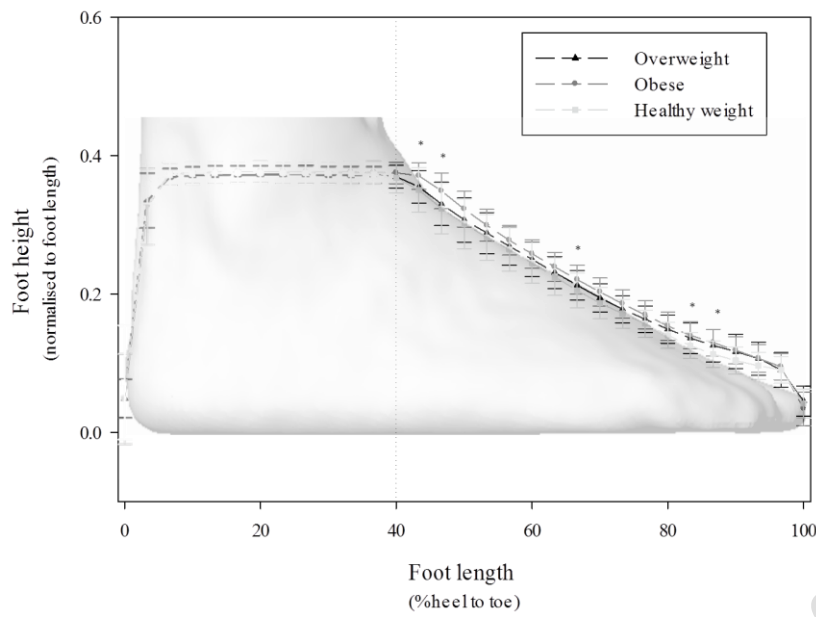


Figure 4. Mean foot width (a), foot height (b) and foot circumference (c) measures for the 30 foot slices normalised to foot length for the population groups where error bars denote standard deviation: *significant difference between healthy and obese, ^xsignificant difference between overweight and obese. Vertical line (40% of foot length from heel to toe) denotes point of statistical testing and foot image is provided from an example healthy weight participant.

4. Discussion

The data collected within this study demonstrates that the feet of obese adults significantly differ from those of adults who are overweight and a healthy weight. The feet of the obese adults in this study had larger dimensions for ball height, and widths (heel, ball and foot) and circumferences (heel and ball) of the foot. It is proposed that with increases in mass, the foot structure spreads and increases its dimensions with increases in weight bearing (Tsung et al., 2003; Xiong et al., 2008). Additionally that the foot morphology of the overweight and obese population may differ from that of the healthy weight population due to increased adiposity, localised swelling of feet from venous insufficiency or foot deformity due to excessive weight bearing (Mickle et al., 2006; Wearing et al., 2006). Within a group of people it has been demonstrated that ball girth dimensions correlate with BMI ($r = .357$, $P < .001$) (Park, 2012) and the obese foot is wider than that of healthy weight individuals (Hills et al., 2001). This is supported by the cross-sectional comparison in this study where the obese adults had feet with a larger width and circumference, whereas differences in height, although significant in some regions, were of a smaller magnitude.

The feet of the overweight group did not differ in morphology from the healthy group using anatomical or cross-sectional measures within this research, suggesting that changes to foot morphology occur once BMI exceeds 30 kg.m^{-2} . This may be due to a higher BMI, therefore the magnitude of the mass, leading to foot morphology changes, or alternatively the obese sub-group having carried excess mass for a longer period and the duration of the excess mass being the factor which influences the foot morphology. Differentiating the influence of the duration of excess weight or the magnitude of excess weight would require further

longitudinal work. If the sources of the morphology differences identified in this research are considered to be adiposity, or structural changes due to weight-bearing, then the differences between the overweight and obese groups are likely an interaction of both mass and duration. This finding contrasts with previous research where more differences were evident between the healthy weight and overweight, perhaps due to the larger sample size providing greater sensitivity to changes between groups (minimum $n = 79$) (Mickle and Steele, 2015). However, non-matched gender groups in this earlier study may mean that identified differences may be a result of gender as opposed to mass; in the current research the solely male groups eradicates any influence of gender on foot shape, however it does make results less generalisable to the whole population. Furthermore, the external validity of the findings was enhanced by the inclusion of diabetic patients in each group as representatives of a comorbidity of obesity. This was an attempt to match their frequency to that in the wider obese population and to enable participant numbers in the obese population to be maintained by not excluding diabetic patients. The influence of diabetes on feet varies, but the participants were homogenous, all in a pre-ulcerative state, with no evidence of significant disease progression and changes in foot structure or tissues.

The absolute measures of foot length between the three populations were consistent within this study and none of the three length measures differed (arch length and metatarsal lengths) when normalised to foot length. This contrasts earlier research where obese children (Mickle et al., 2006; Morrison et al., 2007) and adults (Mickle and Steele, 2015; Park, 2012) have reportedly significantly larger foot lengths when weight-bearing than healthy controls. However, it is consistent with earlier work where a discrepancy in footwear fit was evident for obese adults for foot width and depth, but not length (Price and Nester, 2015). Incremental weight bearing up to healthy body weight has been associated with increased foot length

(Tsung et al., 2003). However in the current study, the sampling of male adults of matched shoe sizes would have limited the interaction of foot length as a variable.

Previous literature alludes to a reduction in instep height in obesity due to a “collapse” of the weight-bearing longitudinal arch, which arises from quantification of increased ground contact in the midfoot in standing in obese adults (Gravante et al., 2003; Hills et al., 2001) and a lower longitudinal arch height in obese children (Gilmour and Burns, 2001; Mickle et al., 2006). However, this justification is not supported by the anatomical nor cross-section values in this research. The instep height from the anatomical measures recorded no significant differences and the cross-sectional foot heights and circumferences in the midfoot both increased in the obese feet. This suggests the structural integrity of the longitudinal foot arch maintained consistent with the healthy and overweight groups. As proposed by Wearing et al. (2004), the previously identified increased midfoot contact in obese adults may be due to larger soft tissue volumes as body adiposity is a confounding factor when interpreting these quantitative measures. This is consistent with literature which identifies an increase in midfoot soft tissue thickness in obese adults in comparison to healthy and overweight (Mickle and Steele, 2015). Alternatively, it may be that the transverse arch of the foot is flattened with the increase in mass in obese adults. This hypothesis may be evidenced by the increase in the anatomical width measures across the midfoot and the ball circumference and cross-sectional widths in comparison to the healthy and overweight populations. Increases in foot width in standing are consistent with other literature (Hills et al., 2001) and this hypothesis could be tested using radiographic measures. Additionally, this data identifies that the use of anatomical landmarks is not sensitive enough to identify dimensional differences at this region of the foot. The cross-sectional analysis provides more detailed information, particularly for footwear designers attempting to accommodate the midfoot in an item of footwear.

An array of literature has utilised standard anatomical measurements to compare differences in foot dimensions between populations (Krauss et al., 2010; Mickle and Steele, 2015; Wang, 2010). Comparing standard measures computed by software has the advantages of being automated and simple to implement, having anatomical relevance and generally being the measures utilised for footwear design. For specific populations, however, this method has the disadvantage of assuming that the key anatomical points of the foot are both automatically identifiable and suitable to characterise the effect of factors affecting the foot (e.g. obesity, aging, or a disease process). This may not be the case in populations where adiposity, oedema and foot deformity are apparent, evident by the differences in the midfoot identified above. Therefore it is recommended that additional quantification of dimensions and morphology are undertaken with the feet of adults who are obese to fully define their foot morphology. In particular, quantification of the midfoot dimensions appears significant in this group and being able to better accommodate the dimensions of this region within footwear may reduce the apparent discomfort reported by this population. Thus, it is important for clinicians and footwear designers to incorporate these measures in footwear designs.

The recruitment and categorisation of participants utilised in this study, would have benefited from the definition of the duration of the populations current BMI. For example, it is likely that if one participant was obese since childhood their foot structure would be different to someone who became obese a year prior to the study. Additionally, increasing the sample in terms of number, and additionally gender, would also offer an increase in power and inform any influences of increased body mass which differ in females compared with the all-male population within the current data set. Further consideration of the dynamic behaviour of the foot is also important for considerations of footwear and foot injury and the onset of clinical conditions in this population, including the musculotendinous structure of the foot (Faria et al., 2010) and the loading (Birtane and Tuna, 2004; Sheehan and Gormely, 2013).. The recent

development of measurement technology to quantify dynamic foot shape may enable this research to be extended in future (Fritz et al., 2013).

5. Conclusions

It is evident that the morphology of the feet of obese adults differ significantly from those of overweight and healthy weight adults. The reliance on anatomical landmarks to describe foot shape may not be sensitive enough to fully quantify the foot affected by obesity; however additional cross-sectional measures are able to define differences between these populations in foot regions. Researchers, clinicians and footwear designers should consider the foot holistically as a complex volume as opposed to a set of discrete landmarks through the use of higher resolution foot measures. This will enable better descriptions of foot shape to enable more sensitive comparisons between populations, increased specificity of footwear interventions such as orthotics and footwear and a more detailed understanding of the influence of conditions and symptoms on foot morphology.

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