Is retail footwear fit for purpose for the feet of adults who are obese?

Carina Price and Christopher J. Nester

School of Health Science Research, University of Salford, Salford, U.K.

Corresponding author:

Carina Price: Room PO33 Brian Blatchford Building, Frederick Road Campus, University of Salford, Salford M6 6PU, c.l.price@salford.ac.uk

Abstract

Background: The internal morphology and dimensions of shoes are determined by lasts on which they are manufactured, defined by foot shape, aesthetics and manufacturing requirements. Obese adults have larger foot dimensions with flatter morphology and report ill-fitting, uncomfortable footwear. Therefore, it is likely that lasts are not fit for purpose for this subset of around 30% of adults. This research quantified the relationship between the healthy weight foot and retail shoe and compared this with the foot of obese adults and wide-fit shoes targeted at those who are obese. *Methods:* A 3D foot scanner determined the morphology and dimensions of standard and wide-fit retail lasts and the feet of healthy weight and obese adults. Standard anatomical measurements and differences between multiple cross-sections of foot and lasts were compared with ANOVA. The relationship between a standard retail last and the foot of a healthy weight adult defined a level of acceptable difference in foot/last morphology/dimension, and was thus a benchmark to compare the difference between the obese foot and wide-fit last. *Results:* The comparison of standard measures demonstrated less spacious dimensions in the wide-fit shoes, specifically heel circumference and ball height. The cross-sectional analysis identified the wide-fit footwear has less spacious width in the rearfoot. In the midfoot and forefoot one of the wide-fit shoes exceeded the benchmark and provided significantly more space than the standard retail shoe. *Conclusion:* The results alluded to wide-fit footwear not currently being fit for purpose for obese adults; notably the footwear should be wider in the rearfoot. Meeting the footwear needs of the obese wearer may improve foot health and satisfaction, with potential benefits of increasing activity, consequently improving overall health.

Introduction

Obesity has been termed an epidemic and may now affect 10-30% of the adult population worldwide (World Health Organisation (WHO), 2014). Importantly, this population are required to maintain good levels of physical activity for weight management and to improve cardiovascular health (WHO, 2014). This relies on adequate foot health and appropriate footwear for mobility. However, it is more difficult to find comfortable and appropriate footwear as B.M.I. increases (Jelinek and Fox, 2009). There is also a higher prevalence of disabling foot pain and perceptions of poor foot health in populations who are overweight and obese (Butterworth et al., 2013). These factors may be related to difficulties with the fit of retail footwear, which may be due to differences between foot and shoe last dimensions and/or morphology that are specific to those who are obese. The implications of a discrepancy between footwear and foot morphology/dimensions may be significant because the reduced sensitivity of the foot in adults who are obese means it is potentially at higher risk of injury from ill-fitting footwear (Birtane and Tuna, 2004; Fabris et al., 2006; Scheinfeld, 2004).

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; Park, 2012) are evident in feet of adults and children who are obese compared to healthy weight controls. These changes (when normalised to foot length) suggest current retail footwear will be unsuitable for the foot of obese adults if the footwear is built using a last of standard morphology and dimensions. However, ranges of wide-fit retail footwear are targeted towards the needs of populations with non -standard foot dimensions/morphology and may suit the needs of obese adults. It is not clear how these products are developed in terms of their scaling or any assumptions relating to how the last should be modified at specific parts of the foot. The process may make the assumption that the foot of an obese person has the same morphology as a healthy weight person, which is unlikely to be the case for all regions of the foot (Park, 2012).

The dimensional differences between feet of adults who are obese and those who are of a healthy weight may be isolated to the key anatomical locations that relate to the standard measures used to define the last and thus the shoe (such as the ball girth, instep height; Wang, 2010). If so, the definition of a new last for wide-fit footwear, more suited to the obese foot, can be based on these specific and readily attainable measurements from Computer Aided Design (CAD) software. Comparing foot and last morphology at key foot locations is a common approach in the existing literature and straightforward to execute in CAD software packages (e.g. Krauss et al., 2010; Wang, 2010). However, morphological differences may occur at locations which are not at obvious anatomical locations or captured with these standard measures. This is particularly relevant for populations, such as adults who are obese, where oedema and other factors (Scheinfeld, 2004) influence foot regions non-systematically. An alternative approach quantifies the total variation in each of three directions of points sampled along the longitudinal axis of the foot/last (e.g. every 2 mm) and around cross-sectional slices at these respective points (every 3°) (Borchers et al., 1995). This approach encapsulates the morphology and dimensions of the entire foot, which may be key to effective footwear fit and essential to inform last designs that meet the needs of specific populations.

The current study was undertaken to systematically compare the relationship between foot and shoe morphology in obese adults to the same relationship in those of a healthy weight. We compared the foot shape of a selection of obese adults to a selection of retail footwear designed to meet their footwear requirements. This foot/last relationship was compared to a benchmark of the same relationship between the foot of an adult who is of a healthy weight and standard retail shoe. The measurement approach uses well recognised standard foot and last measurements, but also cross-sections taken along the length of the foot, making no assumption about the location of differences between obese and healthy weight groups.

Methodology

The methodology consisted of a three stage process to capture data (last and foot scans), measure the morphology (standard last measures and cross-sectional measures of last and foot) and undertake comparisons (obese foot/wide-fit shoe relationship compared to healthy weight foot/shoe relationship).

Capture Data

Scanning of the feet and lasts were undertaken using a 3D scanner and Foot3D software (INESCOP, Spain), which generated point clouds. The mean (range) measures from 13 Male participants who were categorised as obese (age = 56 (26-78) years, mass 100 (80-130) kg, B.M.I. 33 (30.3-39.9) kg.m^{-2}, 11 Diabetic) defined the measure of the obese foot (OF). The mean measures from 12 Male participants of a healthy weight (age = 45 (20-81) years, mass 73 (61-90) kg, B.M.I. 23.2 (20.0-24.9) kg.m^{-2}, 5 Diabetic) defined the measure of the healthy weight foot (HF). All were self-reported shoe size 43 and gave informed consent prior to taking part in the study. A single foot size was chosen to limit the number of shoes that would be required and simplify data analysis since normalisation of data to last size would not be required. Participants stood barefoot bi-laterally in a comfortable, even stance and only their right feet were measured to ensure statistical independence within the samples (Menz, 2004).

Three leather lace-up retail shoes were selected which represent wide-fit retail footwear in the UK (size 43 H), alongside a comparable price and style standard-fit retail shoe (size 43) (Figure 1). These shoes were selected based on the assumption that they are representative of a first solution for an obese adult who is considering their foot health and dissatisfied with standard fit retail footwear. The inner morphologies of the wide-fit retail shoes (WL_N) and standard-fit retail shoe (RL) were determined using plaster to fill the right shoe. The footwear was all laced with the tongue and laces in the standard open position without tightening the footwear to the point where the vamp and quarters were creased and without being loose. No standardisation of lacing was undertaken beyond this (Figure 1). To quantify their volume, the plaster forms (approximations of the lasts) were positioned in the scanner to mirror the standing position of participants.

Figure 1

Morphology

The Foot 3D software (INESCOP, Spain) was utilised to reconstruct the point clouds (.asc) to geometry (.stl file) following the automatic closing of sections and manual deletion of noise. The standard foot/last parameters were computed from the automatic anatomical positions generated (e.g. medial and lateral metatarsal points), which were visually checked for correctness and following which no manual adjustments were made (Figure 2).

Figure 2

To investigate dimensional aspects of the foot/last which may not be characterised by the standard measures, cross-sectional measures along the length of the foot were computed in Rhinoceros 5 (Robert McNeel & Associates, Seattle). Prior to measurement the foot/last scans were aligned on their longitudinal axis (heel centre to head of the second metatarsal) and a measure of length was attained along this axis. All scans were cropped at 65 mm from the plantar surface, which was the lowest plaster depth from the shoe "last" for comparison. A command was written in the software to create cross-sections of the foot/last scans at 10 mm intervals along the foot length from the heel to toe. To produce the cross-sections, Non-uniform rational B-spline (Nurb) surfaces were generated from intersections between the foot/last mesh and an array of rectangular planes (Figure 3).For each of these cross-sections the width, height (plantar surface to top surface of foot) and circumference were computed (Figure 3). The first 14 cross-sections of measures for height and circumference were removed from the analysis (this was the length at which the deepest shoe depth was less than 65 mm) as comparison was irrelevant due to this cropping.

Figure 3

Comparison of Foot and Last Measures

Once these variables were computed for each foot/last a comparison of foot/last relationships was undertaken between the healthy weight and obese groups. For both the standard and cross-sectional measures, the difference between the healthy foot and retail last (HF-RL) acted as a "benchmark" to which the difference between the obese foot and wide last (OF-WL_N) was compared. Therefore assuming that retail consumers of a healthy weight buy footwear which is represented by the HF-RL fit, and that this fit is a suitable target for those who are obese (i.e. OF-WL_N). This comparison was undertaken by subtracting the population average OF/WL difference from the population average HF/RL difference. Therefore, for the standard last measures there were 10 measures of difference and three shoes ($W_{1, 2, 3}$). For the cross-sectional measures there were measures of difference for width, height and circumference for each of the cross-sections along the length of the foot, plus separate measures of length for each of the three shoes.

Statistical Analysis

Statistical analysis was undertaken in SPSS (Version 20, IBM, U.S.A.) using one-way ANOVA with Dunnett's post-hoc test to compare the three OF-WL_N differences to the healthy control condition difference (HR-RL) with $p < .05$ to define significance. The data presented is the difference (mm) between obese and healthy weight groups in the relationship of their foot to the lasts, not the difference between foot and last in each group. A difference of 0 mm represents a perfect match between the healthy wearers (HF-RL) and obese wearers (OF-WL_N) fit, a negative value less spacious for the obese foot in the wide fit shoe.

Results

For the standard last measures the obese OF- WL_N difference was lower than the equivalent healthy weight value (mean -4.9±20.8 mm; Figure 4). For the heel circumference parameter, all of the wide-fit retail shoes were significantly less spacious than deemed acceptable by the benchmark relationship (denoted by 0 in Figure 4; all $p \leq .029$). Overall WL_2 was the best match to the benchmark, but provided 7.9±5.3 mm less height at the ball of the foot ($p < .001$), and

19.6±8.9 mm less comparative length to the arch (p = .043). For ball width, WL_1 (p = .043) was less spacious than the benchmark and had dimensions that were smaller than that of the mean OF. The wide-fit footwear did not differ significantly from the benchmark in terms of the comparative length. This was despite the absolute internal length of the shoes (WL_1, WL_2, WL_3) being 4-10 mm shorter than the healthy shoe (RL)

Figure 4

The analysis of the cross-sectional data indicated lower values than the benchmark relationship (denoted by 0 in Figure 5a) for the width along most of the foot length, therefore less comparative space. This was particularly evident in WL_1 where 16 of the 28 values were significant The exception was the toe region where the wide-fit shoes provided comparatively more spacious width for the foot than the healthy shoe (positive values), but these differences were not significantly different to the healthy difference (p = .197-.735 for slices 23-27). The obese OF- WL_N had less spacious toe height than the healthy HF-RL difference in the most distal slice of the foot for all wide-fit shoes (slice 28; all $p \leq .001$). Also in the more proximal toe region, this difference also reached significance for WL_1 and WL_2 (slice 22; WL_1 p = .016, WL_2 p = .007, WL_3 p = .214). More spacious fit was evident in some regions, for example the WL_1 condition for circumference (slices 16 and 17; p = .002-.048) and height (slices 17-20; p = .002-.009).

The results from the cross-sectional method varied in some regions from the standard measures. In the heel average differences from the benchmark for cross-sections 1-6 for heel width were WL_1= -11.0±1.1 mm, WL_2 = -4.3±2.0 mm, WL_3 = -7.4±1.4 mm (p = .000-.573, Figure 5a). Despite being in the same direction, this was larger than the heel measures in the standard measures, which showed no significant differences (WL_1= -6.9±4.9 mm, WL_2 = -2.9±4.9 mm, WL_3 = -6.9±4.9 mm, p > .05) (Figure 4). Additionally, the findings relating to ball circumference contrast between the two measurement methods. The standard last measures identify the obese OF- WL_N difference to be less spacious than the benchmark relationship, significantly for WL_3 (-26.2±17.3 mm, p = .033; Figure 4). However, in the cross-sectional method the circumference measures in the forefoot region there are no significant differences between the wide-fit footwear and the benchmark healthy relationship (Figure 5c).

Figure 5

Discussion

The data collected within this study demonstrates that high-street wide-fit footwear may not meet the needs of the adult wearer who is obese. The footwear does not provide the same comparative fit as the footwear available for a healthy weight adult. In the heel and ball regions specifically, the footwear lacks appropriate dimensions to accommodate the foot morphology in those who are obese. This is consistent with previous literature that identifies adults with higher B.M.I. find appropriate and comfortable footwear harder to find and are dissatisfied with the footwear available to them (Jelinek and Fox, 2009; Park, 2012).

Assuming the healthy weight foot/shoe relationship is an appropriate benchmark, the data from the standard measures indicates that the wide-fit footwear incorporates insufficient dimensions for width, heights and circumferences across regions of the foot. Deviation from the benchmark ranged from -26.2 mm to +4.71 mm, with only four dimensions providing comparatively more spacious fit than the footwear designed for the healthy weight foot. The results from the cross-sectional method demonstrate similar trends in some regions as the standard measures, particularly in the width measures, where there was less spacious fit (-3.7±8.2mm). The height (-1.8±5.2mm) and circumference (-12.1±22.0mm) measures were more variable in terms of meeting the benchmark. The deviation from the benchmark was not consistent along the length of the foot, particularly for the shoe WL_1. For example in the heel the obese shoe was 7.5±5.1 mm comparatively less spacious in width, reducing further to 11.0±1.1 mm in the toe region. This infers that the wide-fit footwear lasts do not appropriately represent the foot dimensions or the morphology of the population for which the footwear may be targeted, modifications can therefore be recommended, specific to foot regions.

The wide-fit footwear did not differ significantly in length from the benchmark healthy relationship, suggesting that there was consistent space in the length of the wide-fit footwear despite the wide-fit footwear being shorter. This was due to the feet of the obese participants being shorter than the healthy control (mean 7.3 mm shorter than healthy population). This is consistent with findings in American female college students; as B.M.I. increased the students tended to wear larger shoes (Park, 2012). Within the current study this finding can be attributed to the larger maximum width dimension of the obese adults feet (98.4±5.2 mm) compared with the healthy adults (95.4±6.1 mm), despite the shorter feet. This may require the wearers to select a larger shoe size (and therefore length) to accommodate their extra foot width and, since the inclusion criteria was use of a size EU 43 shoe, this would explain the comparatively shorter feet in the obese group. This is consistent with work which identified a strong correlation between body mass and foot width (r = 0.782, $p < .05$; Xiong et al., 2009). Additionally it has been demonstrated that when weight bearing the foot width increases more than foot length (Xiong et al., 2009).

In the rearfoot, the cross-sectional measurement approach identified that the heel width within the wide-fit footwear was below that of the benchmark, therefore less spacious, particularly in conditions WL_1 and WL_3. Heel width has been demonstrated to increase with increased weight bearing (by approximately 2%; Xiong et al., 2009) and due to swollen feet (by 4.6%; Mickle et al., 2010). This measure has also been shown to correlate with B.M.I. (r =

.602, $p < 0.05$; Park, 2012). . All these factors relate to those who are obese and therefore relate to the population in this study. Other research demonstrates the difference between foot and last heel width correlates with subjective overall ($r = 0.478$, $p < 0.01$) and rear-foot comfort ($r = .467$, $p < 0.01$; Cheng and Hong, 2010) and therefore fit in the heel is an important consideration for footwear comfort. The results from the present study suggest that increasing the shoe heel width by 3-13 mm may improve obese wearer satisfaction with wider-fit retail footwear.

In the forefoot and midfoot, there was a trend for the wide-fit shoe (WL_1) to be more spacious in height and circumference in some cross-section regions for the foot of the obese adults. The requirements for certain traditional aesthetics in footwear may have led the design to produce a larger width midfoot and toe due to a larger width being required throughout the rest of the footwear. Despite the differences in width of the toe of the footwear conditions not reaching significance in this comparison, the midfoot depth and height were significantly more spacious in WL_1. The inconsistent effect that obesity has on morphology in different areas of the foot (Hills et al., 2001; Mickle et al., 2006) could create a discrepancy between shoe and foot dimensions in one foot region (e.g. forefoot) when the morphology needs of another region (e.g. rearfoot) are addressed by scaling existing lasts. Altering standard footwear design, specifically morphology, to better meet the needs of this population is recommended. If the footwear dimension is to not match the foot of an obese adult, any discrepancy is easier to manage if the morphology is suitable, for example by wearing a larger size. Further to this, as aforementioned, participants were recruited on their self-selection of size 43 footwear, and the obese population had shorter feet. This could lead to misrepresentation of the toe width compared to the healthy population due to cross-sections being taken at different relative locations from the heel. Irrelevant of the basis, this excess room in the footwear may lead to poor footwear fit, adverse frictional forces and blisters (Knapik et al., 2012; Rossi, 1988).

For some of the regions the results from the standardised and cross-sectional measures differed, notably in the heel. This could be due to differences in the landmarks used to parameterise each region. The standardised measure of heel width was taken at 15% of the foot/last length along the longitudinal axis from the heel. In the cross-sectional analysis, however, the width was determined by the two extreme medial/lateral points of the cross-section, irrespective of their alignment or position from the floor. Similar disparities exist between the methodologies in other regions. Measuring ball circumference, for example, the standard measure was an average of 16.8±4.8° from the longitudinal axis of the foot in the healthy population. The equivalent measure in the cross-sectional analysis was taken perpendicular to the foot longitudinal axis. Additionally, the standard measures do not consider the relative position of the foot to the shoe e.g. the ball girth measures are not taken at the same distance from the heel, they are relative to anatomical features. In the cross-section approach this weakness is removed by taking measures at centimetre increments from the heel such that measures are compared at consistent points from both the foot and the shoe irrespective of the relative anatomy.

The implementation of the relationship between the foot and retail last as a benchmark relies on the assumption that the relationship between the foot of a healthy weight adult and retail shoe is applicable to an obese foot and wide-fit shoe, and is a limitation in this study. Firstly, it assumes that standard footwear lasts (and specifically the shoe we selected) are effective and suitable for the general population and thus the relationship between the last and the foot of a healthy weight adult represents "fit for purpose". Secondly, that our sample of healthy weight and obese adults are representative, which may be limited by the study sample size. Additionally it assumes that the dynamic differences between last/foot are consistent in obese adults compared to healthy weight adults and that the preferences for fit in specific foot regions in an obese wearer are the same as in a healthy weight wearer. However, the sensitivity of the foot of an adult who is obese is likely reduced due to increased thickness of subcutaneous tissue (Scheinfeld, 2004) and nervous system impairment (Miscio et al., 2005). Additionally, an increase in mean pressure on foot mechanoreceptors is thought to reduce their sensitivity (Hue et al., 2007). Therefore what may be acceptable positive and negative differences in foot/last dimension at specific foot regions in a healthy weight population may not be the same in an obese population. Co-morbidities such as diabetes could further compound these issues and obesity and diabetes are very common joint presentations due to their common origins. The inclusion of healthy weight people with diabetes in the healthy weight group (N = 5) within this research nears those with diabetes in our obesity group (N = 11), and supports investigation of obesity as the independent variable whilst maintaining a real world obesity sample (i.e. including comorbidities). Future work should therefore consider testing additional footwear designs and coupling measures such as foot sensitivity, footwear fit and fit preferences with objective analysis of foot morphology.

Conclusions

This study has identified that wide-fit footwear and the feet of obese adults do not replicate the relationship which is evident in standard fit footwear and the feet of healthy weight adults. The relationship was altered in inconsistent ways along the length of the foot, demonstrating that the morphology of the shoe does not match that of the foot of an obese adult. Wide-fit footwear for obese adults is not currently fit for purpose. From the current data it is recommended that a greater heel width and circumference would accommodate the obese foot in wide-fit retail in a similar way as the feet of healthy weight adults is accommodated in a standard retail comfort shoe. Meeting the footwear needs of the obese wearer may improve satisfaction and foot health, with potential benefits of increasing activity in this every increasing proportion of the global population.

Acknowledgements

With thanks to Dr Jonathon Chapman, Dr Ana Martinez Santos and Lee Willan for data collection and Dr Daniel Parker for assistance with the use of Rhinoceros 5 software.

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Figures

Figure 1. Standard and wide-fit retail comfort shoes (Left to Right) RL (Ecco Transporter), WL_1 (Marks & Spencer Collection Airflex), WL_2 (Clarks Collection Line Day), and WL_3 (Padders Taxi).

Instep Height	66mm
Heel Width	71mm
Heel Circumference	359mm
Ball Height	43mm
Ball Width	105mm
Ball Circumference	256mm
Arch Length	165mm
Foot Width	102mm
Toe Length	252mm

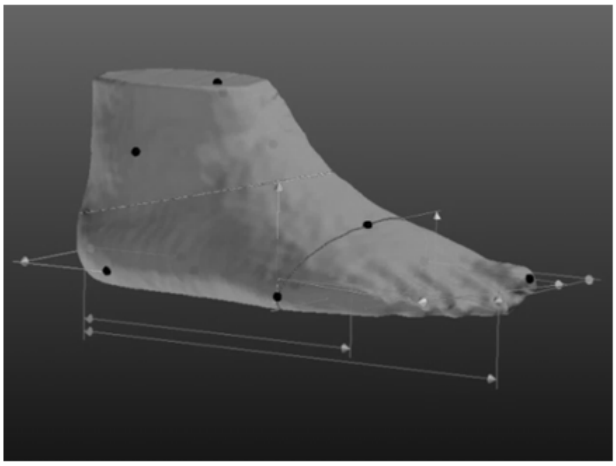

Figure 2. Definition of standard last/foot measurements and the automatically generated landmarks used to calculate them.

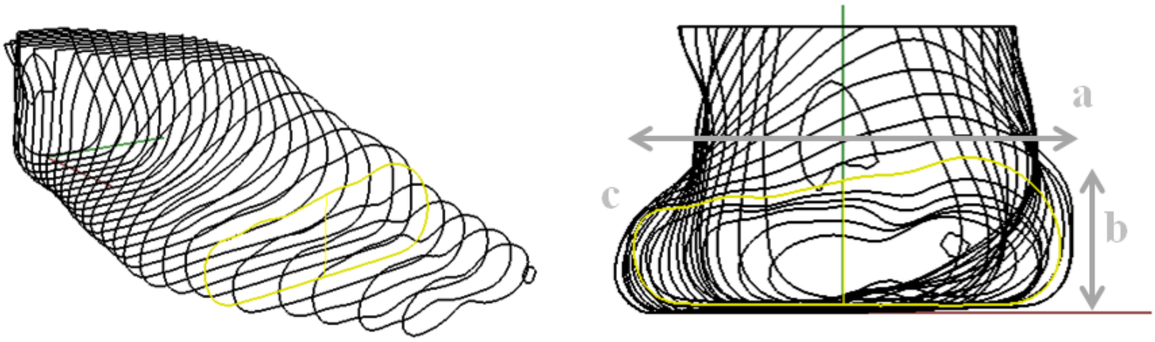

Figure 3. Example of cross-sections of the foot scan in Rhinoceros 5 and the cross-sectional measures taken for each cross-section: a: width, b: height and c: circumference.

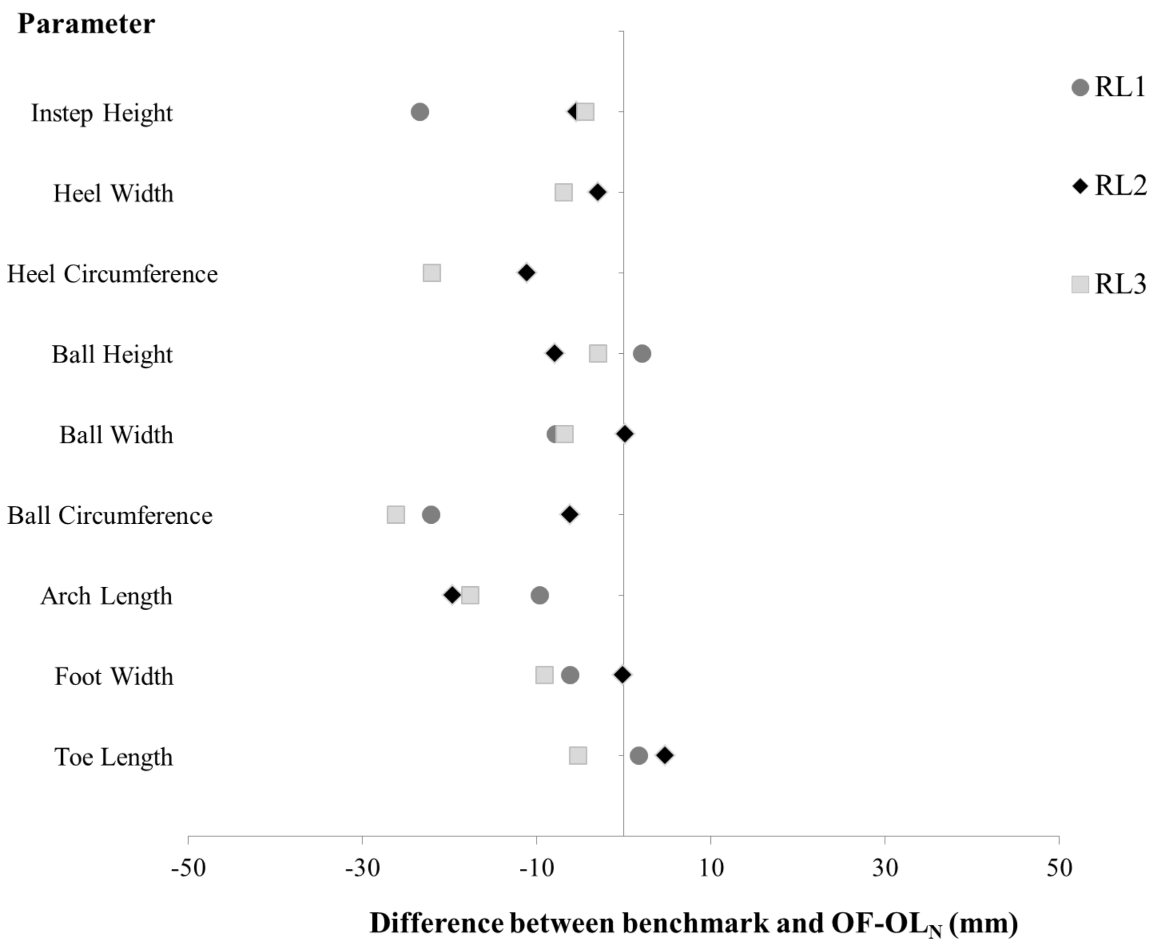

Figure 4. Difference (in mm) between benchmark values (0) and the obese foot to wide last difference (OF-WL$_N$) for generated parameters for the three footwear conditions.

WL1 (Marks & Spencer Collection Airflex), WL2 (Clarks Collection Line Day), and WL3(Padders Taxi). Negative values indicate a less spacious fit and positive values indicate a more spacious fit relative to the healthy foot/retail last fit. Statistically significant differences from the standard shoe (0 value) are denoted by *.

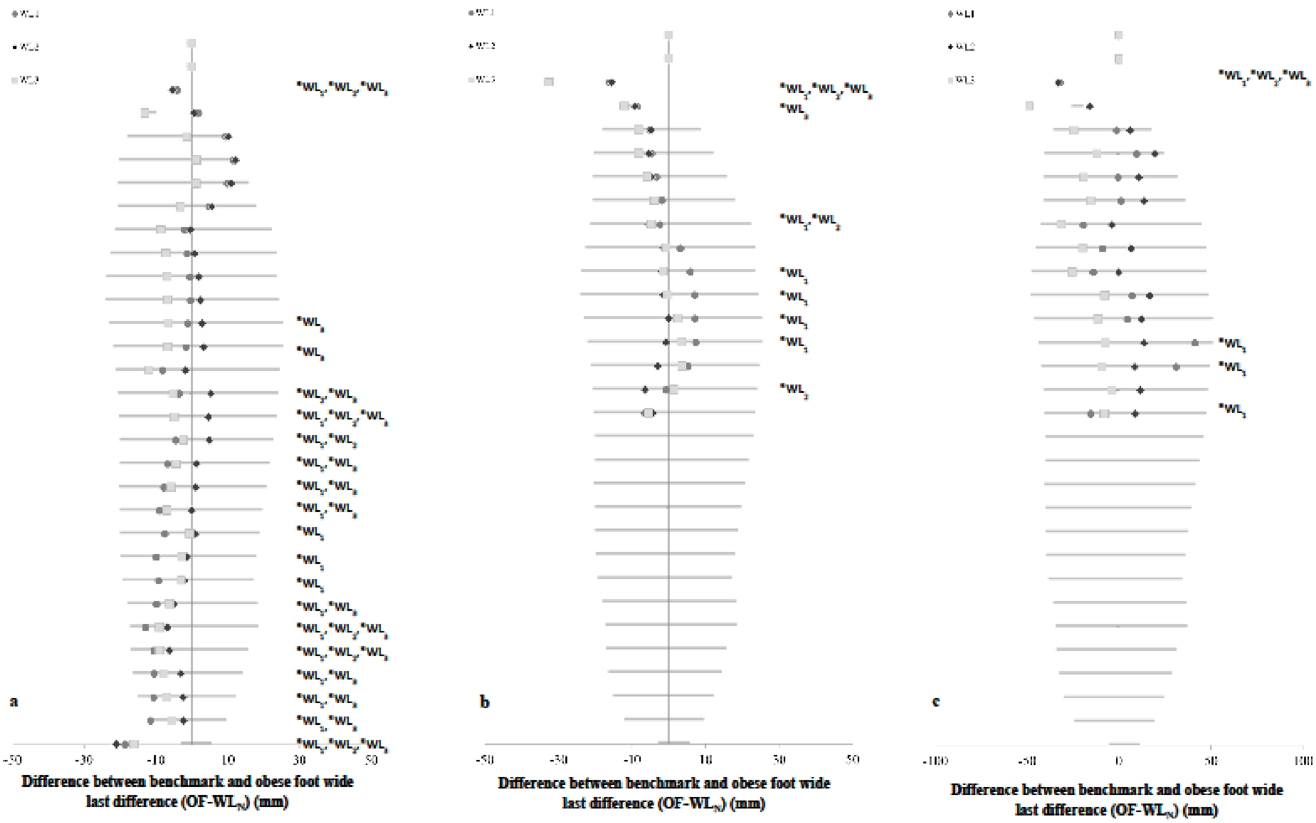

Figure 5. Difference (in mm) between benchmark values (0) and the obese foot to wide last difference (OF-WL_N) for width (a), height (b) and circumference (c) parameters for the 30 cross-sections of the foot from heel to toe for the three footwear conditions. WL_1 (Marks & Spencer Collection Airflex), WL_2 (Clarks Collection Line Day), and WL_3 (Padders Taxi). Negative values indicate a less spacious fit and positive values indicate a more spacious fit relative to the healthy foot/retail last fit. Statistically significant differences from the standard shoe (0 value) are denoted by *.