Foot Anthropometry in Hong Kong

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Abstract
Even though numerous devices are available for measuring the foot, generally, only one or two dimensions are used when sizing a foot. The study reported here is an attempt to find "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 in the forefoot, midfoot and rearfoot to model the foot better.

Index words: Foot, Anthropometry, Sizing.

1. Introduction
Devices such as the Ritz, Brannock, and Scholl are available to measure foot size (Cheskin, 1987). The more popular among the three is the Brannock device, which allows one to measure the following dimensions:

1. Overall length from the tip of the most prominent toe to the heel with three Brannock units corresponding to one inch.
2. Ball joint or metatarsophalangeal joint (MPJ) position with respect to the heel (called arch length) and
3. 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. From a mathematical viewpoint, it is almost impossible to generate a foot form of 3-dimensions using a set of 2-dimensional measures of foot length and width. 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 paper is an attempt to evaluate the relevant dimensions of the Hong Kong male foot so that they 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 a voluntary consent form. Their 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 (Figure 1). Fourteen dimensions on the left foot were measured for each subject (Figure 2 and 3).

A *Brannock*[1] Device was used to measure the foot length (D1), foot width (D2), and arch length (D3) defined as the ball-to-heel length in Brannock units. Foot width was not measured as specified in the Brannock device. Instead, the markings which 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 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[2] (D4) and height of MPJ joint at the 1st toe (D5). A *measuring tape* was used to measure the circumference of the MPJ joint (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 3.

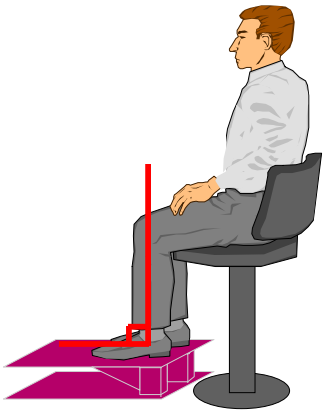


Figure 1. "Unloaded" foot posture during measurement

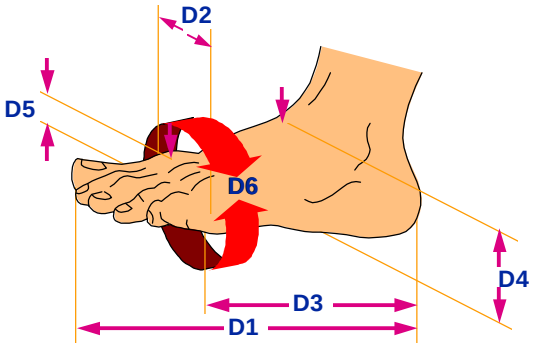


Figure 2. Dimensions D1 to D6

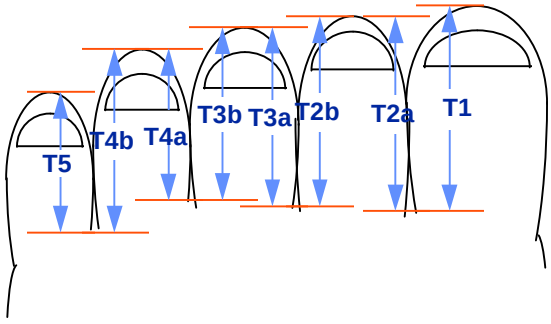


Figure 3. Toe dimensions

[1] *Brannock* is sold by the Brannock Device Company, Syracuse, New York.

[2] Dorsal arch height is the distance from the floor to the point where the top of the foot meets the front of the leg as defined by Pheasant (1994).

3. Transformation

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

Foot Length (FL) in mm = 187 + (25.4 / 3) x (D1 - 0.5)

Foot Width (FW) in mm = 64.3+ 3.2 x (D2 -1)

Arch Length (AL) in mm= 173.5 + 5.6 x (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.

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

Variable	Mean	Standard Deviation	Minimum	Maximum
Age (years)	22.1	1.37	20	25
[3]Stature (mm)	1726	70.67	1550	1870
[3]Weight (kg)	65.62	12.17	43.2	101
Foot Length, D1 (Brannock units)	8.2	1.28	5	10.5
[3]Foot Length, FL (mm)	252.00	10.82	225.1	271.67
[3]Foot Width, FW (mm)	94.03	4.31	85.1	103.98
Arch Length, D3 (Brannock units)	8.8	1.54	5.25	11.6
Arch Length, AL (mm)	183.38	8.60	163.7	199.26
Foot Height, D4 (mm)	75.83	4.31	66.8	84.8
Height of MPJ joint at first toe, D5 (mm)	36.61	1.98	32.8	39.8
Circumference of foot along MPJ joint, D6 (mm)	245.90	12.59	214	275
First toe length, T1 (mm)	43.81	3.13	37.13	50.79
Second toe length on side of first toe, T2a (mm)	41.51	3.98	33.48	50
Second toe length on side of third toe T2b (mm)	37.71	4.04	30.28	45.08
Third toe length on side of second toe T3a (mm)	30.40	3.60	23.09	40.08
Third toe length on side of fourth toe T3b (mm)	36.78	3.86	31.23	44.98
Fourth toe length on side of third toe, T4a (mm)	26.41	3.69	19	35.32
Fourth toe length on side of fifth toe, T4b (mm)	38.94	4.09	31.21	46.62
Fifth toe length on side of fourth toe T5 (mm)	24.93	4.19	15.82	33.48
Toe 1 to heel, T1H (mm)	251.48	10.56	225.1	269.10
Toe 2 to heel, T2H (mm)	249.18	11.13	220.27	271.67
Toe 3 to heel, T3H (mm)	241.87	10.86	219.27	264.55
Toe 4 to heel, T4H (mm)	231.49	10.79	209.70	253.47
Toe 5 to heel, T5H (mm)	217.49	10.99	197.68	241.51

[3] The mean (and standard deviation) for stature, weight, foot length, foot width reported by Pheasant is 1680 cm (58), 59.9 kg (8.6), 250 mm (10), 95 mm (5).

The heel-to-toe length for each of the five toes were 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)

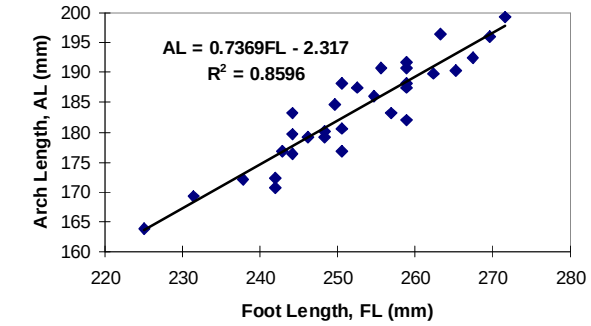
It was seen that 21 out of the 31 subjects (68%) had the big toe (toe 1) longer than the second toe (i.e., T1H > T2H).

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. Pearson correlation coefficients greater than 0.65 ($p < 0.05$) are shown in Table 2.

Table 2. Correlation analysis. Pearson correlation (R) coefficients greater than 0.65 are shown.

Variables	R^2	Variables	R^2
Foot Length and Stature		T1H and FL	0.99
FL and H	0.44	T1H and FW	0.44
Weight and Foot Width		T1H and AL	0.89
W and FW	0.49	T1H and D6	0.49
Foot width and Foot Length		T1H and T2H	0.89
FW and FL	0.43	T1H and T3H	0.85
Arch length and Foot Length		T1H and T4H	0.81
AL and FL	0.86	T1H and T5H	0.68
Circumference and Weight		T2H and FL	0.93
D6 and W	0.43	T2H and AL	0.81
Circumference and Foot Length		T2H and D6	0.45
D6 and FL	0.49	T2H and T3H	0.95
Circumference and Foot Width		T2H and T4H	0.87
D6 and FW	0.86	T2H and T5H	0.79
		T3H and FL	0.88
T2a and T2b	0.69	T3H and AL	0.78
T2a and T3a	0.57	T3H and D6	0.47
T2a and T3b	0.54	T3H and T4H	0.94
T2b and T3a	0.62	T3H and T5H	0.83
T2b and T3b	0.71	T4H and FL	0.84
T2b and T4a	0.51	T4H and FW	0.45
T3a and T3b	0.69	T4H and AL	0.77
T3a and T4a	0.56	T4H and D6	0.46
T3b and T4a	0.54	T4H and T5H	0.87
T4a and T4b	0.52	T5H and FL	0.73
T4a and T5	0.5	T5H and AL	0.61

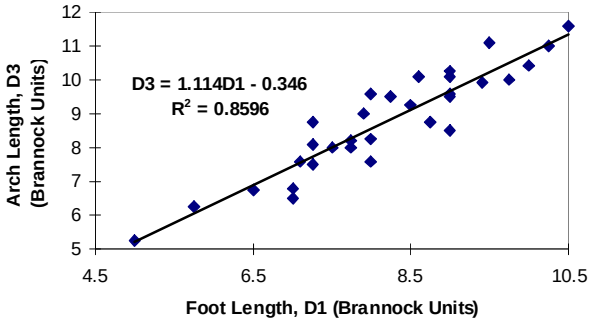
A linear regression analysis was performed to obtain the relationship between arch and foot length as well as the linear relationship between foot circumference and foot width. The scatter plots and the fitted lines are shown in Figure 4.



A least squares fit between arch length (AL) and foot length (FL) gave the following results;

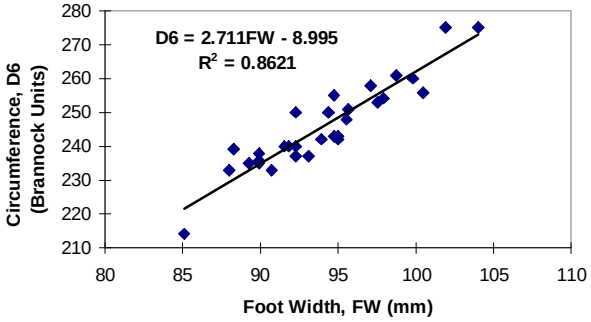
AL = (0.7369) FL – 2.317 ; (p < 0.0001)

Note that AL and FL are measured in mm.



If Brannock units are used instead, the least squares fit is as follows:

D3 = (1.114) D1 – 0.346 ; (p < 0.0001)



Similarly, the least squares fit between foot circumference (D6) and foot width (FW) gave the following results;

D6 = (2.711) FW – 8.995; (p < 0.0001)

Note that D6 and FW are measured in mm.

Figure 4. Least squares fit for foot length, arch length, foot width and circumference

Three separate factor analyses (Tables 4, 5, and 6) were performed using the principal component method with varimax rotation. The first was using the toe dimensions (Table 4), the second using the heel to toe dimensions (Table 5) and the third excluding all toe dimensions (Table 6). The first factor analysis (Table 4) showed the emergence of 8 dominant factors (variance explained = 95%). The interesting finding is the grouping of the measured dimensions in the rotated factor loadings as shown in Table 4. Factor 1 is dominated by the toe dimensions of the second, third, and fourth toes ("centre toe lengths"). Foot width (FW) and circumference (D6) dominate factor 2 ("width"), foot length (FL) and arch length (AL) dominate factor 3 ("critical length"). T1 ("big toe length"), D4 ("midfoot height"), D5 ("forefoot height"), T4b, and T5 ("small toe length") dominate 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 6) grouping is the "same" as Table 5 when all toe dimensions are excluded.

Table 4. 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	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 5. Factor analysis with varimax rotation including toe-to-heel 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 6. Factor analysis with varimax rotation excluding all toe dimensions
(Only factor loadings greater than 0.5 are shown)

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
FL	0.89	-	-	-	-	-
FW	-	0.89	-	-	-	-
AL	0.94	-	-	-	-	-
D4	-	-	-	0.98	-	-
D5	-	-	0.97	-	-	-
D6	-	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%

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 7. When the natural logarithms were used, the Eigen values and the Eigen vectors hardly changed as shown by the values in parenthesis (see Table 7). It is easier to explain the principal components with the logarithmic transformations as shown below:

For example, Principal component $_1$ $= 0.55*\ln(FL) + 0.58*\ln(FW) + 0.38*\ln(D4) + 0.46*\ln(D5)$

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

Hence the first principal component may be viewed as the ln(volume) of foot with adjusted dimensions. For instance, the adjusted length is (length $^{0.55}$), adjusted width is (width $^{0.58}$), and adjusted depth is ($D4^{0.38} * D5^{0.46}$), 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.

Table 7. Principal Component Analysis with FL, FW, D4 and D5 (values in parenthesis are for those with the natural logarithmic transformations of each variable).

Eigen values 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)

Eigen vectors

	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)

5. Conclusions and Limitations

The factor analyses suggest that length, width (or circumference), "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 which 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 transformation may not be as accurate as a caliper or ruler reading.

6. References

Cheskin, M. P. (1987). *The Complete Handbook of Athletic Footwear*. New York: Fairchild Publications.

Pheasant, S. (1994). *Bodyspace*. London: Taylor and Francis.

Rossi, W. A. (1988). The Futile Search for the Perfect Shoe Fit. *Journal of Testing and Evaluation*. Vol. 16(4), pp. 393-403.