DIMENSIONS FOR FITTING FOOTWEAR

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Footwear sizing often relies on foot length and foot width even though several studies have shown that foot length and foot width are somewhat correlated. Thus, the traditional sizing system based on foot length and foot width may not be the ideal for footwear fitting. Twenty-seven variables of fifty Hong Kong Chinese male participants that included weight, height, 8 lengths, 7 widths, 7 heights and 3 foot curvature variables were measured in an attempt to find the foot dimensions that can be used for sizing. The first 4 factors of the factor analysis were "length" (explained variance = 32.04), "height" (explained variance = 14.88), “curvature” (explained variance = 11.66) and “width” (explained variance = 7.36). A simplified factor analysis of 7 variables showed that foot length and foot curvature can account for 64.2% of the variance for 2-parameter sizing while foot length, height (or width), and curvature accounts for 77.2% of the variance for 3-parameter sizing; and length, width, height and curvature accounts for 86.3% of the variance and may be used for 4-parameter sizing. Overall, the importance of foot curvature and its variation is highlighted.

Key words: foot, anthropometry, footwear sizing, foot flare, footwear fit

INTRODUCTION

Attempting to obtain a perfect physical fit between feet and footwear at every location may be complex and infeasible due to the structural and functional variations of the human foot. Often, footwear is sized according to its length, or length and width, due to retailer inventory considerations, thus compromising the functional fit at other locations. Foot length and foot width show a low correlation (R^2 = 0.43) (Goonetilleke et al., 1997) and hence it is not surprising that sometimes foot length alone is used for fitting purposes. Even though a large number of parameters can model the foot shape, using a *n-dimensional* vector for this purpose may be costly in terms of footwear selection and inventory. Thus, it becomes necessary to find the minimum number of dimensions to adequately describe the foot shape. Factor analysis may be one way to determine the factors that explain the largest variance (Johnson and Wichern, 1992), thereby measuring different "dimensions" of data. In this study, several anthropometric variables were subjected to different factor analyses, so that the resulting "factors" can form the basis for foot sizing.

METHODOLOGY

Participants

Fifty staff and students from the Hong Kong University of Science and Technology participated in this study. All of them were Chinese, aged between 18 and 39 years. None of the participants had any foot illnesses or foot abnormalities.

Procedure

Each subject filled a voluntary consent form. Their stature and weight were recorded. Then, the left foot was measured (Figures 1 and 2) under “no-load” conditions (Goonetilleke et al, 1997). A Sony digital gauge was used to measure all the height dimensions while a digital caliper was used to measure all the length and width dimensions. In order to measure the dimensions related to the arch, a "cookie" was made using children's Play-Doh®. With the subject seated, Play-Doh was inserted into the longitudinal arch and any additional Play-Doh outside the foot was cut and removed. The Play-Doh arch mold was then removed and measured (Figure 2).

Seven heights (first toe height, T_1H; height near the toe phalange joint, PH; height at metatarsal phalangeal joint (MPJ), MPJH; height at 30% foot length - $FL_{30}H$; height at 40% foot length, $FL_{40}H$; height at 50% foot length, $FL_{50}H$; arch or "Cookie height", AH), seven widths (heel width, HW; foot width, FW; widths at 50% foot length, $FL_{50}W$; width of first toe, T_1W; width of first and second toes, $T_{12}W$; width of third, fourth and fifth toes, $T_{345}W$; arch width or "cookie width", AW) and eight lengths (arch length, AL; cookie length, CL; foot length, FL; length from heel to first toe, HT_1L; length from heel to second toe, HT_2L; length from heel to third toe, HT_3L; length from heel to fourth toe, HT_4L; and length from heel to fifth toe, HT_5L) were measured. The foot outlines were used to determine the three foot curvature measures (yavat, ratio, pc), based on Yavatkar (1993), Freedman et al. (1946), and Goonetilleke and Luximon (1999) methods.

ANALYSIS and RESULTS

All statistical analyses were performed using the SPSS 10.0 package. The descriptive statistics of the subjects are given in Table 1 along with the results of the factor analysis with varimax rotation. Table 1 shows only 13 factors since the explained variance of each of the factors 14 and beyond is less than 0.9% of the total variance. The first 13 factors explain 95.69% of the variance. The first 4 factors were “length” (explained variance = 32.04), “height” (explained variance = 14.88), “flare” or “curvature” (explained variance = 11.66) and “width” (explained variance = 7.36).

Based on the 13 factors, length, width and height variables (FL, FW and MPJH), together with the length, width and height measures of the arch (CL, AW, AH) and the foot curvature measure (pc) were subjected to another factor analysis. The 2, 3 and 4 factor decompositions are shown in Table 2. The results show that if two sizing parameters are needed, then length and flare measure can be used (explained variance = 64.2%). Furthermore, length, flare and (height or width) may be used for a three parameter sizing system (explained variance = 77.2%) and length, width, height and flare measures can be used for a four parameter sizing system (explained variance = 86.3%).

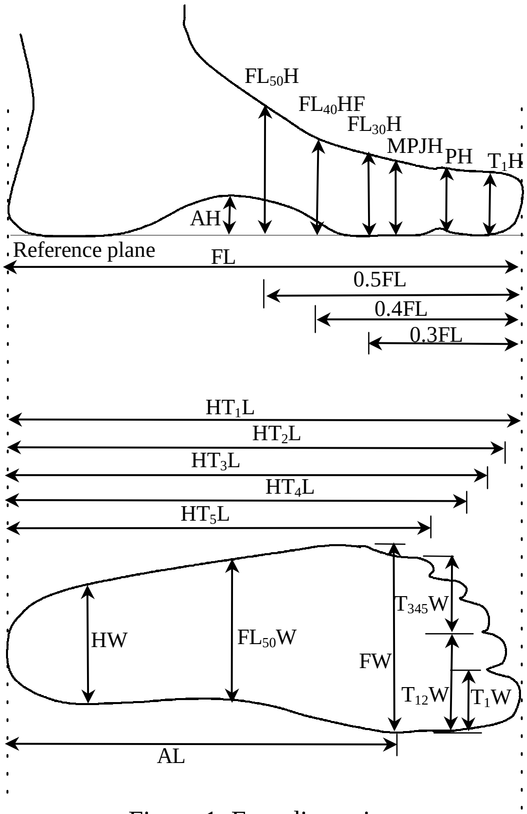

Figure 1. Foot dimensions

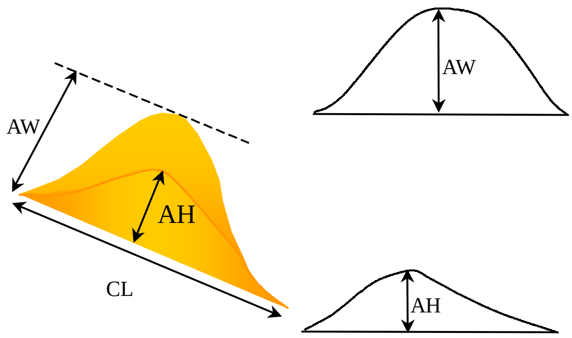

Figure 2. PlayDoh® arch cookie and the relevant arch dimensions.

Table 1. Simple statistics and rotated factor loadings with all 27 variables (factor loadings greater than 0.6 are shown. Only 13 factors are shown since the explained variance of each of the other factors beyond 13 is less than 0.9%).

			Factors												
	Mean	SD	1	2	3	4	5	6	7	8	9	10	11	12	13
W	66.2	11.26	-	-	-	-	-	-	-	-	-	0.70	-	-	-
H	1720.0	62.71	0.81	-	-	-	-	-	-	-	-	-	-	-	-
FL	254.6	12.29	0.94	-	-	-	-	-	-	-	-	-	-	-	-
AL	184.9	10.30	0.88	-	-	-	-	-	-	-	-	-	-	-	-
CL	132.1	7.32	0.61	-	-	-	-	-	-	-	-	-	0.73	-	-
HT_1L	254.1	12.50	0.92	-	-	-	-	-	-	-	-	-	-	-	-
HT_2L	250.2	11.88	0.97	-	-	-	-	-	-	-	-	-	-	-	-
HT_3L	241.4	11.23	0.97	-	-	-	-	-	-	-	-	-	-	-	-
HT_4L	226.2	10.22	0.95	-	-	-	-	-	-	-	-	-	-	-	-
HT_5L	209.5	9.61	0.95	-	-	-	-	-	-	-	-	-	-	-	-
FW	93.2	5.17	-	-	-	-	0.65	-	-	-	-	-	-	-	-
HW	65.6	4.96	-	-	-	-	-	-	-	-	-	-	-	-	0.62
AW	46.6	6.43	-	-	-	-	-	-	-	-	0.81	-	-	-	-
$T_{12}W$	48.5	4.45	-	-	-	0.85	-	-	-	-	-	-	-	-	-
T_1W	32.4	2.48	-	-	-	0.84	-	-	-	-	-	-	-	-	-
$T_{345}W$	39.4	5.09	-	-	-	-	-	-	0.89	-	-	-	-	-	-
$FL_{50}W$	82.3	4.75	-	-	-	-	0.80	-	-	-	-	-	-	-	-
T_1H	17.7	2.41	-	-	-	-	-	-	-	0.97	-	-	-	-	-
PH	27.6	3.20	-	0.95	-	-	-	-	-	-	-	-	-	-	-
MPJH	36.9	3.76	-	0.88	-	-	-	-	-	-	-	-	-	-	-
$FL_{30}H$	42.9	4.62	-	0.88	-	-	-	-	-	-	-	-	-	-	-
$FL_{40}H$	56.4	5.39	-	0.72	-	-	-	-	-	-	-	-	-	-	-
$FL_{50}H$	68.4	5.52	-	0.61	-	-	-	-	-	-	-	-	-	0.63	-
AH	30.6	5.09	-	-	-	-	-	0.84	-	-	-	-	-	-	-
yavat	-0.58	2.14	-	-	0.98	-	-	-	-	-	-	-	-	-	-
pc	-3.18	2.56	-	-	0.98	-	-	-	-	-	-	-	-	-	-
ratio	0.514	0.064	-	-	-0.97	-	-	-	-	-	-	-	-	-	-
% Variance			32.04	14.88	11.66	7.36	5.48	4.17	3.99	3.95	3.24	2.49	2.40	2.28	1.77
Cumulative (Cum..) %			32.04	46.91	58.57	65.93	71.41	75.58	79.56	83.52	86.76	89.24	91.64	93.92	95.69

Researchers tend to separate the foot into the three regions: forefoot, midfoot and rearfoot. Hence, a different factor analysis was performed using variables from each region, as well as FL and pc. AL, FW and MPJH were forefoot region variables, while $FL_{50}W$ and $FL_{50}H$ were midfoot variables and HW was the rearfoot variable.

The varimax rotated factor analyses with 2, 3 and 4 factors are shown in Table 3. The analyses show that 4 factors can explain 89.95% of the variance with the first factor loaded on "length" measures (even though HW has a loading of 0.69), the second factor loaded on the "width" measures, the third factor loaded on the "height" measures, and the fourth factor loaded on the "flare" measure. This shows that length, width, height and flare can explain a significant portion of the foot shape variation. Similarly, the 3-factor solution shows that length, height and flare measures explain 81.33% of the variance. With two factors, only 69.29% of the variance is explained with variables such as length, flare or height. Even though the height variable has a high loading, the measurement corresponding to height can generally be adjusted with the lacing, depending on the type of shoe. In such cases, it may be more important to consider foot curvature.

Table 2. Factor analysis of 7 variables (loadings greater than 0.5 are shown in bold)

	2 factors		3 factors			4 factors			
	1	2	1	2	3	1	2	3	4
FL	**0.92**	0.02	0.42	**0.81**	-0.17	**0.82**	0.38	0.18	-0.16
FW	**0.84**	0.17	**0.62**	0.58	-0.17	**0.59**	**0.55**	0.30	-0.16
MPJH	**0.53**	0.40	**0.71**	0.20	-0.01	0.18	0.19	**0.94**	0.03
CL	**0.70**	0.08	0.04	**0.93**	0.22	**0.93**	-0.03	0.09	0.23
AW	0.46	**0.70**	**0.75**	0.19	0.34	0.20	**0.60**	0.44	0.35
AH	0.47	**0.57**	**0.81**	0.09	0.10	0.11	**0.91**	0.11	0.11
PC	-0.19	**0.83**	0.14	0.01	**0.96**	0.01	0.12	0.04	**0.96**
% Variance	40.0	24.2	32.8	27.8	16.5	28.1	24.1	17.4	16.7
Cum. %	40.0	64.2	32.8	60.7	77.2	28.1	52.2	69.6	86.3

Table 3. Factor analysis with variables from the three regions of the foot (loadings greater than 0.5 are shown in bold)

	2 factors		3 factors			4 factors			
	1	2	1	2	3	1	2	3	4
FL	**0.92**	-0.04	**0.91**	0.10	-0.11	**0.91**	0.31	0.12	-0.04
AL	**0.89**	-0.01	**0.90**	0.10	-0.05	**0.94**	0.24	0.13	0.04
MPJH	0.46	**0.70**	0.32	**0.82**	0.09	0.24	0.22	**0.82**	0.09
FW	**0.85**	0.26	**0.83**	0.34	0.07	0.43	**0.83**	0.28	-0.03
$FL_{50}H$	0.32	**0.74**	0.13	**0.90**	0.00	0.09	0.12	**0.90**	0.01
$FL_{50}W$	**0.76**	0.26	**0.78**	0.23	0.21	0.30	**0.92**	0.16	0.07
HW	**0.84**	0.18	**0.76**	0.41	-0.18	**0.69**	0.34	0.41	-0.15
PC	-0.20	**0.58**	-0.03	0.05	**0.97**	-0.05	0.03	0.06	**0.99**
%Variance	49.94	19.35	45.27	22.92	13.13	31.38	23.41	22.34	12.82
Cum. %	49.94	69.29	45.27	68.20	81.33	31.38	54.80	77.14	89.95

DISCUSSION and CONCLUSIONS

Often, feet are sized using foot length or foot length and foot width. However, with a limited sample size it has been shown that foot length and foot curvature may be more appropriate for footwear fitting if two variables can be used to account for the foot dimensional variances. If many variables (n-dimensional vector) are used for sizing, the large number of combinations coupled with the large number of styles, will create an exorbitant inventory. Hence it is important that the number of sizing variables be minimized. The results show that foot length is suitable for one parameter sizing. But, foot length and foot curvature may be more suitable for two-parameter sizing, length, curvature and height for three-parameter sizing, and length, width, height and curvature measures may be used for a four-parameter sizing system. If these are not adequate, then at least two dimensions may be used from each region (forefoot, mid foot and rear foot) to accurately describe the foot for footwear fitting (Goonetilleke et al., 1997).

ACKNOWLEDGMENTS

The authors would like to thank the Research Grants Council of Hong Kong for funding this study under grant HKUST 6074/99E.

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