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Assessing the Impact of Age on Foot Morphology and Feature Prioritisation using PERMANOVA and AHP Analysis

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Abstract

Foot morphology changes with age advancement, which can impact the comfort and fit of footwear, as well as the long-term well-being of the foot, particularly in physically active women. Nevertheless, few studies have systematically examined age differences in foot morphology, prioritising the most important aspects of footwear design. The proposed research will investigate the existence of any meaningful differences in morphology between the different age groups, identify the most burdened characteristics of the foot due to ageing, and rank the features to design age-specific footwear. The UK Data Service provided secondary data consisting of 265 physically active women between the aged of 18-79 years. The participants were grouped six age groups, each spanning 10 years in age. Permutational Multivariate Analysis of Variance (PERMANOVA) was used to determine the overall morphological differences between the age groups. Then the univariate ANOVA was used to determine the key characteristics of an individual foot. The above features were further ranked by the Analytic Hierarchy Process (AHP). The results of the PERMANOVA indicate that age has a statistically significant impact on the overall foot morphology. Univariate ANOVA shows that there is a substantial difference between the foot width, the heel breadth, the height at 50% of the foot length, the circumference of the foot length at 50%, and the hallux valgus angle across age groups. The results of the AHP also suggest that the most significant item to consider in relation to age-specific footwear is foot width, taking into account the footwear's heel-related dimensions. By combining PERMANOVA and AHP, a holistic method of analysis and prioritisation is achieved for understanding how the morphology of feet varies with age. These results provide a valuable understanding of the ergonomics design of footwear and preventive foot health measures designed for women at various stages of life.

1. Introduction

Foot morphology refers to the physical form, shape, and proportions of the human foot, including components such as arch height, foot length and width, heel position, and toe alignment. The human foot is a complex structure composed of bones, muscles, and ligaments that supports posture and enables movement. Understanding foot morphology is essential in biomechanics, ergonomic product design, and clinical assessment [1]. It plays a critical role in shock absorption, force distribution, and balance during walking, running, and standing. Changes in foot anatomy, such as collapsed arches or extreme pronation, can negatively affect the knees, hips, and spine, potentially leading to discomfort or injury [2].

Foot morphology naturally varies across the lifespan. During childhood, the foot is relatively flat, and the arch develops with musculoskeletal maturation [3]. Structural differences are observed among individuals, influenced by factors such as body weight, physical activity, and heredity. As people age, foot abnormalities become more common, including flatfoot, toe deformities, and hallux valgus, which can cause pain and limit physical activity [4]. Footwear that does not accommodate these changes can exacerbate discomfort, highlighting the need for age-specific design that considers arch support, toe box space, and heel width.

The societal and economic implications of foot morphology are also significant. The global footwear market, valued at over USD 400 billion annually, is increasingly moving toward personalised and ergonomic designs [5]. Despite technological advances such as 3D printing and smart insoles, there remains a gap in products tailored to age-related structural differences, particularly for older women who often report poor fit and discomfort. With populations ageing worldwide, including Malaysia and the United Kingdom, age-sensitive footwear and orthotic devices are crucial for maintaining mobility, preventing falls, and reducing healthcare costs [6]. Cultural and lifestyle factors, including prolonged use of high heels or narrow shoes, further influence foot morphology and must be considered in product design and preventive education [7].

To examine age-related differences in foot morphology, this study applied Permutational Multivariate Analysis of Variance (PERMANOVA), which accounts for correlations between multiple variables and reduces the risk of false positives. To identify the most critical features affecting footwear design, the Analytic Hierarchy Process (AHP) was used to rank the importance of each foot measurement, guiding decisions for age-specific footwear and foot care interventions [8]. Combining PERMANOVA and AHP allows researchers to detect meaningful morphological differences between age groups and prioritise features such as foot width, midfoot height, and hallux valgus angle. These results provide practical recommendations for footwear designers, medical practitioners, and sports professionals to develop more comfortable, supportive, and personalised solutions for women across different age groups.

2. Methodology

This section discusses about the methodology by outlining the data description, PERMANOVA, and the AHP. PERMANOVA was applied to examine differences between groups, while AHP was used to rank and prioritise important factors based on their level of importance.

2.1 Data Description

The dataset was obtained from the "Foot Morphology Data Across Age Groups for Women Active in Sport, 2022–2024" study, conducted by Dr. Sharon Dixon (University of Exeter) and Dr. Joanna Reeves (Cardiff University) [9]. Measurements were taken from 264 female racket and team sport athletes across the United Kingdom. The participants were assigned to age groups: 20 and below, 30–39, 40–49, 50–59, and 60 and above years. Foot lengths were taken with 3D scanning equipment under 50% weight-bearing conditions. Variables included in the dataset are foot width, ball of foot circumference, short heel circumference, dorsum height, and hallux valgus angle, which are all normalised to the measure of foot length to eliminate individual size differences.

For analysis in this study, a subset of the dataset for women aged 20–49 was picked according to the research objectives. The subgroup contains 90 observations, evenly distributed over five age groups: 20 and below, 30–39, 40–49, 50-59 and 60 and above years. To foster clarity and ease in data management, variables used in this study are correctly defined in terms of type, description, and intended role in analysis. Table 1 shows all the key variables used in the study.

Table 1 All variables Information

No.	Variable Name	Description	Analysis Purpose
1.	Age_Groups	Participant's age in years	Grouping variable for PERMANOVA
2.	Foot_Length	The overall length of the foot.	Foot morphology analysis (PERMANOVA)

3.	Foot_Width	The overall width of the foot.	Foot morphology analysis (PERMANOVA)
4.	Foot_Ballfootwidthdiagonal	The diagonal width of the ball of the foot.	Foot morphology analysis (PERMANOVA)
5.	Foot Width Straight	Distance straight across the widest part of the feet	Foot morphology analysis (PERMANOVA)
6.	HeelToMTPJ1	Heel to 1st metatarsophalangeal joint distance	Foot morphology analysis (PERMANOVA)
7.	HeelToMTPJ5	Heel to 5th metatarsophalangeal joint distance	Foot morphology analysis (PERMANOVA)
8.	HeightAt50pcFootLength	Instep height, measured at 50% of the foot's length.	Foot morphology analysis (PERMANOVA)
9.	CircumferenceAt50pcFootLength	Circumference around the foot at the 50% foot length mark.	Foot morphology analysis (PERMANOVA)
10.	HeelBreadth	The breadth of the heel.	Foot morphology analysis (PERMANOVA)
11.	HalluxValgusAngle	Hallux valgus (bunion) angle	Foot morphology analysis (PERMANOVA)
12.	Prioritized Features (via AHP)	Ranked importance of foot features based on design considerations	Feature prioritization (AHP)

2.2 Descriptive Analysis

To summarise the distribution of foot morphology variables across various age groups, descriptive analysis was conducted. The variables to be measured include foot length, foot width, heel breadth, ball foot breadth, the angle of hallux valgus, and the height and circumference of the 50% foot length, which are essential parameters of foot size and structural peculiarities. The descriptive statistics reveal findings that can be observed in terms of the various measurements of the age groups, where older participants tend to have higher values of width measurements in circumferential measurements compared to the younger groups. This suggests that there are systematic structural changes in the morphology of the foot with age, likely due to age-related weight-bearing, soft tissue adjustments, and biomechanical loads.

Moreover, the patterns of the distributions indicate significantly more variability in the measures of foot morphology in the cases of older age groups, as depicted by the wider ranges and greater dispersion in the graphical presentations. Interestingly enough, the hallux valgus angle demonstrates the tendency to get bigger with age, which presupposes that the forefoot deviation is more common among older participants. The variability of this nature highlights the heterogeneity of age-related changes in the foot and underscores the importance of considering age as a key variable in assessing foot morphology. In general, the descriptive results demonstrate primary evidence of age-based variation in foot structure, justifying the use of PERMANOVA and ANOVA for further inferential analysis.

2.3 Permutational Multivariate Analysis of Variance

Permutational Multivariate Analysis of Variance (PERMANOVA) is a non-parametric method used to test for significant differences in multivariate data among groups based on a distance matrix [10]. Contrary to conventional MANOVA, PERMANOVA does not presuppose the assumption of such characteristics as a normal distribution or homogeneity of variances. It is invaluable in cases where the data is multivariate (consisting of many features), as it operates by generating a distance matrix of the samples and testing whether the distances within the groups differ significantly. The analysis begins by computing a dissimilarity matrix, commonly using the Euclidean distance, defined as in Equation (1);

$$d(x,y)=\sqrt{\sum_{i=1}^{n}(x_i-y_i)^2} \tag{1}$$

where:

x and y represent two data points,

x_i and y_i are the values for each variable (foot measurements) for the two observations,

n is the number of variables (e.g., number of foot measurements being compared).

Once the distance matrix is computed, it will be used to compare the groups based on the dissimilarities between them. The PERMANOVA pseudo-F statistic. The statistics calculated as in Equation (2):

$$F=\frac{MSB}{MSW} \tag{2}$$

where:

MSB is the mean sum of squares between groups (variance due to differences between group centroids),
MSW is the mean sum of squares within groups (variance within each group).

After calculating the pseudo-F statistic for the observed data, compare it with the distribution of pseudo-F statistics from the permutations to calculate the p-value. The p-value is the proportion of permuted pseudo-F values greater than or equal to the observed pseudo-F value.

In PERMANOVA, the null hypothesis is that there are no significant differences in the group means in the multivariate space. The alternative hypothesis is that there are significant differences between the groups' centroids.

- Null Hypothesis (H_0): No significant differences exist between the groups.
- Alternative Hypothesis (H_1): At least one group differs from the others.

The null hypothesis assumes no difference in multivariate foot morphology between age groups, while rejection of the null hypothesis indicates a significant age effect [11]. Following the PERMANOVA results, univariate ANOVA was performed on each foot morphology variable to identify individual features that significantly differ across age groups. Before analysis, assumptions of normality and homogeneity of variance were evaluated using the Shapiro-Wilk test and Box's M test, respectively. Variables with statistically significant ANOVA results were selected for subsequent prioritisation analysis.

2.4 Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making method used to prioritise significant foot morphology features identified through ANOVA [12]. The process begins with the construction of a pairwise comparison matrix $A=[a_{ij}]$, where each element represents the relative importance of the criterion i over criterion j, based on a nine-point intensity scale, can be seen in Equation (3);

$$a_{ij}>0, a_{ij}=\frac{1}{a_{ij}} \text{ for all } i, j=1,2,\ldots,n \tag{3}$$

where:

a_{ij} expresses how many times more important feature i is compared to feature j,

$a_{ij}=\dfrac{1}{a_{ij}}$ ensures reciprocal consistency.

In AHP, the pairwise comparison matrix is the central element that captures expert judgment of relative importance among decision choices. Each element of this matrix is an estimate of the comparative preference of a morphological attribute of one foot over another with respect to some criterion, in this case, their ability for age-specific shoe design. The matrix enables qualitative judgements to be translated into quantitative weights, the basis for consistent, reproducible decision-making. Each criterion or alternative is compared with every other element in a pairwise manner using a scale of relative importance (Saaty's fundamental scale from 1 to 9) can be seen in Table 2, the intensity of importance is represented by a numerical scale ranging from 1 to 9, with 1 representing equal importance and 9 representing the relative significance of one factor over another.

Table 2 Nine-point intensity scale for pairwise comparison

Relative Importance	Explanation
1	Two criteria contribute equally to the objective
3	Experience and judgement slightly favour one over another
5	Experience and judgement strongly favour one over another
7	Criterion is strongly favoured and its dominance is demonstrated in practice
9	Importance of one over another affirmed on the highest possible order
2, 4, 6, 8	Used to represent a compromise between the priorities listed above

The Consistency Ratio (CR) is used to assess the logical consistency of the pairwise comparison judgments made during the decision-making process. Since AHP relies on subjective comparisons between criteria, it is essential to verify that these judgments are coherent and not made randomly [13]. Equation (4) is the CR formula;

$$CR = \frac{CI}{RI} \tag{4}$$

where:

If $CR < 0.10$ (or 10%), The matrix is considered acceptably consistent,

If $CR \geq 0.10$ The matrix is too inconsistent and needs to be revised.

To mix the weights across the hierarchy, the weight of each sub-criterion's local value is multiplied by the weight of its parent criterion. The multiplication process proceeds precisely through every hierarchy stage until it reaches the last level, which encompasses the decision options. The consequence of this procedure is a set of global priority ratings for the possibilities, reflecting their general hierarchy position, and considering all criteria and sub-criteria [9]. The results of the structured comparisons in the AHP procedure are combined in this step to create a final alternative ranking.

3. Results and Discussion

This section presents the empirical findings obtained from the descriptive analysis, PERMANOVA, univariate ANOVA, and AHP. The results are interpreted to examine age-related differences in foot morphology, identify foot morphology features that vary significantly across age groups, and determine the relative importance of these features for footwear design.

3.1 Descriptive Statistics

The descriptive statistics were used initially to describe the nature of the distribution of the foot morphology variables across different age groups. The analysis measures included foot length, foot width, heel width, ball-to forefoot width, hallux valgus angle, and height and circumference of the foot at 50% of the foot length. These aspects collectively portray the overall size, shape, and structure of the foot. These descriptive results indicate the presence of observable age differences in the various dimensions of the feet, with older age groups, on the whole, exhibiting higher values for width-related and circumferential measurements compared to the younger ones. The trend indicates that this foot structure changes progressively with age, which may be due to mechanical loading and soft tissue adaptation over a prolonged period.

Moreover, the distribution of foot morphology measurements in older age groups exhibited greater variability, as indicated by the measures of dispersion and range, which were more pronounced and spread out in the graphical display. It is interesting to note that the hallux valgus angle showed a rising pattern with age, suggesting that forefoot deviation was more prevalent in older participants. These descriptive results provide initial evidence of an age effect in the morphology of the foot and justify the need for an inferential statistical test to examine the observed differences.

Table 3 presents the demographic characteristics of participants by age group. The study sample comprised a total of 264 female participants, who were successfully stratified into five age categories to facilitate comparative analysis across the adult lifespan. The distribution of the sample across these age groups was not uniform. The most significant proportion of participants fell into the older age brackets, with the 60 and above group representing the majority at 39.0%, n=103, followed by the 50-59 age group, at 25.0%, n=66. Conversely, the 30–39 group was the smallest, accounting for only 9.1% (n=24) of the total sample.

It is an essential consideration of unequal distribution because it reflects either a research focus or elevated rates of recruitment for older groups. Although this distribution is sensitive to the vigorous non-parametric testing implied by PERMANOVA, it suggests that the results are best explained by the morphological characteristics of the older women involved in sports. The standard deviation and mean value are also consistent within the limits of their respective groups, demonstrating that the stratification process was successful and formed a clear independent variable (Age Group) to proceed with the multivariate analysis.

Table 3 Demographic Characteristics of Participants by Age Group

Age Group (Years)	Sample Size (n)	Percentage (%)	Mean ± SD (Years)
20 and below	32	12.1	22.1 ± 3.20
30-39	24	9.1	34.8 ± 2.84
40-49	39	14.8	44.5 ± 2.59
50-59	66	25.0	54.9 ± 2.66
60 and above	103	39.0	66.6 ± 5.10
Total	264	100.0	-

3.2 PERMANOVA Analysis of Foot Morphology Variations Across Age Groups

Table 4 presents the Shapiro-Wilk test with *p*-values for several foot morphology variables, such as Foot_Length ($p > 0.1$), Foot_HeelToMTPJ1 ($p > 0.1$), and Foot_HeelToMTPJ5 ($p > 0.1$), which exceed the conventional threshold of 0.1, indicating that these variables follow a normal distribution. This suggests that these features of foot morphology are suitable for parametric analyses such as MANOVA, which assumes normality.

However, some variables exhibit significant departures from normality, such as Foot_Width ($p < 0.001$) and Foot_HalluxValgusAngle ($p < 0.001$), which show *p*-values less than 0.001. These results indicate that these two foots features do not follow a normal distribution. This violation may affect the validity of any subsequent multivariate tests. These non-normal distributions may be skewed or contain outliers, which could distort the results of parametric tests. To address these violations, PERMANOVA (a non-parametric alternative) can be considered, as it does not rely on the assumption of normality [14].

Table 4 Shapiro-Wilk Test for Normality of Foot Morphology Variables

Foot Morphology	Test Statistic (W)	*p*-value
Foot_Length	0.99303	**> 0.1**
Foot_Width	0.97774	**< 0.001**
Foot_HeeltoMTPJ1	0.99401	**> 0.1**
Foot_HeeltoMTPJ5	0.99537	**> 0.1**
Foot_Ballfootwidthdiagonal	0.98095	**< 0.01**
Footwidthstraight	0.98428	**< 0.01**
Foot_Heightat50%footlength	0.98644	**< 0.05**
Foot_Circumferenceat50%footlength	0.9861	**< 0.05**

Foot_Heelbreadth	0.99112	**> 0.1**
Foot_Halluxvalgusangle	0.9505	**< 0.001**

Moving on to Table 5, which presents Box's M-test, the p-value is less than 0.001, indicating an extremely small value, which leads us to reject the null hypothesis that the covariance matrices are equal across the groups. This result suggests that the assumption of homogeneity of covariance is violated. Since PERMANOVA does not require this assumption, this further strengthens the case for using PERMANOVA in this analysis.

Table 5 Box's M-Test for Homogeneity of Covariance Matrices

Statistic	**Value**
Box's M Chi-Square (χ^2)	378.05
Degrees of Freedom (DoF)	220
p-value	< **0.001**

The results of the PERMANOVA, presented in Table 6, reveal that the two age groups have a significant effect on the morphology of the feet, as the p-value is less than the significance level of 0.05. This implies that age groups exhibit specific differences in the morphology of the foot, and the model is material-specific. By analysing the R^2 value, the model accounts for 3.79% of the variation in total foot morphology. In the meantime, this value can be considered low; however, there is still a contribution from age groups in the variation of foot characteristics, especially in the various foot features that have been measured, including foot length, foot width, and heel breadth. The low R^2, however, also indicates that there are other factors, besides age, that may contribute substantially to the determination of foot morphology.

The result is further supported by the F-statistic of 2.5494, which compares the variability between groups to that within groups. The F-statistic ($p < 0.05$) indicates that the observed differences between the groups are unlikely to be due to chance.

Table 6 PERMANOVA Result

Component	**DoF**	**Sum of Squares**	**R^2**	**F-statistic (F)**	***p*-value**
Model	4	0.005117	0.03788	2.5494	< **0.05***
Residual	259	0.129962	0.96212		
Total	263	0.135079	1.00000		

The ANOVA results in Table 7 for foot morphology across age groups reveal that several foot characteristics show significant differences. In contrast, others do not, highlighting the impact of age on foot structure. Foot Width ($p < 0.05$) was found to be substantial, indicating that the width of the foot varies across different age groups. This suggests that changes in foot width may occur as individuals age, potentially due to factors such as alterations in tissue composition or changes in weight distribution over time. Similarly, Height at 50 % Foot Length ($p < 0.01$) and Circumference at 50% Foot Length ($p < 0.01$) also showed significant differences, suggesting that the shape of the foot, particularly in terms of height and circumference, is influenced by age. These findings emphasise the role of age in shaping the overall foot structure, with older individuals likely experiencing more pronounced changes in these areas.

The Heel Breadth ($p < 0.05$) was also significant, indicating that the width of the heel changes across age groups. This may reflect the foot's adaptation to different levels of activity, weight, and foot function over time. On the other hand, Foot Length, HeelToMTPJ1, and HeelToMTPJ5 were not significant ($p > 0.1$), indicating that these foot dimensions remain relatively stable across age groups. This suggests that overall foot length and specific structural dimensions may not change significantly with age; however, other aspects, such as foot width, height, and circumference, are more susceptible to age-related changes.

The foot width straight was marginally significant ($p > 0.1$), suggesting a potential trend toward age-related differences in this feature. However, further analysis with a larger sample size might yield more conclusive results. The Hallux Valgus Angle ($p < 0.001$), however, was highly significant, revealing that this foot feature, often associated with foot deformities such as bunions, changes significantly across age groups. This result highlights the importance of considering foot conditions in footwear design, particularly for older populations.

Table 7 Univariate ANOVA Result

Foot Morphology Variable	**DoF**	**Sum of Sq**	**Mean Sq**	**F-value**	***p*-value**
Foot Length	4	161	40.18	0.363	> 0.1
Foot Width	4	325	81.25	3.036	< **0.05**

HeelToMTPJ1	4	217	54.15	0.787	> 0.1
HeelToMTPJ5	4	104	26.05	0.438	> 0.1
Ball Foot Width Diagonal	4	172	42.94	1.574	> 0.1
Foot Width Straight	4	211	52.79	2.285	> 0.1
HeightAt50%FootLength	4	289	72.27	4.066	**< 0.01**
CircumferenceAt50%FootLength	4	1767	441.8	3.437	**< 0.01**
Heel Breadth	4	139	34.68	2.637	**< 0.05**
Hallux Valgus Angle	4	2302	575.6	9.571	**< 0.001**

3.3 Tukey HSD Analysis Results

Table 8 shows results that foot morphology differs significantly across age groups, indicating that ageing affects foot structure. Tukey HSD post-hoc analysis identified significant differences in Foot Width, Height at 50% Foot Length, Circumference at 50% Foot Length, Heel Breadth, and Hallux Valgus Angle, especially between older adults and younger or middle-aged participants.

For Foot Width, significant differences were observed between the 40–49 age group and those aged 20 and below, as well as between participants aged 60 and above and the 40–49 group, suggesting that foot width increases with age. Height at 50% Foot Length differed significantly between the 40–49 and 30–39 groups and between the 60 and above group and the 40–49 group, indicating changes in midfoot structure. Circumference at 50% Foot Length was higher in participants aged 60 and above compared to those aged 40–49, while Heel Breadth showed significant differences between the 40–49 and 20-and-below groups. Hallux Valgus Angle was notably higher in participants aged 60 and above, highlighting age-related forefoot changes.

These findings emphasise the need for age-specific footwear design. Footwear should accommodate age-related changes in foot width, midfoot height, girth, and toe alignment to improve comfort, support, and foot health. A one-size-fits-all approach is insufficient, and manufacturers should consider these structural differences to develop ergonomically appropriate shoes for different age groups.

Table 8 Tukey HSD Post-hoc Comparisons of Foot Features by Age Group

Foot Feature	Age Group Comparison	Mean Difference	Lower CI	Upper CI	p-value
Foot Width	40–49 vs ≤20	3.45	0.06	6.84	< 0.05
Foot Width	≥60 vs 40–49	-2.77	-5.44	-0.10	<0.05
Height at 50% Foot Length	40–49 vs 30–39	3.09	0.09	6.09	< 0.05
Height at 50% Foot Length	≥60 vs 40–49	-2.84	-5.02	-0.66	< 0.01
Circumference at 50% Foot Length	≥60 vs 40–49	-7.84	-13.70	-1.98	< 0.01
Heel Breadth	40–49 vs ≤20	2.78	0.41	5.16	< 0.05
Hallux Valgus Angle	≥60 vs ≤20	5.04	0.73	9.35	< 0.05
Hallux Valgus Angle	50–59 vs 30–39	5.42	0.34	10.50	< 0.05
Hallux Valgus Angle	≥60 vs 30–39	8.79	3.96	13.62	<0.001
Hallux Valgus Angle	≥60 vs 40–49	6.35	2.35	10.36	<0.001
Hallux Valgus Angle	≥60 vs 50–59	3.37	0.01	6.73	< 0.05

3.4 Foot Morphology Feature Prioritisation using AHP

This section aims to prioritise major foot morphology features in relation to their relevance to age-specific footwear design. To do this, the Analytic Hierarchy Process (AHP) is used, which enables making systematic decisions according to the importance of various characteristics. The features are contrasted by their relative significance, and weights are assigned to control the design process of the shoes.

In the case of Foot Width, the *p*-value of 0.05 is less than 0.05 and indicates that there is a statistically significant difference between the age groups and that foot width is relevant in determining the shoe fit. Foot width is important as it is vital in making shoes comfortable, in particular for a person with varying foot shapes [15], so it has a weight of 0.30, which is moderate to significant in designing the footwear.

Height at 50% Foot Length has an even stronger level of significance with a *p*-value of less than 0.01, hence it is one of the most significant features. The effect this feature has on the shoe fit and comfort is significant, especially regarding the overall foot shape [16]. Since it determines the overall structure and fit of shoes, it has the highest weight of 0.35, since it plays a very crucial role in the design of age-specific shoes.

Circumference at 50% Foot Length also reveals a significant difference that has a p-value below 0.01, which means that it is a significant characteristic that influences comfort and design of the shoe. It is a very important fit consideration, but still slightly less important, compared to foot width or height at 50% foot length, in overall fit and comfort. It is on this account that it is given a moderate weight of 0.20.

Heel Breadth (0.05 p-value) indicates a significant difference, but has a rather smaller influence on the shoe design as compared to the other features. In the meantime, the breadth of the heels is significant to provide the foot with stability and support, yet it does not influence the overall shoe fit as strongly as other parts of the foot [17]. In this regard, it is assigned a weight of 0.10, which indicates its low influence on the overall process of designing.

Lastly, the Hallux Valgus Angle is very low, with a p-value of less than 0.001, which implies high significance. This is important to allow deformities of the feet, such as bunions, that are more predominant in old age. Since the p-value is very important and has a strong implication in the aspect of foot health, it is still given a relatively low weight of 0.05. The reason is that it does not influence the overall comfort and fit as much, and this effect is mostly limited to particular foot conditions, which is why it is not as universal between all age groups, but it remains a vital point to be considered when designing footwear for patients with foot deformities [18].

Finally, the weight assigned to each feature of the foot will be the relative importance of such features in the results of the ANOVA. The features that have lower p-values, meaning larger differences in the age groups, receive more weight, which guarantees the most significant features of the foot will be prioritised in the footwear design process.

Table 9 Assigned Weights for Foot Morphology Features Based on ANOVA Results

Foot Feature	*p*-value	Assigned Weight	Justification
Foot Width	< 0.05	0.30	Significant difference in foot width across age groups.
Height at 50% Foot Length	< 0.01	0.35	Highly significant, it influences overall shoe fit.
Circumference at 50% Foot Length	< 0.01	0.20	Significant effects on comfort and shoe design.
Heel Breadth	< 0.05	0.10	Significant, important for heel support.
Hallux Valgus Angle	< 0.001	0.05	Highly significant, critical for accommodating foot deformities.

The pairwise comparison matrix shown in Table 10 was then established to assess the relative importance of each feature in foot morphology for footwear design based on the nine-point scale of Saaty. It can be observed that the foot width is given priority at the top, as it receives the most significant comparison values among other features. It appears to be considerably more critical, on the other hand, than the HV angle, Foot Height (50%), Heel Breadth, and Circumference (50%). This high priority indicates that the width of the foot is significant for the overall fit and comfort of shoes, especially in coping with the varied foot shapes among age groups. Correct shoe width is essential to decrease pressure, increase comfort, and accommodate for age-associated shape changes of the foot.

Height at 50% Foot Length is identified as the second most crucial variable, indicating its role in construction and vertical space in the shoe. circumference at 50% Foot Length is categorised as moderately necessary, associated with midfoot fit and overall comfort, particularly in wide foot types. For Heel Breadth and Hallux Valgus Angle, in contrast, their relative importance is lower, as they affect the foot less globally across regions and under different conditions. Although these features are still relevant, especially for older adults or those with deformities, the AHP outcomes suggest that design areas in current footwear should focus on foot width and midfoot height across age groups to achieve a better fit, comfort and functional support.

Table 10 Pairwise Comparison Matrix for Foot Morphology Features

Foot Feature	**Foot Width**	**Height at 50% Foot Length**	**Circumference at 50% Foot Length**	**Heel Breadth**	**Hallux Valgus Angle**
Foot Width	1	5	7	7	9
Height at 50% Foot Length	1/5	1	3	5	7
Circumference at 50% Foot Length	1/7	1/3	1	3	5
Heel Breadth	1/7	1/5	1/3	1	3

Hallux Valgus Angle	1/9	1/7	1/5	1/3	1

The normalised matrix indicated above indicates the outcomes of pairwise comparison of the foot morphology features. All the elements in this matrix symbolise the normalised significance of one particular foot feature to the rest of the features. The values on the matrix are obtained by dividing the values on the pairwise comparison by the sum of the matching column, such that the matrix gives the relative weight of each feature.

Foot Width is the most normalised value in the rows, which means that it has a strong impact on the AHP decision process. Foot Width has the highest level of normalised value 0.6262 in the comparison of the two features, the Foot Width and the Foot Width. Also, the importance of other features, such as Heel Breadth and Hallux Valgus Angle, is always less than that of the Foot Width, and this is shown by higher values of normalised values in the matrix.

Height at 50% foot length also has relatively high significance, with normalised values of 0.7489 in comparison with the foot Width. This implies that Height at 50% Foot Length is more important in footwear design and determines the overall shoe fit, especially in the older age groups, where the size of the feet varies.

Circumference at 50% Foot Length has the smallest normalised values, that is, 0.6069, and therefore it is not very vital compared to Foot Width and Height at 50% Foot Length, but it is a crucial factor in the design and comfort of shoes. Its price is determined by its average importance, especially when it comes to the comfort of the foot shapes.

Heel Breadth values of all comparisons have lower normalised values, thus showing that although it is important in heel support, it is not as important as other features of heel support, such as Foot Width and Height at 50% Foot Length. The normalised value of 0.4286 in the comparison of the Foot Width and Heel Breadth indicates that it is not very critical in general in the foot shoe design.

Hallux Valgus Angle exhibits the least normalised values as an indication of its particular applicability to foot deformities such as bunions, particularly among the older groups. The normalised value of 0.36 in relation to Foot Width implies that it is less important during the design process to accommodate a more general population, despite its essentiality to those people with foot deformities.

Table 11 Normalised Matrix of Pairwise Comparisons for Foot Morphology Features

Foot Feature	Foot Width	Height at 50% Foot Length	Circumference at 50% Foot Length	Heel Breadth	Hallux Valgus Angle
Foot Width	0.6262	0.7489	0.6069	0.4286	0.36
Height at 50% Foot Length	0.1252	0.1498	0.2601	0.3061	0.28
Circumference at 50% Foot Length	0.0895	0.0499	0.0867	0.1837	0.20
Heel Breadth	0.0895	0.0300	0.0289	0.0612	0.12
Hallux Valgus Angle	0.0696	0.0214	0.0173	0.0204	0.04

The priority vector results shown in Table 12 are found by averaging this value over the elements in each row of the normalised matrix. A priority vector is the relative importance of each foot feature in footwear design. Foot Width is most relevant with an Importance Value of 0.5541. The 50% Length Height is next, with a value of 0.2243. The importance of Priority at 50% Foot Length is 0.1219, indicating that it is moderately important. The lowest priority values are assigned to Heel Breadth and Hallux Valgus Angle, as 0.0659 and 0.0337, respectively, which play lesser roles in the general footwear fit & design for public use.

The weighted matrix and priority vector provide a reasonable ranking of the foot features in relation to their significance in designing special footwear. The most essential characteristics themselves seem to be Foot Width and Height at 50% of the Length (and, second in the list, Circumference at 50% of the Foot Length). Heel Breadth and Hallux Valgus Angle: This is not essential, but should be noted, especially when considering specific foot shapes and design limitations.

The determined Consistency Ratio (CR) is 0.0912, which is less than 0.1 as a threshold value. This implies that the pair wise comparisons in AHP are consistent in principle. The CR of 0.0912 for the relative importance judgments on the foot morphology features demonstrates that these judgments are not entirely in disagreement with each other. A CR greater than 0.1 would indicate inconsistency in comparisons, and hence, the pairwise comparison matrix needed to be modified. Since the CR value is acceptable, the results of the pairwise comparisons and priority vector can be considered as reliable, and the features ranking could provide a consistent and credible decision.

Table 12 Priority Vector of Pairwise Comparisons for Foot Morphology Features

Foot Feature	Priority Value
Foot Width	0.5541
Height at 50% Foot Length	0.2243
Circumference at 50% Foot Length	0.1219
Heel Breadth	0.0659
Hallux Valgus Angle	0.0337

The results and rankings of foot morphology features showed that Width is the most essential feature in developing footwear, followed by Height at 50% of Foot Length. I'm addressing the features first, since they're most impactful on how the shoes fit and feel. A Circumference at 50% Foot Length; they have a moderate role in the proper fit, with a lower role to play (for Heel Breadth and Hallux Valgus Angle, since there is a higher relevance of use only for heel support and also only when some foot deformities are involved). This ranking would be used to create age-based shoe models based on which parts of the feet are most important and what they prioritise in terms of comfort and function.

Table 13 Final Ranking on The Importance of Foot Morphology Across Age Groups

Rank	Foot Feature
1	Foot Width
2	Height at 50% Foot Length
3	Circumference at 50% Foot Length
4	Heel Breadth
5	Hallux Valgus Angle

4. Conclusions

This study successfully achieved its objectives by investigating age-related differences in foot morphology and identifying the most critical foot features for footwear design. Descriptive analysis revealed observable variations in foot dimensions across age groups, with older participants generally exhibiting increased width-related and circumferential measurements, indicating structural changes associated with ageing.

The PERMANOVA results confirmed that overall foot morphology differs significantly across age groups, demonstrating that age has a meaningful influence on combined foot structure. Subsequent univariate ANOVA identified specific foot morphology variables that contribute to these differences, particularly foot width, height at 50% of foot length, circumference at 50% of foot length, heel breadth, and hallux valgus angle.

Furthermore, the Analytic Hierarchy Process (AHP) was effectively applied to prioritise significant foot morphology features for age-specific footwear design. The results indicated that foot width and height at 50% of foot length are the most critical features influencing footwear fit and comfort across age groups, while circumference at 50% of foot length plays a moderate role. Heel breadth and hallux valgus angle, although necessary for specific conditions and older populations, were found to have lower overall priority. Overall, this study provides a structured and evidence-based framework for understanding age-related changes in foot morphology and offers practical guidance for the development of ergonomic, age-appropriate footwear designs.

Despite these findings, several limitations should be acknowledged. The study was conducted with a relatively small and uneven sample size, which may limit the generalisability of the results to a larger population. In addition, the study focused only on static foot measurements and did not include dynamic factors such as gait, pressure distribution, or foot movement during daily activities. Other factors related to foot health, such as muscle strength, foot arch type, and postural stability, were also not considered, which may affect the completeness of the findings.

Based on these limitations, future research is recommended to involve a larger and more diverse sample to improve the reliability and generalisability of the results. Incorporating dynamic biomechanical measurements, such as gait analysis and plantar pressure assessment, would provide a more comprehensive understanding of foot function during movement. Future studies may also benefit from using advanced technologies such as 3D foot scanning and wearable sensors, as well as conducting longitudinal studies to examine the long-term impact of age-specific footwear on foot health. These improvements would support the development of more effective, ergonomic, and age-appropriate footwear designs.

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Conflict of Interest

The authors declare no conflict of interest in the paper's publication.

Author Contribution

The authors confirm their contribution to the paper as follows: ***study conception and design:*** *Nazatul Aina Nasuha Nazarudin, Norziha Che Him;* ***data collection:*** *Nazatul Aina Nasuha Nazarudin;* ***analysis and interpretation of results:*** *Nazatul Aina Nasuha Nazarudin, Norziha Che Him;* ***draft manuscript preparation:*** *Nazatul Aina Nasuha Nazarudin, Norziha Che Him, Noor Azliza Abd Latif, Yusliandy Yusof. All authors reviewed the results and approved the final version of the manuscript.*

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