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Analysis of stature prediction from foot anthropometry: a South Korean case study

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The investigation of footprints or dismembered foot dimensions from the scene of a crime or disaster plays a crucial role in the effort to determine some characteristics of the suspects or victims. Previous studies have shown the importance of foot dimensions for that purpose. However, the foot length and foot breadth were frequently studied; the present research investigated the relationship between stature and diverse foot dimensions such as of the heel, metatarsal edge, instep, metatarsal, and lateral malleolus – in addition to the foot length and foot breadth. The feet of 461 subjects (175 male & 286 Female) were scanned and measured. The mean age of the male participants was 41.6 (from 20 to 69) and 38.4 for female participants (from 20 to 68). A t-test was used to compare the gender difference in each dimension. Pearson’s correlation coefficients were computed to identify correlations among various part measurements and heights. Regression equations were derived using single or multiple variables. Foot length showed the highest relationship in males (R = 0.753) and females (R = 0.433). For males and females, prediction accuracy was highest in the linear regression equation using foot length alone (R^2 = 0.567 for males, R^2 = 0.188 for females; SEE ± 4.332 cm for males, ±4.825 cm for females). In addition to foot length, length-related variables such as the distance from the heel to both ends of the metatarsal were also reliable predictors. These research results are expected to be useful information for forensic medicine, and for medical appliance and sports manufacturers.

Keywords: foot anthropometry; forensic anthropometry; stature estimation; Korean foot

1. Introduction

Forensic identification involving anthropometry is well known for identifying suspect’s gender, age, race, and even body profile1–4. The investigation of footprints at the scene of a crime plays a crucial role in estimating some characteristics of suspects such as gender, stature and weight4. In a similar way, forensic investigation using an anthropometric approach is widely applied to estimate the identities of victims. Of highest priority in the investigation of a crime scene is to track the gender and the height5–6. Specifically, since each individual has different variations of body profile, estimating someone’s height can have an important role in an investigation7. Estimating stature is also important in identifying victims of airplane crashes or other mass disasters, because fragmented and dismembered feet may be found at such scenes7–8.

In forensic identification, evidence in the form of a footprint could provide much more useful information than other body parts. This is because foot length has a positive correlation with stature. Furthermore, at almost all crime scenes there are
footprints. Especially, in most Asian countries such as Korea, Japan, and China, people take off their shoes indoors. Thus, in case of an indoor crime, the bare foot plays a key role in profiling a suspect. In addition, a foot has 26 bones, 33 joints, and 19 muscles, all of which provide various data pertaining to body profiles. All of this information can be used for identifying gender, weight, height, and age, all of which effectively decrease the pool of potential criminal suspects. Previous studies proved the importance of forensic information when it comes to the foot.

Krishan derived linear equations for estimating stature from foot measurements. He measured foot dimensions (foot length, foot breadth) of 246 Indians and reported the standard error of estimates (SEE). In his study, foot length is the predictor that shows the highest accuracy among the variables hand length, handbreadth, foot length, and foot breadth. Zeybek estimated 249 individuals’ foot lengths, foot breadths, malleolus height, and navicular heights. He estimated genders and heights by the use of each part of the foot data. In his research, the most valuable data to relate one’s height was the length of foot, and the correlation coefficients were male 0.741, female, 0.678. Moorthy collected 1020 Egyptians’ footprints, then created an estimation regression equation by measuring the lengths between the heel and each toe tip. Hisham measured the lengths and breadths of the feet of 213 Malaysians, and then created an estimation regression equation with the data. In her study, the regression equation involving the length of the foot provided the highest R² for females, the length of the foot provided an R² of 0.572. In other research conducted by Hemy, she reported a regression model using data on the feet of West Australians: foot length, foot breadth, and foot heel. In her research also showed that the length of foot played a key role in estimating heights. However, due to the multi-racial representative population sample, R² rates were less than for other similar research. Kanchan used various foot dimensions of Indians for deriving estimation regression models. He collected footprints of 100 Indians, then defined foot benchmarks such as the length from the heel point to each toe tip. By using these lengths an R² of 0.637 was produced. In his research, the R² was higher in the male population than in the female population. Pablos used a robust regression method in order to estimate stature. He analysed 564 foot bones from 94 individuals. Using the length of the talus and metatarsal, his study yielded an R² of 0.952. However, the accuracy was quite different depending on ancestry. Ozaslan derived stature estimation regression models for 356 Turkish people. In her study, foot length showed the highest R² among the variables hand length, handbreadth, wrist breadth, foot length, foot breadth, and ankle breadth – and the lowest SEE. In this way, the previous studies showed that the regression equations that use foot length and breadth are reliable for estimating a suspect’s stature. However, if the foot or its footprints are damaged at the scene, there the circumstances may be that we are unable to estimate stature by using foot length and foot breadth. In this case, regression equations from various other dimensions of the foot can provide a solution because the foot consists of numerous bones and joints. Hence there is other useful information with which to estimate stature and body profile.

There were some studies that measured Korean foot dimensions and reported characteristics of Korean feet. Fernandez measured 7000 Korean female workers’ foot dimensions (foot length and breadth). He compared these dimensions with other Asian nationalities’ foot dimensions. Jung classified elderly Koreans’ foot types. He measured 252 elderly Koreans’ feet and identified 3 foot types (slender, standard and broad) by using a foot index (the ratio of foot width to foot length). Seong also studied Korean foot shape types. He identified 7 principal factors that determine foot shapes.
such as foot breadth, thickness of the ankle bone, shape of the big toe, height of the ankle, distance from heel to instep navicular, ratio of upper and lower part, and shapes of the little toe\textsuperscript{19}. However, there were few studies that focused on the applicability of Korean foot dimensions in forensic science.

Therefore, in this study, it will be useful for profiling stature and body condition from measurement data from certain foot dimensions such as heel, metatarsal edge, instep, metatarsal, and lateral malleolus. Thus, in addition to foot length and breadth measurement data, which are frequently featured in previous studies, this research provides a valuable regression model based on specific data such as dimensions pertaining to the instep, metatarsal, and lateral malleolus. Besides, there has been little practical research done using Koreans’ foot measurements suitable for practical application to meet medicolegal standards. Previous research reported that stature estimation equations derived from one race or group of races have lower accuracy when applied to other ethnic groups\textsuperscript{20}, and most of the stature estimation formulas were derived in West Asia and Africa. Thus, it is an urgent work to develop stature estimation equations for Korean and other ethnic groups that have similar characteristics. For these reasons, the authors expect to this research to provide, not only for use in forensic medicine, a body of information for use by the fashion industry and by medical appliance and sports equipment manufacturers.

2. Method

2.1. Subjects

This research used the results of a 3D features measurement project (Size Korea Project) of the Korea Technology Standards Institute. In this project, 461 participants who had no known foot or backbone defects participated in the foot scanning (175 male, 286 females). The average age of the males was 41.6 (minimum: 20, maximum: 69) and 38.4 for females (minimum: 20, maximum: 68). Equal rate of each age group were selected, and the maturity of participants’ feet were examined to ensure that there was to be no more growth.

This research has been approved by the research ethics committee of the Seoul National University. All subjects were informed and provided written consent.

2.2. Measurement

In the study, based on the prior research and ISO 7250 standard\textsuperscript{10,21} features of foot dimensions were finally selected, as in Table 1 and Figure 1. In addition, a 3D scanner (Enfoot, K&I technology, South Korea) was used for faster and clearer determinations (Figure 2). This scanner automatically extracted data characterising the features in about 18 s by using a CCD camera and laser. This scanner and analysis programme can identify the position of a selected point on a surface and measure the distance between selected points. The accuracy of this scanner was 1 mm, and to subjects markers were attached at the 1st, 5th metatarsal head, navicular height, and at a prominent point on the malleolus. Participants then were asked to step up into the scanner with their right foot being placed outside of the scanner and the left foot inside, as parallel as possible. They were also asked to stand up straight and with the toes facing forward with a natural stance. For heights, participants were asked to place their heels together, to open their feet to an angle of almost 30 degrees and to maintain their stand in such a way
that the Frankfurt plane would be parallel to the paddleboard of the measuring apparatus.

Measurements were performed by one data collector to avoid multi-observer variations. Foot measurements were taken from 20 subjects twice at different times and the measurement error was evaluated. Intra-observer error was measured by calculating the relative technical error of the measurement (rTEM) and the coefficient of reliability (rTEM < 5%, R > 0.95). Observer error was considered to be precise for all measurements.

### 2.3. Statistical analysis

Data of 461 participants’ foot dimensions were performed by using a statistical package of SPSS21, then the averages and deviations of each dimension were provided. The t-test was applied to compare gender differences in each dimension. Moreover, Pearson’s correlation coefficients were computed to identify correlations of various foot measurements with height. Multivariate regressions were performed using the data for the various measurements. And for comparing prediction accuracy among prediction models, the coefficient of determination (R²) and standard error of estimate (SEE) were used. Additionally, a stepwise method that drew a regression equation by combining various variables was used.
3. Results

3.1. Descriptive statistics

Descriptive statistics (mean, SD) were calculated, and the results of t-test (difference in the measurements of each foot part between males and females) are shown in Table 2. Statistically, some of the foot measurements from males were relatively bigger than the corresponding measurements for females (p value < 0.001). Thus, in order to get more accuracy, a regression model needs to be derived for each gender. For men, the circumference at instep (IC) was the maximum measurement with the dimension of 25.5 cm, while the height at the ball (BH) was measured at 3.7 cm as the minimum. For women, the maximum and minimum measurements were the circumference at ball (BC) at 23.3 cm and the height at the ball (BH) at 3.3 cm. The most different variables between male and female was circumference at instep (IC). The men’s average was 25.5 cm, and the women’s average was 22.9 cm. The t value was 23.5. On the other hand, height at the lateral malleolus (MAH) variable shows a small difference (0.5 cm) between male and female, and its t value was 10.1, which showed the least differences in foot dimensions.

3.2. Correlation analysis

Correlation between subjects’ height and measurement values were analysed by comparing the Pearson correlation coefficient (Table 3). Among all of the variables, foot length (FL) showed the highest relationship in males (r = 0.753) and females (r = 0.433). On the other hand, height at the instep (IH) was less relevant to height. Males’ length variables such as FL, PGL, PMTL and PMFL indicated more than 0.6 in the correlation coefficient, and female was more than 0.3. Considering all parts of the foot, males’ correlation coefficient are all in excess of the females’ coefficients. But for the height at the ball (BH) and

Figure 1. Various foot landmarks in human foot.
Figure 2. Foot scanner used for measurement.

Table 2. Descriptive statistics for foot measurement (cm) in Korean male and female.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Male (n = 175)</th>
<th>Female (n = 286)</th>
<th>T-test (T)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Stature</td>
<td>169.7</td>
<td>6.6</td>
<td>159.7</td>
<td>5.3</td>
</tr>
<tr>
<td>FL</td>
<td>25.2</td>
<td>1.2</td>
<td>23.1</td>
<td>1.0</td>
</tr>
<tr>
<td>PGL</td>
<td>25.1</td>
<td>1.2</td>
<td>23.1</td>
<td>1.0</td>
</tr>
<tr>
<td>PMTL</td>
<td>18.4</td>
<td>0.9</td>
<td>17.0</td>
<td>0.8</td>
</tr>
<tr>
<td>PMFL</td>
<td>15.9</td>
<td>0.9</td>
<td>14.8</td>
<td>0.8</td>
</tr>
<tr>
<td>FB</td>
<td>9.9</td>
<td>0.5</td>
<td>9.2</td>
<td>0.5</td>
</tr>
<tr>
<td>DFB</td>
<td>10.2</td>
<td>0.5</td>
<td>9.5</td>
<td>0.5</td>
</tr>
<tr>
<td>BH</td>
<td>3.7</td>
<td>0.3</td>
<td>3.3</td>
<td>0.3</td>
</tr>
<tr>
<td>IH</td>
<td>6.1</td>
<td>0.5</td>
<td>5.2</td>
<td>0.6</td>
</tr>
<tr>
<td>MAH</td>
<td>7.2</td>
<td>0.5</td>
<td>6.7</td>
<td>0.6</td>
</tr>
<tr>
<td>BC</td>
<td>25.4</td>
<td>1.2</td>
<td>23.3</td>
<td>1.0</td>
</tr>
<tr>
<td>IC</td>
<td>25.5</td>
<td>1.2</td>
<td>22.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

***p < 0.001 is significant.
height at the instep (IH), the correlations were statistically significant for all foot part dimensions \((p < 0.01)\). Furthermore, only females’ instep heights (IH) suggested a negative correlation coefficient, yet it was not statistically significant. For relative variables of length, among FL, PGL, PMTL and PMFL, the correlation coefficient of foot length (FL) was the highest. For breadth-related variables, between foot breadth (FB) and diagonal
breadth at the metatarsal (DFB), FB was at the highest. And for height-related variables among height at the ball (BH), height at the instep (IH), and height at the lateral malleolus (MAH), MAH had the highest correlation.

3.3. Regression analysis
Tables 4 and 5 show correlation coefficients for foot length, for men and women. For men, prediction accuracy was the highest when the regression equation involved foot length ($R^2 = 0.567$), and the SEE ($\pm 4.332$ cm) was the lowest. However, the height at the instep (IH) had the lowest prediction accuracy. Length-related variables FL, PGL, PMTL, and PMFL all indicated $R^2 > 0.4$, and SEE between 4.3~4.9 cm. Nevertheless, the height-related variables of BH and IH’s $R^2$ was less than 0.014, and also SEE was $\pm 6.5$ cm which indicate comparatively poor predictability. For women, foot length (FL) had the highest prediction accuracy and the lowest SEE ($R^2 = 0.188$, SEE = $\pm 4.825$ cm).

For length-related variables FL, PGL, PMTL, PMFL the $R^2$'s were over 0.108 and SEE was between 4.8~5.0 cm. Height at the instep (IH) had the lowest correlation coefficient and $R^2$ was also the lowest, 0.003. In this study, by the stepwise method, multiple regression was performed using various combinations of variables (Table 6). When multiple regression was practiced for both males and females by the use of foot length (FL) and height at the lateral malleolus (MAH), the R-squared value for the regression model was 0.600 and SEE indicated $\pm 4.802$ cm. For men, by FL and MAH, the R-squared improved to 0.608, and SEE was $\pm 4.110$ cm. In this research, this was the highest R-squared and the lowest SEE. For females, by using FL and PMTL, R-squared became 0.186, and SEE was $\pm 4.822$ cm.

3.4. Bland-Altman plot
A Bland-Altman plot was constructed to assess whether the actual stature and the estimated stature are consistent. For men and with the multiple regression of Figure 3 B, the 95% CI was reduced more than with the single regression model using just FL of Figure 3 A. However, in women the 95% CI was almost the same (Figure 3 C-D). When predicting the stature with FL or with the multiple regression model in males, there was no tendency with respect to stature in the difference between the actual stature and the estimated value. However, in females there was a tendency for the difference to be greater among the subjects of higher stature.

4. Discussion
The purpose of this research is to develop a trustworthy estimation model by using measurements of various foot parts. Standard deviations and average were calculated from

<table>
<thead>
<tr>
<th>Case</th>
<th>Regression (stepwise) equation</th>
<th>$R$ square</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pooled</td>
<td>$S = 69.9 + 3.582(FL) + 1.961(MAH)$</td>
<td>0.600</td>
<td>4.802</td>
</tr>
<tr>
<td>Male</td>
<td>$S = 60.5 + 3.526(FL) + 2.5825(MAH)$</td>
<td>0.608</td>
<td>4.110</td>
</tr>
<tr>
<td>Female</td>
<td>$S = 105.5 + 1.790(FL) + 0.750(PMTL)$</td>
<td>0.186</td>
<td>4.822</td>
</tr>
</tbody>
</table>
Figure 3. Bland-Altman plots show stature estimation using multiple regression model (B) has better reliability than single regression model (A) using FL, however, the regression model (C, D) showed almost same reliability.
measurements of participants’ feet. In addition, the study calculated the differences between men and women, which determined that the circumference at the instep (IC) and the circumference at ball (BC) were the most different foot dimensions. These results seemed similar to the results of Lee’s research that studied the feet of Taiwanese men and women. However, the variables most different between the genders (IC, BC) showed weak prediction accuracy and correlation coefficients with stature.

Among various foot parts, the present research results match those of prior researchers who found that FL is strongly related to heights. In Zeybek’s research with 249 Turkish subjects, FL for men produced $r = 0.749$; for women, $r = 0.678$. That research also revealed a strong co-relationship of the length with the foot breadth, malleolus height, and navicular height. Hemy’s research of course showed that FL’s relationship with height had higher correlation compared to FB and foot heel breadth. Additionally, the correlation coefficient for FL was higher than coefficient for the measurements between the foot heel and the toe tips. Therefore, based on the outcome of prior research and this study, FL is the most accurate foot dimension among other trial foot dimensions.

In this research, using various foot-part measurements, a regression model was derived for estimating heights, with allowances for gender. The regression model using only FL was shown to be the most reliable predictor. For men the R-squared was 0.567; for women, 0.188 (Figure 4). With these measurements it was possible to draw comparisons with other regression models of the prior studies that were created for other nationalities, also involving only the FL. The regression model for men in this study showed an R-squared of 0.567 and a SEE of ±4.332 cm. The $R^2$ of the regression

![Figure 4. Scatter graph and trend line showing the relation between foot length (FL) and stature in Korean population.](image-url)
model with the FL alone for Korean females was 0.185. This was lower than the same statistic of the same model applied to Malaysians (0.572), West Australians (0.544), Turkish subjects (0.549), and Indians (0.197).

In this research, there was a gap of prediction accuracy with the regression equation for foot length alone, with regard to gender differences. The $R^2$ for men was 0.567, which is higher than for almost any other ethnic group; female’s $R^2$ for women was 0.185, which was lower than that for any other ethnic group. These results showed, as compared to prior research (Table 7), that for Korean males foot length prediction accuracy was higher than that for Indian, Turkish, West Australian, and Egyptian subjects. However, for Korean females the accuracy was less than that for Indian, Turkish, West Australian, and Egyptian subjects. There could be several reasons for this. First, the Korean research participants differed by age more than did the subjects in the foreign groups. Additionally, because many younger Korean females have had the tendency to put on high heels and pointed shoes, which may cause variation of features of the foot, the foot measurements could be relatively smaller. That may affect prediction accuracy.

For estimating height based on the foot, it was better to use length-related variables such as FL, PGL, PMTL, PMFL rather than variables of breadth and height. This result was similar to the findings of Zeybek’s research with Turkish subjects in which foot length (FL) was the most effective variable with which to create a prediction model. Furthermore, the research on West Australians also showed that a regression model based solely on foot length had better predictability than one based on breadth. With regard to variables of breadth alone, foot breadth (FB) had higher accuracy than diagonal breadth at the metatarsal (DFB). And in for height-related variables, height at the lateral malleolus (MAH) showed the highest accuracy. Variables of circumference, for which all of the $R^2$’s were between 0.041 and 0.104, had lower prediction accuracy so that using circumference in stature estimation cannot be recommended. Overall, when various foot dimensions were used for estimating height, the use of FL, PGL, PMTL, and PMFL will provide higher accuracy than variables of circumference and height.

This research focused on only the Korean population. Thus, the accuracy of these formulas will be maintained only when applied for to Korean or similar ethnic groups that have similar physical characteristics. Although all of the subjects were asked to stand while maintaining balance on both feet, the imbalance may affect measurement. These can be considered to be some limitations on the accuracy of this research.

Table 7. Comparison between mean of stature, foot length, $R^2$ and S.E.E from previous studies.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Country</th>
<th>Stature</th>
<th>Foot length</th>
<th>$R^2$</th>
<th>S.E.E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td>This</td>
<td>2015</td>
<td>South Korea</td>
<td>169.7</td>
<td>159.7</td>
<td>25.2</td>
<td>23.1</td>
</tr>
<tr>
<td>Zeybak</td>
<td>2008</td>
<td>Turkey</td>
<td>174.1</td>
<td>161.6</td>
<td>25.6</td>
<td>23.0</td>
</tr>
<tr>
<td>Fawzy</td>
<td>2010</td>
<td>Egypt</td>
<td>–</td>
<td>–</td>
<td>24.8</td>
<td>–</td>
</tr>
<tr>
<td>Hisham</td>
<td>2012</td>
<td>Malaysia</td>
<td>166.0</td>
<td>156.7</td>
<td>22.2</td>
<td>21.2</td>
</tr>
<tr>
<td>Kanchan</td>
<td>2012</td>
<td>India</td>
<td>174.6</td>
<td>156.9</td>
<td>24.1</td>
<td>22.1</td>
</tr>
<tr>
<td>Hemy</td>
<td>2013</td>
<td>West Australia</td>
<td>178.4</td>
<td>163.6</td>
<td>27.3</td>
<td>24.5</td>
</tr>
</tbody>
</table>
5. Conclusion

This study, like prior studies, included specific measurements of foot length and breadth, diagonal foot breadth, instep, circumference, and metatarsal heights – distance from one point on a foot to another. Foot length (FL) was the most accurate single variable with which to estimate stature, and the regression equation with FL alone showed the highest predictability. Also this study determined prediction accuracy for estimating height using multivariate regressions involving various foot measurements. Especially, this study can provide a regression equations based on the distance from the pternion to the first metatarsal tibiale (PMTL) and the distance from the pternion to fifth metatarsal bulare (PMFL) – to put to good use when it comes to footprint analysis. Furthermore, all of these data can be useful for forensic science, and for the designs of costumes and sportswear. More importantly, this study may find medicolegal use with Koreans and with others who have similar body features.

Disclosure statement

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