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Flexion location of the first metatarsophalangeal joint and the location of forefoot bend in general purpose women's footwear

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ABSTRACT

Background: General purpose footwear could have a built-in flexion location which may not match the anatomical fulcrum location for an individual's foot. Mismatched fulcra impact on joint function, and may delay healing of an injured first metatarsophalangeal joint (first MP joint). This study compared the location of the first MP joint in an asymptomatic sample of the South African female population to the bend location set within the lasts (used by footwear manufacturers) to find whether mismatches of the flexion locations of the joint to the bending location of the footwear were likely.
Methods: The study used a three dimensional foot measurement database of 453 female participants to find the fulcrum location of the first MP joint. The distance between the heel and the first MP joint was expressed as a percentage of the overall length of the unshod foot. Similar measures for sandals and closed shoes were derived, and all were compared to manufacturer last data.
Results: The location of first MP joint ranged from 70% to 79% of total foot length, significantly different from last design specifications of 63% or 66% ($p < 0.0001$). The range of first MP joint fulcrum locations in the same size feet occurred in a wide 24 mm mediolateral band under the forefoot, termed a flexion zone.
Conclusions: The first MP joint cannot properly function as a fulcrum unless footwear has a matching flexion location. Footwear designs should incorporate a wide flexion zone located under the forefoot to permit the range of first MP joint flexion locations. Recommendations to patients are to select appropriate flexible footwear to prevent shear forces, reduce strain, prevent injury and enable range of motion function and healing of injury.

1. Introduction

Although some work has been reported on specialized footwear for post-operative orthopaedic recovery [1,2], little is found to connect orthopaedic foot knowledge to the parameters that footwear manufacturers use to make general purpose footwear. The function of the first metatarsophalangeal joint (first MP joint) is adversely affected when the fulcrum of the shoe does not match the fulcrum location of the joint [3]. Adequate range of motion of the first MP joint is dependent on adequate dorsiflexion [4]. The location of flexibility in the shoe is important to allow for a natural range of motion dorsiflexion during the propulsion phase of gait. We thus investigated whether actual foot measurements support the specifications presently used to manufacture general purpose footwear.

In footwear design, last designers position a set location for the flexion location of the first MP joint. European guidelines position the fulcrum at 66% of overall last length for sandals as well as shoes [5,6]. North American last-making guidelines place the fulcrum at 63% of overall last length [7].

Since patients either wear closed shoes or sandals post-operatively, we investigated for differences between sandal as well as closed shoe last lengths. It was found that, for cosmetic appearances, shoe manufacturers allow less toe space beyond the distal ends of the toes to the end of footwear in an open sandal than in a closed toe shoe [7]. The result is that the last for a sandal is shorter compared to that of an open shoe, yet the location of the forefoot bend for a shoe or sandal is set at the same percentage of overall last length. This results in a different bend location from shoe to sandal. To illustrate this, assume a shoe last length of 170 mm. The bend location for the first MP joint would thus be located at 112 mm (using 66% of overall last length). The corresponding sandal last would be 163 mm long in which 66%

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of overall last length would place the bend location for the first MP joint at 108 mm, resulting in a variance of 4 mm from that of the closed shoe in this example.

The first question asked was whether the actual location of the first MP joint in an unshod measured sample was significantly different from the flexion point location of the first MP joint as set by footwear manufacturers for sandals and closed shoes. The second question asked was whether other variables such as population group, age, weight, foot breadth (at the metatarsal break) and forefoot girth are significantly associated with the location of the first MP joint.

2. Participants and methods

The primary author (ATT) developed a three dimensional (3D) database of foot measurements by laser and point scanning of the right foot of 510 female participants [8]. Participants were randomly selected from a large volunteer pool of working women at the University of Johannesburg and the University of Kwa-Zulu Natal over a period of four months. In addition, a convenience sample of female crew members from the national airline, a national media broadcaster and a church group was included. In descriptive summary, participants' ages ranged from 21 to 69 years, their weight from 34.7 kg to 150.9 kg and their Body Mass Index (BMI) from 13 to 56 BMI. An earlier foot measurement survey in 1954 had addressed a limited group of South African white female adult feet [9]. To rectify the lack of population group representation in the older study, all four major population groups were represented in the new study as required by South African government statistics so that historical inequalities of focus can be redressed [10]. The names given to these population groups for statistical research purposes are Black African, White, Indian/Asian and Coloured (a local distinct population who have ancestry from African [Khoisan and Bantu], European and Asian [Austronesian and South Asian] ethnic groups) [11]. A pilot study on 10 participants was undertaken to establish inter-rater reliability and to verify the reproducibility of the scanner and stylus instrumentation.

A hand-held laser scanner (FastScan, USA) captured a 3D image of the right foot of each participant by means of successive scanning sweeps. A special platform positioned the foot during scanning. Each participant's foot was guided into a block of orthopaedic impression foam in relaxed calcaneal stance position in one-legged weight bearing [12] and kept immobile. The negative foam impression of the plantar surface of the foot was scanned after a dorsal surface foot scan and digital stylus marking of bony landmark points. Post-processing custom software (Telmo, USA) digitally combined the dorsal and plantar scans to form a 3D image of the foot (Fig. 1).

Linear measurements were derived using custom software. Data for 53 of the 510 participants were excluded due to scanning inclusion errors flagged by the post-processing software. The dataset extracted for this study included data for selected palpated bony landmarks, gender, population group, age, weight, height, calculated BMI, foot length, foot breadth and forefoot girth.

2.1. Ethics

The study was conducted in accordance with the Helsinki Declaration. The Biomedical Research Ethics Committee of the University of KwaZulu Natal, College of Health approved the current analytical study via Ethics Clearance BCA058/17 dated 27th March 2017. Informed consent was obtained for data collection from 510 adult female participants under the prior Ethics Clearance Certificate EC212004/009 from the University of Johannesburg.

2.2. Variables

Each landmark point captured (as shown in Fig. 2) is an X, Y, Z coordinate. Cartesian arithmetic was used to derive the linear distances between selected landmark points.

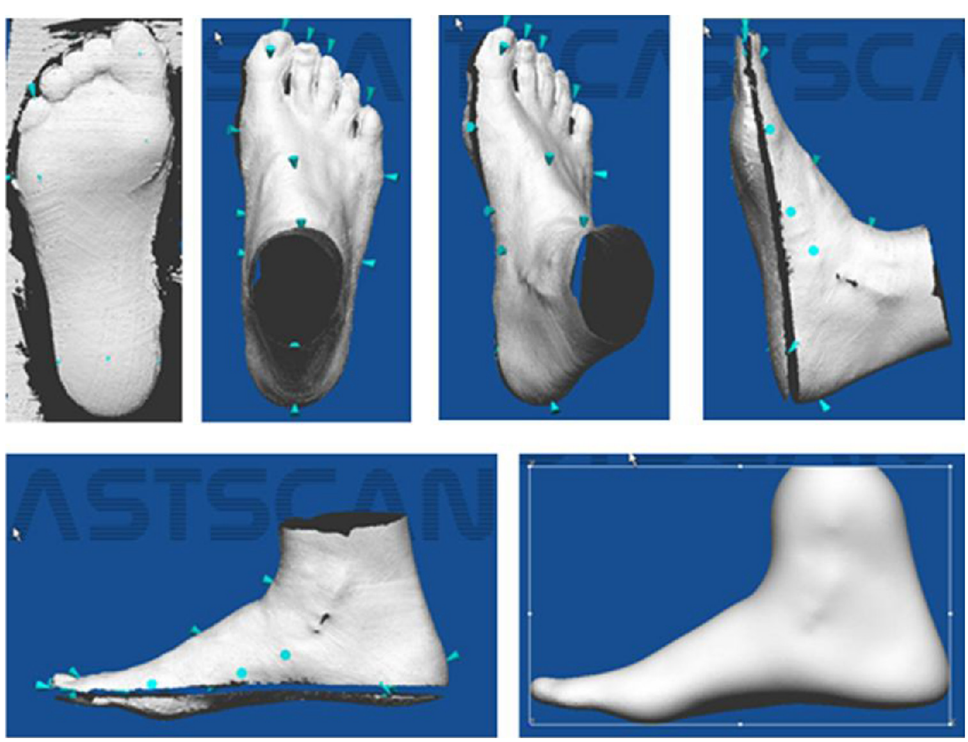

Fig. 1. Three dimensional foot surface data capture. Positive scan halves are fused by custom software into one three-dimensional object surface; blue cones indicate stylus point marking of bony landmarks (Thompson [8]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

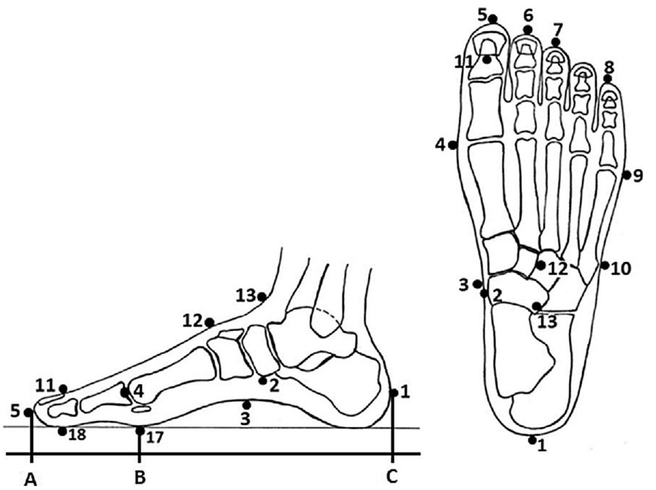

Fig. 2. Medial and dorsal representation of 18 surface palpated landmark points for stylus point data capture (Thompson [8]). Landmark points were used to derive Foot Length (A–C) and Heel to first metatarsophalangeal joint Length (C–B).

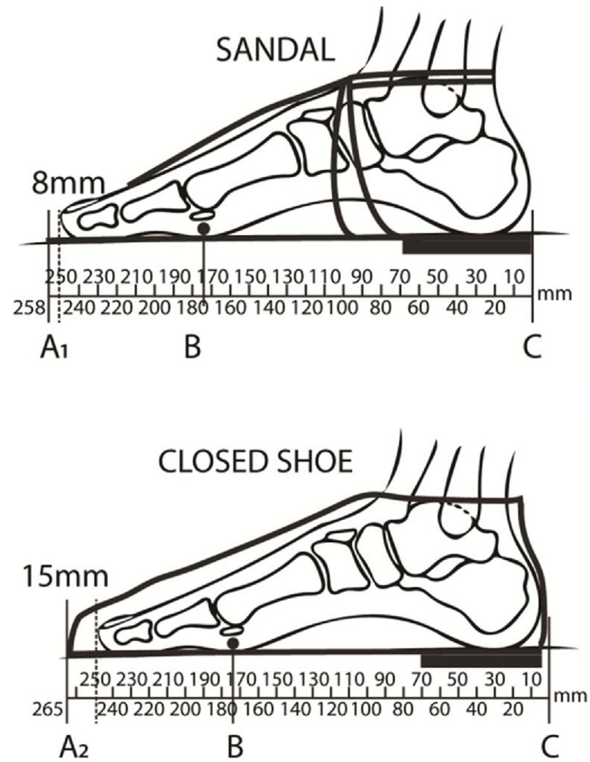

Fig. 3. Example sandal last above allows 8 mm toe clearance ahead of toes (B–A_1) while corresponding closed shoe last below allows 15 mm toe clearance (B–A_2). Thus the example closed shoe last is 265 mm long while the sandal last is 258 mm long. Yet the lasts for either variation place the flexion location at the same fixed percentage of overall last length, instead of using a measure related to the foot.

For the purposes of this study, the selected measurements were foot length (from landmark 1 to 5) and heel to first MP joint distance (from landmark 1 to 17), which we term Heel-1MPJ length. Based on landmark data, Fig. 2 illustrates the derived foot length (distance A–C) and the Heel-1MPJ length (distance B–C).

- Foot length (mm)—defined as the distance from the most proximal surface of the heel to the distal tip of the hallux or longest toe.
- Heel-1MPJ length (mm)—defined as the distance from the most proximal surface of the heel to the first MP joint landmark in a medial view.
- Heel-1MPJ expressed as a percentage of foot length (%)—calculated as $\frac{\text{Heel}-1\text{MPJ length}}{\text{Foot length}} \times 100\%$

To postulate what would occur in lasts for both types of footwear across the sample of feet, 8 mm and 15 mm was added to each foot length (represented by the dotted lines in Fig. 3) to obtain the theoretical last lengths for a sandal (A_1 to C in Fig. 3) and a closed shoe (A_2 to C in Fig. 3), respectively. The location of each first MP joint was then re-calculated as a percentage of overall last length for the two types of lasts.

The following variables were investigated in the study:-

Heel-1MPJ % of sandal length (%)—calculated as $\frac{\text{Heel}-1\text{MPJ length}}{\text{Foot length}+8} \times 100$.

Heel-1MPJ % of closed shoe length (%)—calculated as $\frac{\text{Heel}-1\text{MPJ length}}{\text{Foot length}+15} \times 100$.

Gender (F)—this study included only female participants.

Population group—participants self-identified their ethnicity based on the four population groups as previously defined in the South African governmental census: Black, Indian or Asian, White and Coloured [10,11]. Each participant was allocated to one of four sub-samples based on their self-identification, and random selection continued until each sub-sample contained at least 125 participants.

Age (years)—as self-reported by the participant.

Weight (kg)—as measured on a medical digital scale (Beurer, Germany).

Height (m)—as measured using a digital stadiometer (Seca, Germany).

Body Mass Index (BMI)—calculated as $\frac{\text{Weight}}{\text{Height}^2}$.

Foot breadth (mm)—width of the metatarsal break or the linear distance between landmark points 4 and 9 (Fig. 2).

Forefoot girth (mm)—tape circumference around the first and fifth metatarsophalangeal joints, manually measured around landmarks 4 and 9.

Concept of a zone width of possible first MP joint fulcrum locations whether in sandals or closed shoes (mm) – —it is impractical for footwear manufacturers to make footwear for all first MP joint fulcrum locations in different footwear styles. Instead, an analogous design concept to describe the largest variation that could exist may be useful, to describe a zone into which most fulcrum points fall for sandals and closed shoes. The extent in width of this zone is based on $\max(\text{Heel} - 1\text{MPJ\%of sandal length})$ and $\min(\text{Heel} - 1\text{MPJ\%of closed shoe length})$.

The variable zone width of possible first MP joint fulcrum locations from sandals to closed shoes (mm) is calculated as:

$$\left(\frac{\text{foot length} \times \max(\text{Heel} - 1\text{MPJ\% ofsandal length})}{100}\right) - \left(\text{foot length} \times \frac{\min(\text{Heel} - 1\text{MPJ\%of closed shoe length})}{100}\right).$$

This variable is also referred to as the zone width variable, or flexion zone (conceptually depicted in Fig. 4).

2.3. Statistical analyses

Data analyses were performed in a statistical software package (R, version 3.3.2). Continuous variables were first tested for normality using the Shapiro–Wilk and Shapiro–Francia tests. In order to assess the distribution of non-parametric continuous variables, Median and Interquartile Ranges (IQRs) as well as the minimum and maximum values were computed.

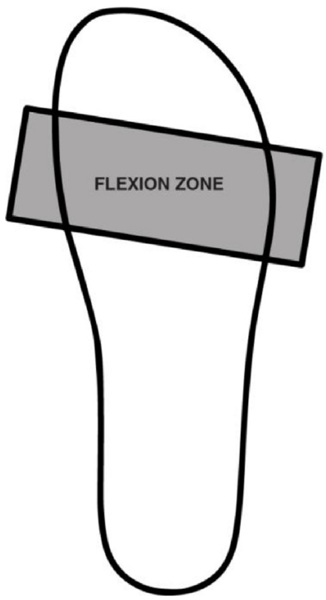

Fig. 4. Variation in location of first metatarsophalangeal joints requires matching variation in footwear flexion, conceptualized as a zone of flexion or flexion zone.

To determine the distribution of the Heel-1MPJ % of foot length (%) and Heel-1MPJ % of sandal length (%) among study participants and show whether this deviated from the North American (USA) and South African (SA) industry parameters, we produced scatter plots with horizontal lines running through the data to indicate the location of mean values. A one sample t-test was run to determine whether the Heel-1MPJ % of foot length (%) and Heel-1MPJ % of sandal length (%) among study participants were different from the USA and SA industry parameters.

We used inferential statistics to assess whether the distribution of the variable zone width of possible first MP joint fulcrum locations from sandals to closed shoes (mm) differed by population group. This involved using the Kruskal–Wallis test which tested whether the mean ranks of this variable were the same in all four population groups. A Dunn's test [13] was computed to test the median differences between multiple pairwise comparisons of population groups following a Kruskal–Wallis test. The median differences between groups and the associated IQRs were plotted using a boxplot with jitters. In order to assess the strength of the relationship between the variable zone width of possible first MP joint fulcrum locations from sandals to closed shoes (mm) and other continuous variables (age, weight, foot breadth and tape forefront girth), Spearman's correlation tests were performed. The two-way correlations between these variables were plotted using a scatter plot matrix. A visual inspection of the relationship between the response variable and each predictor variable adjusted for other predictor variables was achieved by plotting Multivariate Lowess Smooths [14]. By simultaneously computing the smooth of the response variable on all predictor variables, this non-parametric multiple regression method is able to adjust each smooth for the others. Throughout the analysis the level of statistical significance was set at $p < 0.05$.

3. Results

This study found that the bending position in footwear made according to South African and USA last parameters does not match the average first MP joint location in the measured sample. The mean Heel-1MPJ length, expressed as a percentage of sandal last length (72%) was significantly higher than the stated South African (66%; $p < 0.0001$) and North American (63%; $p < 0.00001$) industry measurements. Similarly, the mean Heel-1MPJ length expressed as a percentage of closed shoe length (70%) among study participants was significantly higher than the stated South African 66% ($p < 0.00001$) and North American 63% industry measurements ($p < 0.0001$). This means that the forefoot flexion location of most subjects is more distal to that which is built in to footwear made according to either South African or USA industry parameters. Fig. 5 illustrates these differences.

The extent of the possible first MP joint fulcrum locations in the sample and extrapolated between what it would be in sandals and secondly, what it would be in closed shoes was found to be a median of 24 mm wide and could range from 21 mm to 29 mm in zone width (Table 1).

When investigating whether other variables were associated with the location of the first MP joint, the analysis found that the variables of population group, weight, foot breadth and forefoot

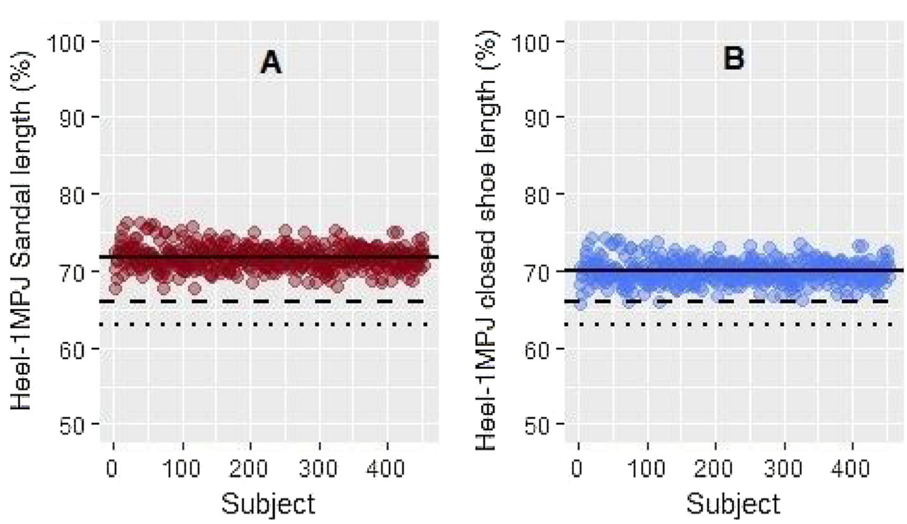

Fig. 5. Two-way scatter plots showing the mean of the distance heel to first metatarsophalangeal joint (Heel-1MPJ) as a percentage of sandal length (Fig. 6A) and Heel-1MPJ in closed shoe length (Fig. 6B) among study participants, compared to the mean estimates recommended by the South African (SA) and United States of America (USA) industry parameters. It is seen in both graphs that the mean estimates in the study sample fall outside the means recommended by both the SA and USA footwear industries. Note: solid lines = observed means for the study sample; dashed line = mean for SA industry; dotted line = mean for USA industry.

Table 1
Distribution of continuous variables in the study sample (N = 453). Note: Heel-1MPJ denotes heel to first metatarsophalangeal joint length. Foot breadth denotes maximum breadth or width across the forefoot.

	Median	IQR	Min	Max
Age (years)	39	[30–52]	21	69
Height (meters)	1.62	[1.56–1.67]	1.42	1.8
Weight (kg)	68.4	[43.9–122.9]	34.7	150.9
Body Mass Index (BMI)	26	[23–30]	13	56
Foot length (mm)	239	[231–248]	206	285
Maximum foot breadth across forefoot (mm)	92	[89–97]	77	110
Tape forefoot girth at metatarsal joints (mm)	232	[222–242]	180	288
Heel-1MPJ % of foot length (%)	74	[73–75]	70	79
Heel-1MPJ % of sandal length (%)	72	[70.7–72.7]	67.7	76
Heel-1MPJ % of closed shoe length (%)	70	[68.9–70.82]	65.8	74
Zone width of possible first MP joint fulcrum locations between sandals and closed shoes (mm)	24	[21.5–27.7]	21	29

girth (but not age) were significantly associated with the location of the first MP joint. The bivariate correlation containing age, weight, foot breadth, forefoot girth and zone width is shown in Table 2. The table shows that at univariate level, the flexion zone width was positively and significantly correlated with tape forefoot girth ($p < 0.001$), foot breadth ($p < 0.001$), and body weight ($p < 0.001$) but not with age.

The comparison of the four population groups in respect of the zone width of possible first MP joint fulcrum locations whether in sandals or closed shoes showed statistically significant differences ($p < 0.001$). Fig. 6 shows that the median flexion zone was highest among white South Africans, followed by black South Africans, with Indian South Africans showing the smallest median.

Table 2
Bivariate correlation between age, weight, foot breadth, forefoot girth and flexion zone (N = 453).

Variable	1	2	3	4	5
1. Age	1.000				
2. Weight	0.177**	1.000			
3. Foot breadth	0.073	0.409***	1.000		
4. Forefoot girth	0.144*	0.533***	0.739***	1.000	
5. Flexion zone width	−0.045	0.435***	0.624***	0.514***	1.000

' ' $p > 0.05$.
* $p < 0.01$.
** $p < 0.001$.
*** $p < 0.0001$.

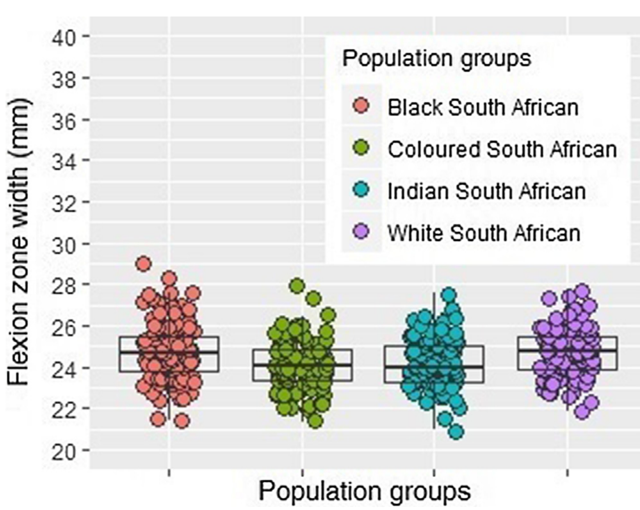

Fig. 6. The comparison between population groups based on the extent of the flexion zone width in millimetres (extent of possible locations for the first metatarsophalangeal joint between the minimum 66% in a closed shoe length and maximum 76% for a sandal length). The graph shows that the median flexion zone was widest among white South Africans, followed by black South Africans, with Indian South Africans showing the smallest median flexion zone extent.

The Black South African and White South African population groups had the highest median Zone widths of possible first MP joint fulcrum locations in both types of footwear. Post hoc comparison of different pairs of population groups based on the zone width variable (Zone width of possible first MP joint fulcrum locations from sandals to closed shoes) used Dunn's multiple pairwise comparison test and showed that South African Indians have smaller median zone widths which were statistically different from Black South Africans ($p < 0.001$) and White South African ($p < 0.001$), but not from South African Coloureds ($p = 0.373$). South African Coloureds had smaller zone widths that were statistically different from White South Africans ($p < 0.001$) and Black South Africans ($p < 0.001$). Lastly, Black South Africans were not statistically different from White South Africans ($p = 0.343$) regarding the extent of the zone width variable.

The multivariate Lowess Smooths of the zone width and each of the four predictor variables (age, weight, foot breadth, and forefoot girth) adjusted for others is shown in Fig. 7.

At multivariate level, the negative correlation between flexion zone width and age showed that age is not statistically significant, but the flexion zone width is positively correlated with weight, foot breadth and forefoot girth, as seen by the Spearman's rho coefficient and associated p values.

4. Discussion

Since we found that the first MP joint was more distal than the location of flexion in footwear, this study raises important concerns regarding the potential of ill-fitting footwear to cause harm, particularly when worn post-operatively. Surgical procedures are routinely performed for congenital and acquired conditions affecting the first MP joint including arthritis, hallux valgus, hallux rigidus, and disease of the hallucal sesamoids. Poor healing may occur after surgery [15–17] and we postulated whether unmatched foot to shoe flexion locations as observed clinically could be a factor not previously considered.

A systematic review of the characteristics of foot structure and footwear associated with hallux valgus [18] found that a long first metatarsal and ill-fitting footwear, inter alia, to be factors that increase the risk of hallux valgus development. Other studies have shown that a first MP joint fulcrum which is located proximal to the fulcrum location in the shoe may lead to hallux valgus formation [19,20].

Studies of the relationship between foot measurements have looked at the primary differentiators of foot length, width and girth [21–23]. Few studies have highlighted first MP joint morphometric differences in the sagittal plane [24,25] although a substantial body

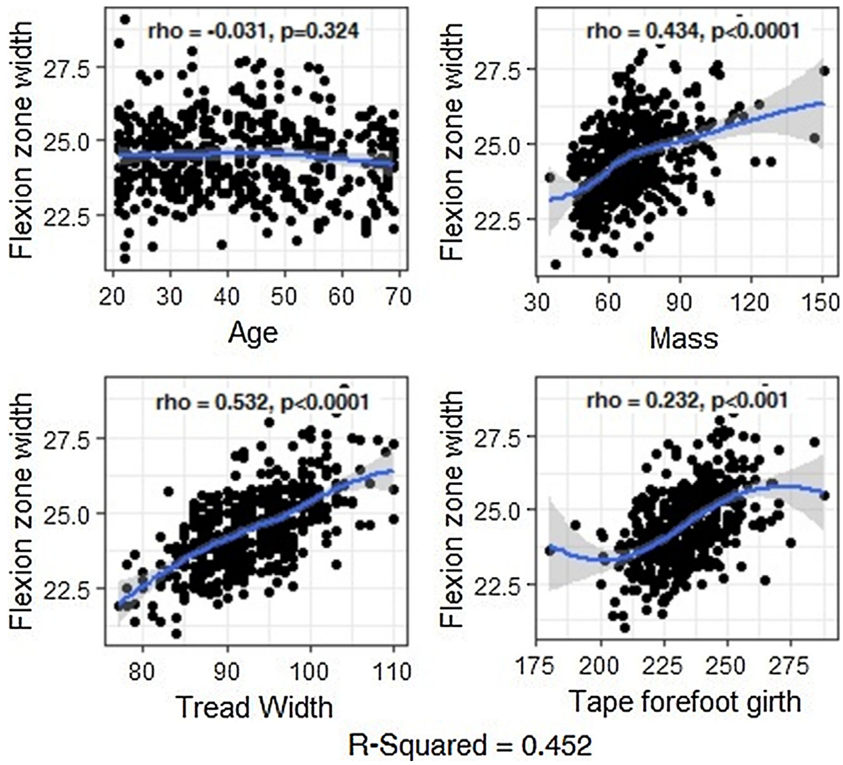

Fig. 7. Multivariate lowess smooths of the flexion zone width and each of the four predictor variables (age, weight, foot breadth and forefoot girth) adjusted for others, and Spearman's rho coefficients and p values associated with each predictor variable. The lack or presence of statistically significant relationships can also be seen from the adjusted smoothed lines running through the fitted values. The figure shows that at multivariate level, the correlation between flexion zone width and age is not statistically significant, but there is positive correlation with weight, foot breadth and forefoot girth.

of work has drawn attention to pathologies due to such disorders [19,26,27]. A first MP joint fulcrum which is located distal to the fulcrum location in the shoe (Fig. 8) will result in forces on the joint, reducing the ability of the hallux to function and is implicated in hallux rigidus [19,20]. In the absence of a functioning fulcrum at the first MP joint, compensatory abduction of the foot may take place; this would place increased force and flexion moments on the lateral four digits and metatarsals, the abnormal stresses of which may lead to fatigue fractures [28]. These considerations are important in light of recent work by Michelson et al. [29] concerning first metatarsal head morphology in hallux rigidus and hallux valgus.

Our sample included both underweight and obese subjects (BMI 13–BMI 56). The obese subjects (BMI > 30) may have exerted greater downward force on the medial longitudinal arch, thereby decreasing the height of the arch [30] thereby lengthening the arch, which might shift the first MP joint to a more distal location. However, the mean variance occurred near the 75 kg marker and one could argue that this weight is not generally considered an obese body weight in average height adult women in South Africa.

The present study was limited in that only female subjects were measured and it is anticipated that male foot measurement data will be examined in future.

The current study measured participants unshod (zero heel elevation). Since the plantar fascia shortens in heel elevation, the percentage of overall foot length represented by the heel to first MP joint segment may vary at differing heel elevations. Our foot segment percentages cannot therefore be used for sandals or shoes with heel elevation. We suggest that future investigation determine the impact of varying degrees of heel elevation on the length calculation of heel to first MP joint (due to shortening of the plantar fascia in heel elevation), so as to complete the data on Heel to first MP joint length in footwear.

We note that, with the exception of surgical fusion of the first MP joint that would require immobilization of this joint via a rigid sole in footwear, most clinical conservative as well as surgical interventions aim to restore flexion function of the forefoot structures.

5. Conclusion

We found evidence that a multi-ethnic population contains individuals whose first MP joint fulcrum location does not match the footwear fulcrum location found in sandals or closed shoes made according to either South African or North American last industry parameters. Furthermore, we calculated that the grouping of such different first MP joint locations would represent a band or zone across the metatarsal spread at least 24 mm wide in the sagittal plane (proximal to the distal foot) in order to accommodate most of the first MP joint locations.

It is impractical for footwear manufacturers to make individual footwear with specific flexion points for all the different first MP joint fulcrum locations within the same size. Since a first MP joint position which may fall outside the set flexion point in a shoe cannot properly function as a fulcrum, it is suggested that medical consultants to footwear manufacturers advise on forefoot flexibility requirements and characteristics to allow for the range of first MP joint fulcrum locations in the population.

We conclude that the results of this study suggest that the public as well as the medical community be informed (Fig. 8) to select and check the flexion fit of footwear, particularly pre- and post-operatively. Failure to do so could potentially result in increased forces of shear and torque from a mismatched shoe fulcrum at the first metatarsophalangeal joint. We believe such forces need to be considered in the risk factors for musculoskeletal as well as skin pathology and non-healing, particularly with pre-existing risk

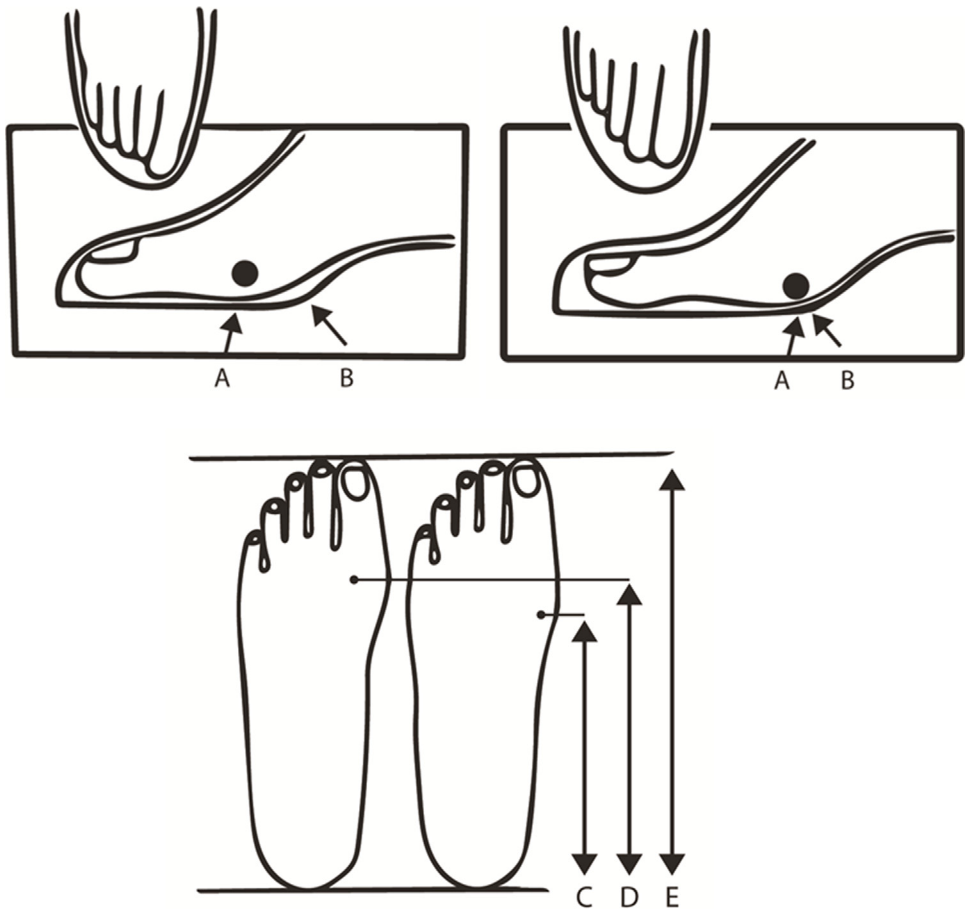

Fig. 8. Explanatory illustration suggested as a clinical informative tool to prevent fulcrum mismatch. Arrows on top left indicate mismatch of first metatarsophalangeal (MP) joint fulcrum A to flexion location B built into a shoe, while arrows on right indicate congruency of flexion location between shoe and foot. C and D indicate potential for variance in location of first MP joint in feet of equal length E.

factors such as diabetic peripheral neuropathy and/or peripheral vascular disease.

Contributions of authors

ATT initiated and planned the study, formulated the methodology, and wrote the core manuscript, CMA and BZ provided input and editing of the manuscript. MM performed the statistical analysis and provided the description of data analysis approach.

Conflict of interest and funding

No conflict of interest declared. The Technology and Human Resources in Industry Program (THRIP) of the National Research Foundation of South Africa, the University of Johannesburg, the South African Footwear and Leather Industries Association and Michelle Footwear provided financial grants to support the cross-sectional data capture project. The entities acknowledged did not plan, gather data, perform analyses, interpret data or otherwise contribute to this manuscript.

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