FOOT SIZING BEYOND THE 2-D BRANNOCK METHOD

Ravindra S. GOONETILLEKE, Edmond C.F. HO & Richard H. Y. SO

Department of Industrial Engineering & Engineering Management
Hong Kong University of Science and Technology, Hong Kong

ABSTRACT

Although numerous devices are available for foot measurement, generally only one or two dimensions are used when sizing a foot. The study reported here is an attempt to find the "orthogonal" dimensions so that a Hong Kong Chinese foot may be properly sized and modelled. Foot dimensions of thirty-one subjects were measured using an anthropometer, digital caliper and a measuring tape. Factor analyses and principal component analysis indicated that the height dimension is important. Hence, it is recommended that at least two dimensions be measured on forefoot, midfoot and rearfoot for more accurate foot modelling.

1 Introduction

Hong Kong has been second to Italy in the exportation of footwear since 1992 [1]. Using the Southern part of China (e.g., Fujian) as the manufacturing base, Hong Kong footwear companies are producing and distributing name brand shoes of different types including sports shoes, dress shoes, boots, children and infant's shoes, sandals and house slippers. In addition to producing these brand name shoes, many footwear companies in Hong Kong have joint ventures with Chinese companies to design and develop their own brands of shoes for the fast-growing mainland market. For the new brands to be competitive, wearer fit is one of the basic requirements. A good fit requires a proper foot sizing system. Sizing systems differ among the different countries. For example, the United States, Japan, United Kingdom all employ their own systems but use the same one or two dimensions to size a three dimensional foot. The Brannock device [2] is primarily used to measure one or more of the following dimensions:

(i) Overall length from the tip of the most prominent toe to the heel (three Brannock units correspond to one inch);

(ii) Ball joint or metatarsophalangeal joint (MPJ) position with respect to the heel (called arch length); and

(iii) Width of foot measured at the MPJ joint (or ball of foot) with alphabetic letters of AAA (narrow), AA, A, B, C, D, E, EE, and EEE (wide). The width is normally obtained relative to foot length.

However, in reality, the Brannock device is used for the measurement of only foot length and sometimes foot width. Even if two dimensions are used, modelling the three dimensional foot becomes very difficult if not impossible. Footwear manufacturers use at least 30 dimensions to build a foot last (Rossi, 1988). Hence the mapping of 2 dimensions to 30 dimensions on a shoe last is clearly inadequate. This research is an attempt to evaluate the relevant dimensions of the Hong Kong male foot so that feet can be categorized or classified better.

2 Methodology

Subjects

A total of 31 Hong Kong Chinese adult male students at the Hong Kong University of Science and Technology were subjects in the experiment. None of the subjects had any foot illness or foot abnormalities.

Procedure

Each subject was asked to fill out a voluntary consent form. The subject's age, stature and weight were first recorded. All measurements were made under "no-load" conditions using an adjustable chair and a height adjustable foot rest with a 90 degree angle at the ankle joint. A total of fourteen dimensions on the left foot were measured (Figures 1 and 2).

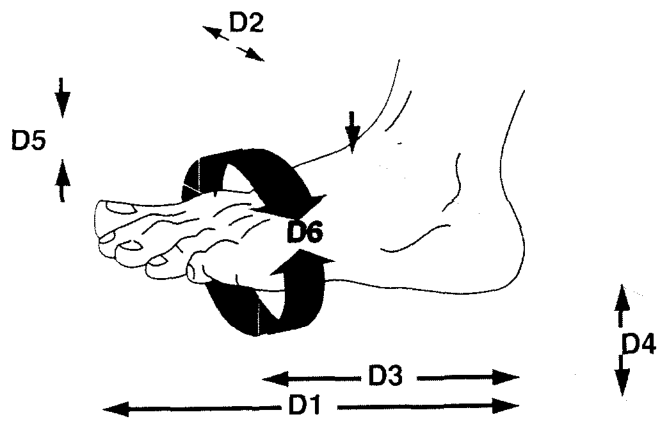


Fig. 1 Dimensions D1 to D6

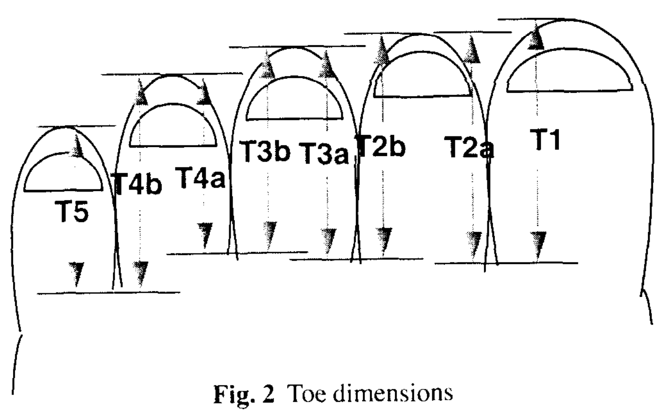


Fig. 2 Toe dimensions

A Brannock Device was used to measure the foot length (D1), foot width (D2), and arch length (D3). Arch length was defined to be the ball-to-heel length. Foot width was not measured as specified by the Brannock device. Instead, the markings that correspond to foot length were used against a reference mark to obtain a numerical value for foot width rather than alphabetic characters between AAA and EEE. This procedure for foot width allows the measurement to be independent of foot length. Independence of foot width from foot length is especially important due to the nature of our study. An *anthropometer* was used to measure the foot height or dorsal arch height (D4) and height of the MPJ joint at the 1st toe (D5). A *measuring tape* was used to measure the circumference of the MPJ (D6). A *digital caliper* was used to measure the length of the 5 toes (T1, T2a, T2b, T3a, T3b, T4a, T4b and T5) as shown in Figure 2.

3 Transformation

Since D1, D2 and D3 were measured in Brannock units, these three dimensions were converted to length measures using the following transformations:

$$\text{Foot Length (FL) in mm} = 187 + (25.4 / 3) \times (D1 - 0.5)$$

$$\text{Foot Width (FW) in mm} = 64.3 + 3.2 \times (D2 - 1)$$

$$\text{Arch Length (AL) in mm} = 173.5 + 5.6 \times (D3 - 7)$$

where D1, D2 and D3 are in Brannock units.

Most subsequent statistical analyses were performed using the transformed measures of FL, FW, and AL.

4 Results and Analysis

The descriptive statistics of the subjects are shown in Table 1.

Variable	Mean	Standard Deviation	Minimum	Maximum
Age (years)	22.1	1.37	20	25
Stature	1726	70.67	1550	1870
Weight (kg)	65.62	12.17	43.2	101
Foot Length, D1 (Brannock units)	8.2	1.28	5	10.5
Foot Length, FL (mm)	252.00	10.82	225.1	271.67
Foot Width, FW (mm)	94.03	4.31	85.1	103.98

Table 1 Descriptive statistics of the subjects (N=31)

The heel-to-toe length for each of the five toes was calculated as follows:

If $T1 > T2a$, then $T1H = FL$ and $T2H = FL - (T1 - T2a)$;

If $T1 < T2a$, then $T2H = FL$ and $T1H = FL - (T2a - T1)$.

Thereafter, $T3H = T2H - (T2b - T3a)$, $T4H = T3H - (T3b - T4a)$, and $T5H = T4H - (T4b - T5)$

It was seen that 21 out of the 31 subjects (68%) had the big toe (toe 1) longer than the second toe (i.e., $T1H > T2H$).

The statistical package SAS was used to perform all analyses. The inter-correlation analysis of all data collected (i.e., FL, FW, AL, D4, D5, D6, T1, T2a, T2b, T3a, T3b, T4a, T4b and T5) shows a significant ($p < 0.05$) correlation between many variables. The coefficient of determination (**R^2**) values greater than 0.80 ($p < 0.05$) are shown in Table 2.

The relationship between arch length and foot length as well as the circumference and foot width were further explored using a linear regression analysis. The scatter plots and the fitted lines are shown in Figure 3.

Variables	R^2	Variables	R^2
Arch length and Foot Length		AL and T2H	0.81
AL and FL	0.86	T1H and T2H	0.89
Circumference and Foot Width		T1H and T3H	0.85
D6 and FW	0.86	T1H and T4H	0.81
FL and T1H	0.99	T2H and T3H	0.95
FL and T2H	0.93	T2H and T4H	0.87
FL and T3H	0.88	T3H and T4H	0.94
FL and T4H	0.84	T3H and T5H	0.83
AL and T1H	0.89	T4H and T5H	0.87

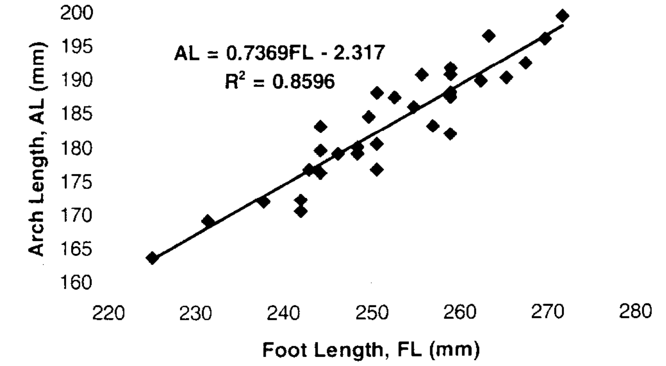
Table 2 Correlation analysis. R^2 coefficients hgreater than 0.8 are shown

Three separate factor analyses (Tables 3, 4, and 5) were performed using the principal component method with varimax rotation. The first used the toe dimensions (Table 3), the second used the heel to toe dimensions (Table 4) and the third excluded all toe dimensions (Table 5). The first factor analysis (Table 3) showed the emergence of eight dominant factors (variance explained = 95%). The interesting finding is the grouping of the measured dimensions in the rotated factor loadings as shown in Table 3. Factor 1 is dominated by the toe dimensions of the second, third, and fourth toes ("centre toe lengths"). Foot width (FW) and circumference (D6) dominated factor 2 ("width"), foot length (FL) and arch length (AL) dominated factor 3 ("critical length"). T1 ("big toe length"), D4 ("midfoot height"), D5 ("forefoot height"), T4b, and T5 ("small toe length") dominated separate factors.

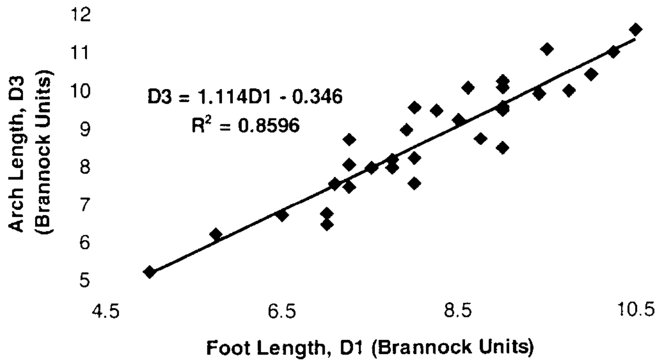
The second factor analysis of the variables, FL, FW, AL, D4, D5, D6, T1H, T2H, T3H, T4H, and T5H shows the emergence of 4 dominant factors explaining 95% of the variance. The groupings are such that factor 1 ("length") is dominated by the length measures of FL, AL, T1H, T2H, T3H, T4H, and T5H; factor 2 ("width") by the width related measures of FW and D6; factor 3 by "height" in forefoot area; factor 4 by "height" in the midfoot region. Interestingly, the third factor analysis (Table 5) grouping is the "same" as Table 4 when all toe dimensions are excluded.

In reality, the toes are not measured. The longest toe is taken to be an important measure resembling the overall length of the foot. Hence, it is reasonable to ignore the toe lengths and consider only foot length. Based on this reasoning, a principal component analysis was performed using the correlation matrix with variables FL, FW, D4 and D5. Foot length (FL) and foot width (FW) were used instead of arch length (AL) and MPJ circumference (D6) since the former two dimensions are commonly used in foot sizing. The results are shown in Table 6. When the natural logarithms were used, the eigenvalues and the eigenvectors hardly changed as shown by the values in parentheses (see Table 6). It is easier to explain the principal components with the logarithmic transformations as shown in the example below:

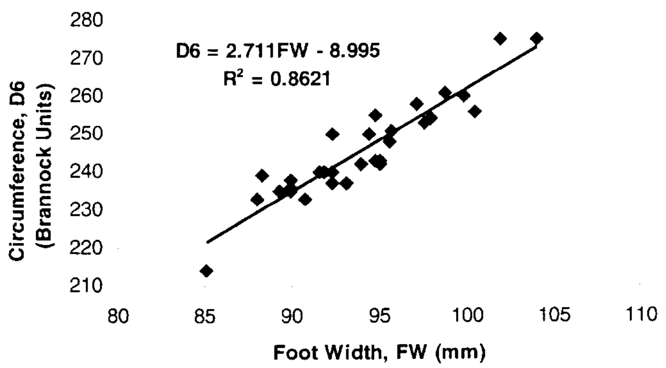
$$\text{Principal component} = 0.55*\ln(FL) + 0.58*\ln(FW) + 0.38*\ln(D4) + 0.46*\ln(D5) = \ln\{FL^{0.55} * FW^{0.58} * (D4^{0.38} * D5^{0.46})\}$$



3 (a) A least squares fit between arch length (AL) and foot length (FL) gave: **AL = (0.7369) FL – 2.317 ; (p < 0.0001).**



3 (b) If Brannock units are used instead, the least squares fit gave: **D3 = (1.114) D1 – 0.346 ; (p < 0.0001).**



3 (c) Similarly, the least squares fit between foot circumference (D6) and foot width (FW) gave; **D6 = (2.711) FW – 8.995; (p < 0.0001)**

Fig. 3 Least squares fit for foot length, foot width and circumference

Hence the first principal component may be viewed as the ln(volume) of the foot with adjusted cube dimensions. For instance, the adjusted length of the cube is (length $^{0.55}$), adjusted width of (width $^{0.58}$), and adjusted height of (D4 $^{0.38}$ * D5 $^{0.46}$), which accounts, in some sense, for the rounded shape of the foot. Similarly, principal component 4 appears to resemble an effect similar to "Poisson's ratio" in the length and width dimensions while principal component 2 may be viewed as a Poisson's ratio in the height and length directions. Principal component 3 on the other hand may be considered as a "minimum height" measure of the foot/shoe.

	Factor													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
FL	-	-	0.78	-	-	-	-	-	-	-	-	-	-	-
FW	-	0.92	-	-	-	-	-	-	-	-	-	-	-	-
AL	-	-	0.88	-	-	-	-	-	-	-	-	-	-	-
D4	-	-	-	-	0.97	-	-	-	-	-	-	-	-	-
D5	-	-	-	-	-	0.92	-	-	-	-	-	-	-	-
D6	-	0.93	-	-	-	-	-	-	-	-	-	-	-	-
T1	-	-	-	0.92	-	-	-	-	-	-	-	-	-	-
T2A	0.77	-	-	-	-	-	-	-	-	-	-	-	-	-
T2B	0.89	-	-	-	-	-	-	-	-	-	-	-	-	-
T3A	0.88	-	-	-	-	-	-	-	-	-	-	-	-	-
T3B	0.94	-	-	-	-	-	-	-	-	-	-	-	-	-
T4A	0.68	-	-	-	-	-	-	-	-	-	-	-	-	-
T4B	-	-	-	-	-	-	0.84	-	-	-	-	-	-	-
T5	-	-	-	-	-	-	-	0.84	-	-	-	-	-	-
Variance explained by each factor	4.017	2.182	1.723	1.151	1.084	1.066	1.060	0.980	0.235	0.170	0.169	0.096	0.036	0.031
Proportion explained by each factor (%)	28.69	15.59	12.31	8.22	7.75	7.62	7.57	7.00	1.68	1.21	1.21	0.69	0.26	0.22
Cumulative Proportion (%)	28.69	44.28	56.59	64.81	72.56	80.18	87.75	94.74	96.42	97.63	98.84	99.53	99.78	100

Table 3 Factor analysis with varimax rotation including toe dimensions (only factor loadings greater than 0.5 are shown).

	Factor										
	1	2	3	4	5	6	7	8	9	10	11
FL	0.92	-	-	-	-	-	-	-	-	-	-
FW	-	0.88	-	-	-	-	-	-	-	-	-
AL	0.91	-	-	-	-	-	-	-	-	-	-
D4	-	-	-	0.98	-	-	-	-	-	-	-
D5	-	-	0.96	-	-	-	-	-	-	-	-
D6	-	0.87	-	-	-	-	-	-	-	-	-
T1H	0.92	-	-	-	-	-	-	-	-	-	-
T2H	0.94	-	-	-	-	-	-	-	-	-	-
T3H	0.92	-	-	-	-	-	-	-	-	-	-
T4H	0.87	-	-	-	-	-	-	-	-	-	-
T5H	0.81	-	-	-	-	-	-	-	-	-	-
Variance explained by each factor	6.028	2.167	1.142	1.100	0.233	0.113	0.078	0.058	0.045	0.034	0.002
Proportion explained by each factor (%)	54.8	19.7	10.38	10.0	2.12	1.03	0.71	0.53	0.4	0.31	0.02
Cumulative Proportion (%)	54.8	74.5	84.88	94.88	97	98.03	98.74	99.27	99.68	99.98	100

Table 4 Factor analysis with varimax rotation including toe-to-heel dimensions (only factor loadings greater than 0.5 are shown).

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
FL (Foot Length)	0.89	-	-	-	-	-
FW (Foot Width)	-	0.89	-	-	-	-
AL (Arch Length)	0.94	-	-	-	-	-
D4 (Foot Height)	-	-	-	0.98	-	-
D5 (Height of MPJ at 1st Toe)	-	-	0.97	-	-	-
D6 (Circumference of MPJ)	-	0.90	-	-	-	-
Variance explained by each factor	1.928	1.883	1.035	1.028	0.067	0.060
Proportion explained by each factor	32.12%	31.38%	17.25%	17.13%	1.12%	1%
Cumulative Proportion	32.12%	63.51%	80.76%	97.88%	99%	100%

Table 5 Factor analysis with varimax rotation excluding all toe dimensions (only factor loadings greater than 0.5 are shown).

5 Conclusions and Limitations

The factor analyses suggest that length, width (or circumfer-

Eigenvalues of the Correlation Matrix			
	Eigen value	Proportion	Cumulative
PRIN 1	2.12 (2.14)	0.53 (0.53)	0.53 (0.53)
PRIN 2	0.86 (0.86)	0.22 (0.22)	0.75 (0.75)
PRIN 3	0.69 (0.68)	0.17 (0.17)	0.92 (0.92)
PRIN 4	0.33 (0.32)	0.08 (0.08)	1.00 (1.00)

Eigenvectors				
	PRIN 1	PRIN 2	PRIN 3	PRIN 4
FL	0.56 (0.55)	−0.44 (−0.46)	−0.17 (−0.17)	0.68 (0.67)
FW	0.58 (0.58)	−0.26 (−0.26)	−0.29 (−0.26)	−0.72 (−0.72)
D4	0.37 (0.38)	0.84 (0.82)	−0.37 (−0.40)	0.15 (0.15)
D5	0.46 (0.46)	0.18 (0.21)	0.87 (0.86)	−0.04 (−0.01)

Table 6 Principal Component Analysis of FL, FW, D4 and D5 (values in parenthesis are log. transformations of each variable).

ence), "height" at midfoot and forefoot, and toe dimensions (toe 1, toes 2-4, and toe 5) need to be considered for proper footwear fitting and when modelling the foot. Most often, feet are sized using only length and sometimes length and width. This study shows that proper fit may only be achieved by including not only length and width, but also the third dimension relating to height. Hence it seems reasonable to divide the foot into three regions: forefoot, midfoot and rearfoot. Based on our study, it appears that at least two dimensions in each of the regions may be needed to describe the foot adequately for better fitting.

The principal component analysis indicates that a "volume" measure, a basic height measure, and two measures indicating dimensional changes in orthogonal directions (similar to a Poisson effect) can explain the variations in the foot. Hence it may be possible to generate an "ideal" (or theoretical) foot that may be "scaled" using principal components to achieve any desired foot shape.

A few limitations do exist in this study. Firstly, even though the foot is a complex structure only fourteen dimensions were measured and analyzed. Secondly, the Brannock device was used to measure foot length, arch length and width. The markings are in units of 0.5 Brannock units and are not as accurate as desired even though the measurement process was very convenient. Hence the measures obtained before the transformations may not be as accurate as a caliper or ruler reading.

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Acknowledgments

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