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Estimation of stature and sex from step length and shoe dimensions for forensic investigation

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Abstract

Footwear impression marks and footwear are among the most commonly found evidence at crime scenes. The aim of this study was to develop a formula for estimation of the stature and gender of an individual if the shoe dimensions and step length of that individual were known. The footwear dimensions (length and width) were collected from 320 subjects, comprising 152 males and 168 females, ranging from 18 to 44 years of age. A statistical model for sex and height prediction was constructed using logistic regression and multiple linear regression analysis, respectively. In general, the stature, shoe width, shoe length and average step length were significantly larger in males than in females ($p < 0.05$). The strongest correlation coefficient (r) was observed in the step length for female and male. While for the pooled sample, the shoe size showed the greatest and strong positive correlation coefficient. The lowest correlation was observed in shoe length in all groups. This study is demonstrated that the dimension of the shoe and the step length can be used to estimate stature and sex of the shoe owner. These models may be useful in the forensic investigation of criminal cases.

Keywords: shoeprint, step length, gender estimation

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1. Introduction

Personal identification plays a critical role in crime scene investigation [1]. In forensic investigations, sex and stature are the most important parameters used to determine the identity of an individual. Identification of the victim's or the defendant's sex alone results in a 50% reduction in the searchable population. Shoeprints and shoes, which are often the only evidence left by a suspect at the scene of crime, are key evidence that can help in personal identification. Information obtained by examination of these prints may help in linking a suspect with the crime scene. The individual morphological structures of shoeprints can be compared to a suspect's shoes or shoeprint [2, 3] to enable a positive identification. The shoe or shoeprint may also provide information on the height (stature) and gender of an individual. Calculation of stature and gender from theses prints may support height estimation of the defendants made by eye-witnesses [3]. Moreover, Atamturk intended to determine if the sex of an individual can be identified by foot lengths, shoe length, and/or footprints. Statistical analyses indicated that univariate models correctly assign approximately 67 – 94% of individuals to their correct sex groups [3]. Shoes and shoe prints found in the vicinity of the incidences may also play an important role in the identification of unknown persons. There have been a very large number of studies on the determination of identity via the individualizing characteristics of foot prints [2, 4 – 6] And there have been quite a few studies conducted to estimate the stature through shoeprint dimensions [7 – 9] .Yet, the number of studies to estimate sex through shoe dimensions is extremely limited [10].

Developing reliable models to estimate stature and sex from the characteristics of shoes and shoeprints can be critically important to facilitate crime scene investigations. This work presents an investigation of the prediction of stature and gender of an individual based on the step length and shoe dimensions generated in a mixed gender Thai population sample. Multiple statistical formulae for stature and gender estimation were developed with these purposes. The potential error in the sex and stature estimation is also evaluated and discussed.

2. Materials and Methods

2.1 Sampling

Measurements of step length during normal paced walking, maximum shoe length and width, and stature of 320 individuals at Silpakorn University (Nakorn Pathom Province, Thailand) were collected from

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Table 1. The descriptive information of male (N = 152) and female (N = 168).

Parameters	Mean ± S.D.	Min – Max	t-value	p-value
Age (y):				
Male	19.2 ± 1.6	19.0 – 36.0	−4.490	0.000*
Female	20.4 ± 2.8	18.0 – 44.0		
Weight (kg):				
Male	70.4 ± 16.1	40.0 – 150.0	8.897	0.000*
Female	57.4 ± 8.8	41.0 – 82.0		
Height (cm):				
Male	175.0 ± 6.2	159.0 – 189.0	16.652	0.000*
Female	163.7 ± 6.0	150.0 – 177.0		
Shoe size (number):				
Male	42.8 ± 1.5	38.0 – 46.0	21.474	0.000*
Female	39.2 ± 1.5	35.0 – 43.0		
Shoe width (cm):				
Male	11.5 ± 1.2	8.0 – 14.5	13.091	0.000*
Female	9.8 ± 1.2	7.0 – 17.0		
Shoe length (cm):				
Male	28.7 ± 2.0	25.0 – 34.0	8.658	0.000*
Female	26.7 ± 1.9	15.0 – 31.0		
Average step length(cm):				
Male	59.8 ± 11.9	36.8 – 89.0	3.968	0.000*
Female	55.5 ± 6.8	37.3 – 76.0		

p*<0.05

February to November 2019. The sampled population included 152 males and 168 females ranging in age from 18 to 44 years. Adult samples were selected using simple random sampling method. None of the individuals had any abnormality in their walking; subjects who did not meet these criteria were excluded from the analysis. The data set was divided into three sub-groups: the male group, the female group and the mix-gender group or pooled sample.

2.2 Participant consent and general information

Potential participants were provided with an overview of the study included the aim of this research. Each potential participant independently decided whether to participate in the study and communicated their decision to the research lead. After agreeing to participate, each participant provided general information, including gender, age, occupation, height, shoe type, shoe size and weight, using a Google form.

2.3 Measurements

Step length was determined based on a walking pattern recorded smooth white paper with a centimeter scale grid. Participants were requested to walk on the white grid paper for approximately10 feet in their normal walking manner. Data collection began after the tip of his/her shoe touched the paper, and ended after the volunteer passed the end of the paper, as shown in Fig. 1 (a). The step length of each step was measured as the straight distance between the rear-most point on the heel of two consecutive steps. The first three steps of each individual were measured and the averages of step were included in the study.

Shoe length and width are defined as the maximum distance directly between the two furthest points on the shoe's vertical and horizontal axis, respectively. Each shoe was placed on a sheet of white paper with a 1 cm scale grid and length and width were measured as shown in Fig. 1 (b). Shoes include in this study included canvas shoes (117 and 134 pairs for male and female, respectively), sandals (33 pairs for each male and female), and "other", which included casual (1 pair for female) and leather shoes (2 pairs for male). The shoe type was not significant between male and female group ($p > 0.05$).

The collected data were analyzed using the standard Statistic Package of Social Sciences (SPSS). Data were analyzed for mean, standard deviation, and standard errors of estimate (SEE). To identify evidence of sexual dimorphism in the sample, inferential statistical tests including the Student's (independent) t -test was employed to compare height, shoe length, and shoe width between the males and females. In order to obtain the most accurate estimate, regression formulae were calculated taking multiple parameters into account. The logistic regression analysis was used for sex prediction. The significance level for differences was set to $p < 0.05$ (95% confidence interval). The Pearson's product moment correlation coefficients (r), assumed as the measure of strength of the association between height and the shoe dimensions, was determined for both the male and female subjects, and also for the pooled sample. The adjusted coefficient of determination (R^2) was estimated to determine how much of the variance in the dependent variable could be explained by its relationship to the other variables.

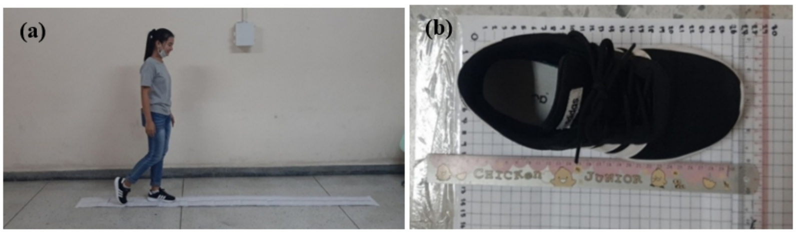

Figure 1: (a) Measurement of step length and (b) Measurement of shoe length and width.

Table 2. The descriptive information of male (N = 152) and female (N = 168).

Group	Parameters	Correlation coefficient (r)	p-value
Males	Shoe dimensions		
(n = 152)	- width	0.514**	0.000
	- length	0.383**	0.000
	- Shoe size (number)	0.575**	0.000
	- Average step length	0.684**	0.000
Females	Shoe dimensions		
(n=168)	- width	0.500**	0.000
	- length	0.473**	0.000
	- Shoe size (number)	0.715**	0.000
	- Average step length	0.718**	0.000
Pooled sample	Shoe dimensions		
(n=320)	- width	0.701**	0.000
	- length	0.579**	0.000
	- Shoe size (number)	0.827**	0.000
	- Average step length	0.632**	0.000

**p<0.05

3. Results and Discussions

3.1 Descriptive information

The majority of participants were college students (95.6%) with an average age of 19.2 ± 1.6 and 20.4 ± 2.8 years old for male and female respectively. The descriptive and inferential statistics of age, weight, height, shoe size, shoe width, shoe length, and average step length in normal walking manner are summarized in Table 1. When grouped by gender, it was observed that the mean values for the male subgroup was significantly greater ($p < 0.05$) than that of the female subgroup for all variables except for age. The age of male group was significantly less than female group. The outcomes show clear evidence of sexual dimorphism within the study sample.

3.2 Correlation between variables

The subjects in this study were divided into three groups, two groups with gender discrimination, namely male and female group and the other without gender discrimination or mix-gender group (Pooled sample). Table 2 summarizes the Pearson correlation coefficients "r" between stature and shoe dimensions, size or average step length for males, females, and the pooled sample. All variables were significantly correlated with stature ($p < 0.05$). The strongest correlation was observed between stature and average step length for both the male and female populations. In the pooled sample, however, stature correlated most strongly with shoe size ($r = 0.827$).

The linear regression equations for stature estimation based on shoe size, shoe dimensions and step length of the male, female, and the pooled sample groups are shown in Table 3. $Stature = a + bx$, where 'a' is the regression coefficient of the dependent variable, i.e. stature, 'b' is the regression coefficient of the independent variable, and 'x' is the shoe size, shoe dimension or step length measurement. The standard error of estimate (SEE) and adjusted R^2 are also included for each equation.

The linear regression models for stature estimations for the female sample resulted in lower SEE values for all variables modeled, suggesting slightly higher reliability for predicting stature from the study parameters of the males, females and pooled samples. The SEE values for the linear regression equations derived from the pooled sample data, on the other hand, were higher for shoe width, shoe length and step length than those generated for either the male or female data sets. This suggests that stature prediction from these variables may be more reliable when both genders were considered separately. This is supported by work from Krishan, Sharma and Kanchan et al., who reported that the foot length and foot breadth in the female samples of their studies provided the most accurate prediction for stature [6, 11].

In an effort to improve the accuracy of stature es-

Table 3. Linear regression equations for stature estimation from shoe size, shoe dimensions and step length of the males, females, and the pooled sample.

Linear regression equation	Adjusted R square	±SEE
Males:		
stature = 72.212 + 2.404(shoe size)	0.326	5.067
stature = 143.717 + 2.728(shoe width)	0.260	5.312
stature = 146.727 + 1.162(shoe length)	0.141	5.722
stature = 153.707 + 0.356(step length)	0.465	4.517
Females:		
stature = 48.148 + 2.994(shoe size)	0.508	4.222
stature = 138.794 + 2.551(shoe width)	0.246	5.228
stature = 124.150 + 1.480(shoe length)	0.219	5.318
stature = 128.190 + 0.640(step length)	0.513	4.202
Pooled sample:		
stature = 46.313 + 3.000(shoe size)	0.682	4.680
stature = 126.580 + 4.019(shoe width)	0.490	5.932
stature = 108.446 + 2.194(shoe length)	0.333	6.780
stature = 138.030 + 0.539(step length)	0.398	6.443

Note: SEE = Standard Error of Estimation, adjusted R^2 coefficient of determination

Table 4. Best fit regression model - males, females, and the pooled sample.

Multi-regression equation	Adjusted R square	±SEE
Males:		
Stature = 92.123 + 1.584(shoe size) + 0.258(step length)	0.565	4.075
Females:		
Stature = 58.399 + 0.336(shoe length) + 1.867(shoe size) + 0.416(step length)	0.707	3.280
Pooled sample:		
Stature = 48.970 + 2.566(shoe size) + 0.266(step length)	0.774	3.952

Note: SEE = Standard Error of Estimation, adjusted R^2 coefficient of determination

timation using shoe size, shoe dimensions, and step length measurements, multiple regression models generated using forward analysis for the males, females, and the pooled sample were evaluated.The best multivariable regression models (in terms of adjusted R^2) including shoe size, shoe width, shoe length, and/or step length and calculated stature are presented in Table 4.

When evaluating shoe size, shoe dimensions and step length measurements using multiple regression analysis, the adjusted coefficient of determination (R^2) between stature and shoe size and step length were found to be 0.774 in the pooled sample. However, the stature estimation formula had a 3 – 4 cm. deviation used according to the gender and both genders. This is a similar standard error of estimate as reported by Fawzy and Kamalin determination of stature for Egyptian males (SEE 3.52 – 4.69 cm) [12]. Gilles and Vallandigham suggested that shoe length was more reliable when used for stature estimation than shoe width, preferably as direct measurement but also indirectly as a shoe size indicator [8]. Similarity, Ekezie have shown a strong positive correlation between stature estimation and shoe length trace [13].

3.3 Sex prediction

Logistic regression analysis was conducted to evaluate the estimation of gender based on shoe size, shoe dimensions and step measurements. The resulting formulae for gender estimation is:

$$\text{Gender} = 0.324(\text{shoelength}) - 2.029(\text{shoesize}) + 74.493 \quad (1)$$

In the formulae, Gender < 0.50 indicates the shoe belongs to a male, while Gender ≥ 0.50 indicates the shoe belongs to a female. Correct estimation rates are shown in Table 5. The model correctly estimates the gender in 91.2% of the pooled sample, and 88.8% and 93.5% in the male and female groups, respectively.

Multiple formulae for calculating the gender using one or more measurements have been previously reported in the literature. Smith suggested that gender determination of the unidentified body parts can be made from distal and proximal phalanges with metatarsal bones. Using the models generated, it was observed that the determination of one's sex could be done with an 86 – 98% accuracy ratio [14]. Ozden et al. developed formulae with logistic regression analysis from foot and shoe sizes on the orthopedically healthy adult patients, and emphasized that it was helpful to find one of the shoes at the crime scene [10].

4. Conclusions

In conclusion, regression analysis of shoe size, shoe dimensions and step length measurements obtained from a representative mixed gender population was

Table 5. Percentages of correctly classified for gender prediction.

Groups	Correct	Incorrect	Percentage correct
Male	135	17	88.8
Female	157	11	93.5
Pooled sample	292	28	91.2

successfully used to develop models to estimate the stature and sex of an individual based on the above variables. The stature estimation formula has a 3 – 4 cm. deviation when used according to the gender and both genders, which agreed with other authors. The gender estimation model has an accuracy rate of $> 88\%$. This suggests that that stature and sex estimation can be achieved with shoe size, shoe dimensions and step length measurements in populations similar to those analyzed in this study. The results from this study will have important applications in the identification the disaster victims and formulation of biological profiles during forensic investigations through the providing of the regression equations for stature and sex prediction from shoe dimensions and step length.

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