Abstract

In forensic intelligence-gathering it would be useful to be able to estimate the size of a perpetrator's foot from a standing bare footprint found at the scene of crime. Currently, the advice is to add a fixed amount to the length of the footprint (typically 1.5 or 2.0 cm), but there is little evidence for this approach. This study used measured footprint and actual foot lengths from 146 participants from the white British student population of a University in the UK. Data were analysed using multiple regression with foot length as the dependent (outcome) variable and footprint length and sex as the independent variable/factor respectively. Sex was not a significant predictor. The regression equation for the best estimate of the foot length is 19.89+0.95 x print length ± 8mm.

Keywords

Footprint, size, estimate, static, inked, length.

Highlights

There was a strong linear relationship between print length and foot length.

The equation 19.89+0.95 x print length ± 8mm can be used to estimate actual foot size.

The same equation is valid for both sexes.

Foot length can be predicted to within 8mm (95% prediction interval).

Formatting of funding sources

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Novelty statement.

In forensic casework if a static bare footprint is found on a firm surface at a crime scene but there is no suspect then this footprint would be shorter than and not as wide as the actual foot responsible for that bare footprint. Later, if a potential suspect is found then, typically 1.5 or 2 cm is added to overall bare inked footprint length to suggest overall foot length. This study suggests this arbitrary 1.5 to 2 cm can be replaced using a simple equation derived from multiple regression to obtain a best estimate of foot length from a static inked two-dimensional bare footprint.

1) Introduction

The term “bare footprints” refers to the marks made by the plantar surface of an unshod foot on a hard surface – a two-dimensional representation of a three-dimensional foot [1]. According to Di Maggio and Vernon [2] and Reel et al. [3] bare footprints can be static or dynamic where static prints are associated with standing and dynamic prints with walking or running. Vernon et al. [4] report that experience has shown that the dynamic form of bare footprints typically presents with two features not usually seen in static prints; namely inner dark and outer ghosting areas at the posterior (heel) and various anterior (toe) areas. A footprint successfully recovered from a scene of crime is known as the ‘questioned’ print and an inked footprint taken from an individual linked with the incident is referred to as the ‘known print’ and has been used in the literature as a comparison with the ‘questioned print’ The questioned print could also be compared with the actual foot length of a suspect [5]. According to Di Maggio and Vernon [2] in forensic casework if a static bare footprint is found on a firm surface at a crime scene but there is no suspect, then this footprint would be shorter than and not as wide as the actual foot responsible for that bare footprint. Later, if a potential suspect is found then, typically 1.5 or 2 cm is added to overall bare inked footprint length to estimate overall foot length. In the absence of ridge patterns like those found in fingerprints [6] [7] [8] there has been increasing interest in the potential of bare footprints as an aid to identification. Bodziak [9] found that there are three types of footprints that can be found at the scene of a crime: (1) the impression left in an insole of a shoe, (2) a true bare footprint, and (3) a socked footprint. Bare footprint comparisons have been widely accepted as a method that can assist with the process of identification [2]. According to Barker and Scheuer [10], in the western world, there is a role for the bare footprint in forensic investigations. Di Maggio and Vernon [2] report that two-dimensional bare footprints are recovered more often at scenes of sexual offences or homicide, and are more prevalent at crime scenes in countries of a warmer climate and forensically aware offenders, who believe they know the system well, may remove their footwear prior to committing a crime because they believe that this would protect them from being caught. In areas such as India such considerations can have greater relevance because of the high proportion of the population who walk barefoot for a variety of socioeconomic, religious, or climatic reasons [11]. Kennedy et al. [12] considered the uniqueness of bare footprints as an aid to identification in a study which, at the time of publication, had utilized 24,000 footprints collected from 12,000 volunteers under standardised conditions. Although he concluded that footprints were individual, Di Maggio and Vernon (2) argue that these standardised conditions do not reflect real-world situations such as interpopulation differences and it may be that the prints are individual in form but may not be unique. Kanchen et al. [11] considered the individuality of footprints in a Gujjar population in North India, particularly considering shape, alignment, creases, size, cuts, cracks, and pits to determine whether these characteristics were individual. The study involved 1040 adult males between 18 and 30 years of age. Bilateral prints n=2080 were taken. Each print was taken using ink that was applied to the plantar surface of the foot after which the participant would step onto white plain paper and then repeat with the opposite foot. The footprints were shown to be highly individual and showed a link with personal identity. Moorthy and Sulaiman [13] conducted a study involving 200 males and 200 females Malaysian participants between 18 and 60 years of age. Eight hundred bilateral prints were collected in total. The results of this study concluded that each footprint

had individual characteristics, therefore supporting the results found by both Kanchen et al. [11] and Kennedy et al. [12]
Bodziak [9] reports that a difference exists between a footprint and actual foot length but does not suggest a method for converting one to another and no literature has been found which systematically addresses this. Di Maggio and Vernon [2], report that multiple methods have been used as a way of measuring bare footprints to aid the identification process. These measurements include the Gunn method, the Optical Centre Method, the Overlay method, and the Reel method. Reel et.al [3] concluded that the Reel method was most reliable for obtaining bare footprints. To test the reliability of her technique, Reel et al. [3] measured three dynamic and three static right barefoot impressions of 61 participants. One length measurement (base of the heel to the apex of the hallux) was used for reliability analysis. To account for the confounding influence of participant sex or the type of foot impression (static or dynamic) on the reliability coefficient, length measurements (base of heel to apex of hallux) were split into sub-groups based on sex and type of foot impressions. The authors found that the length measurement had high test–retest reliability across all groups.

This study aimed to investigate whether a statistical model could be used to predict actual foot length from a static bare footprint in order aid forensic identification of a suspect.

2) Materials and method

An opportunistic sample of 146 participants was recruited from the student population of a University in the UK. Ethical approval for the study was obtained from the Faculty Ethics Committee at the study University. Participants were fully informed of the study by two of the authors and each participant gave their consent to participate in the study. The inclusion and exclusion criteria were that participants were aged over 18, were of White British ethnicity and were able to balance unaided with no self-reported history of falls.

2.1) Method used for obtaining a standing static footprint.

Following the protocol described by Reel et al. [1] an inkless pad was placed on the floor. Participants placed their foot onto the inkless pad in their natural stance position and held it for three seconds. They then transferred their foot onto the treated paper next to the inkless mat in their natural stance, thus creating a two-dimensional static bare footprint. In addition to the Reel protocol the foot was wiped beforehand with antiseptic wipes to prevent cross infection, though Reel et.al [1] reported there have been no known allergies or cross infection associated with this. The process is represented in Figure 1.

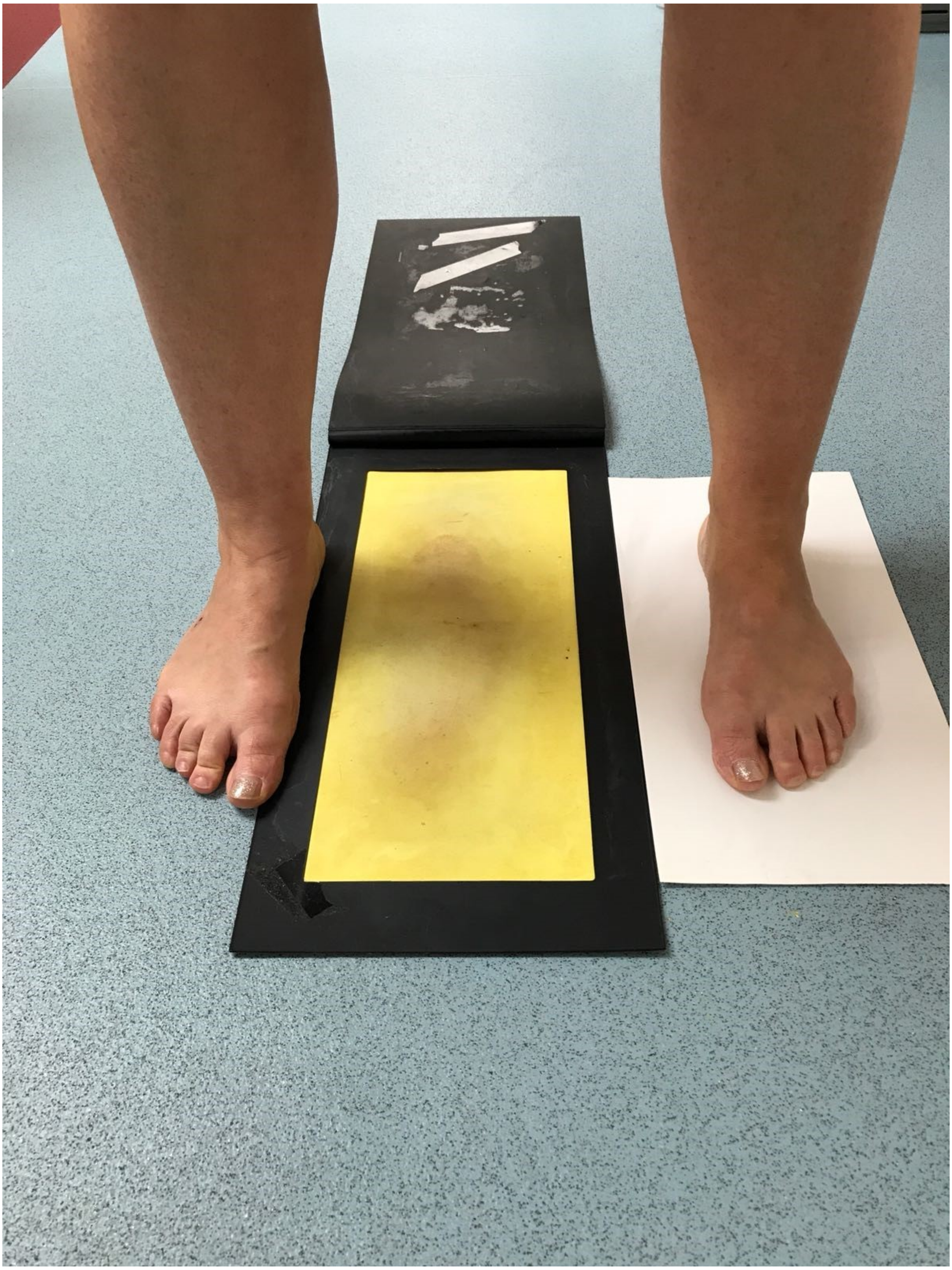

Figure 1 Obtaining a standing static footprint.

2.2) Measurement of actual foot length

The collection of each participant's foot length was obtained from the use of a Ward's® Osteometric board as shown in Figure 2. This technique was used by Howsam and Bridgen [14] to collect foot length for their study on jumping bare footprints. The board was placed on a hard-flat surface and each participant stood with equal weight on both feet and with the right bare foot placed onto the Ward's® Osteometric board. The pternion (the most posterior part of the heel when a person is standing erect.) was placed against the upright edge of the Osteometric board that represents zero on the ruler. The medial aspect of the calcaneus and forefoot were placed parallel to the inner edge of the Ward's® Osteometric board. The toes were then pressed into the device and the gliding measurement panel was retracted back until contacting the most distal part of the foot. Looking vertically above the gliding panel, at the point it meets the ruler aspect on the Ward's® Osteometric board, a measurement in millimetres was obtained and noted onto the paper of the corresponding print.

Figure 2 Obtaining a measurement of foot length using an Osteometric board.

2.3) Footprint Analysis: Scanning GIMP and Reel Method

Following the guidelines set out by Reel [1], Each static bare footprint was scanned at 150 dots per inch and saved as a JPEG file. Each footprint was analysed using GNU Image Manipulation Program(GIMP) 2.8 software.
The central axis of the footprint was found and then the print was rotated until the central axis was vertical. A line was then drawn skimming the lowest heel pixel and crossing the central axis. The highest pixel of the most distal aspect of the foot, regardless to whether it represented the first or second toe as was marked. A line was then drawn from the central aspect of the calcaneus to the most distal part of the foot that had been marked and thus giving a measurement of longest possible footprint length. This measurement was recorded on a Microsoft Excel spreadsheet, together with demographic data and the corresponding foot length measurement.

3) Results

3.1 Sample characteristics

The sample consisted of 146 participants and had equal numbers of male and female participants.

The distribution and age and foot length distributions are shown in Table 1

	Male (n=73)	**Female (n=73)**	**All (n=146)**
Age (years) median (IQR)	34 (18)	51 (21)	41 (25)
Foot length (mm) Median (IQR)	268 (20)	241 (12)	253 (28)

Table 1: Distribution of sample age and foot length (median and inter-quartile range (IQR)

3.2 Regression analysis

Data were analysed using multiple regression (forced entry) with foot length as the dependent (outcome) variable and footprint length and sex as the independent variable/factor respectively using IBM SPSS Statistic software (Version 22).

There was a strong linear relationship between print length and foot length (see Figure 3), justifying the assumption of linearity for the regression analysis. There were no outliers. The correlation coefficient, r was 0.973 (r^2= 0.946) so 95% of variance in foot length could be explained by footprint length.

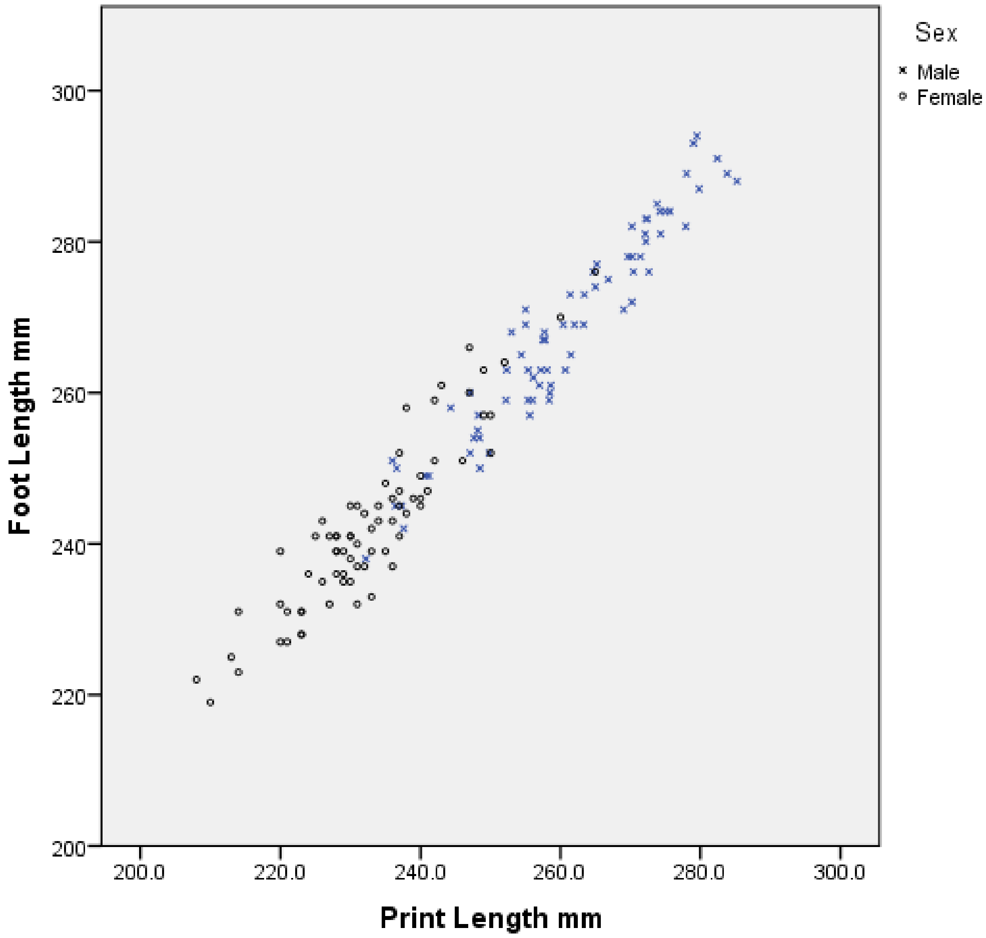

Figure 3: Linear relationship between observed footprint length and foot length

Two regression models were constructed: the first using only footprint length as the predictor variable, and the second adding sex as a factor.

Adding sex to the regression model only increased the model R^2 by 0.001 and did not make a significant improvement to the model with only print length and constant (F_{change}=1.937, p=0.166). The model summaries for both models are shown in Table
.

Model		Unstandardized Coefficients		t	Sig.	95.0% Confidence Interval for B	
		B	Std. Error			Lower Bound	Upper Bound
1	(Constant)	19.888	4.684	4.246	.000	10.630	29.146
	Print Length	.954	.019	50.382	.000	.917	.992
2	(Constant)	10.076	8.455	1.192	.235	-6.637	26.790
	Print Length	.985	.029	33.874	.000	.928	1.043
	Sex	1.480	1.063	1.392	.166	-.622	3.582

Table 2: Model summaries for regression analyses

Post-analysis testing for assumptions found that 7 cases (4.8%) had standardised residuals in excess of ±1.96 and 1 case (0.7%) had a standardised residual in excess of ±2.56 which are in agreement with the expected percentages of 5% and 1% respectively. The residuals were normally distributed (K-S statistic= 0.046, p=0.200). The maximum value of Cook's distance was 0.044 which indicates that no points exerted undue influence over the model. A plot of residuals v predicted values showed that the variance of the residuals did not vary with the magnitude of the predicted value (no heteroscedasticity). All assumptions of regression modelling were therefore justified.

The regression equation for the best estimate of the foot length is 19.89 + 0.95 x print length (in mm). The 95% prediction interval (PI) for an individual foot length based on a footprint measurement gives a range of foot lengths within which 95% of the estimated individual foot lengths calculated by the regression equation from a given measured footprint length will fall. This interval will be larger than that calculated for the mean of all possible predicted foot lengths for a given footprint length as not only is there uncertainty in the parameters of the regression equation but also additional uncertainty due to random scatter of the individual predicted lengths about the regression line. The prediction intervals are narrowest around the mean of the predictor variable and widest at the extremes.

The range of the footprint lengths used in the regression modelling was 208 to 285mm, with a mean of 246.6mm. The corresponding range of predicted foot length values, with their 95% PIs was 218.4 ±8.4mm to 292.1±8.4mm for the extremes and 255.3±8.3mm for the mean. In practice, it would be difficult to measure either footprint length or foot length to an accuracy of more than 1mm, so the 95% PI can be estimated at 8mm throughout the expected foot size range.

As an example, if the print length were measured as 228mm, then the best estimate of foot length = 19.89+(0.95 x 228) = 236mm (to the nearest mm). There is a 95% chance that the (unknown) foot length is between 228mm and 244 mm (236±8mm).

This can also be estimated from the graph shown in Figure 4 by drawing a vertical line upwards from the measured footprint length (x axis). The value on the y axis where that line meets the centre regression line gives the estimated foot length; the y values where it crosses the two outer lines give the upper and lower 95% PI.

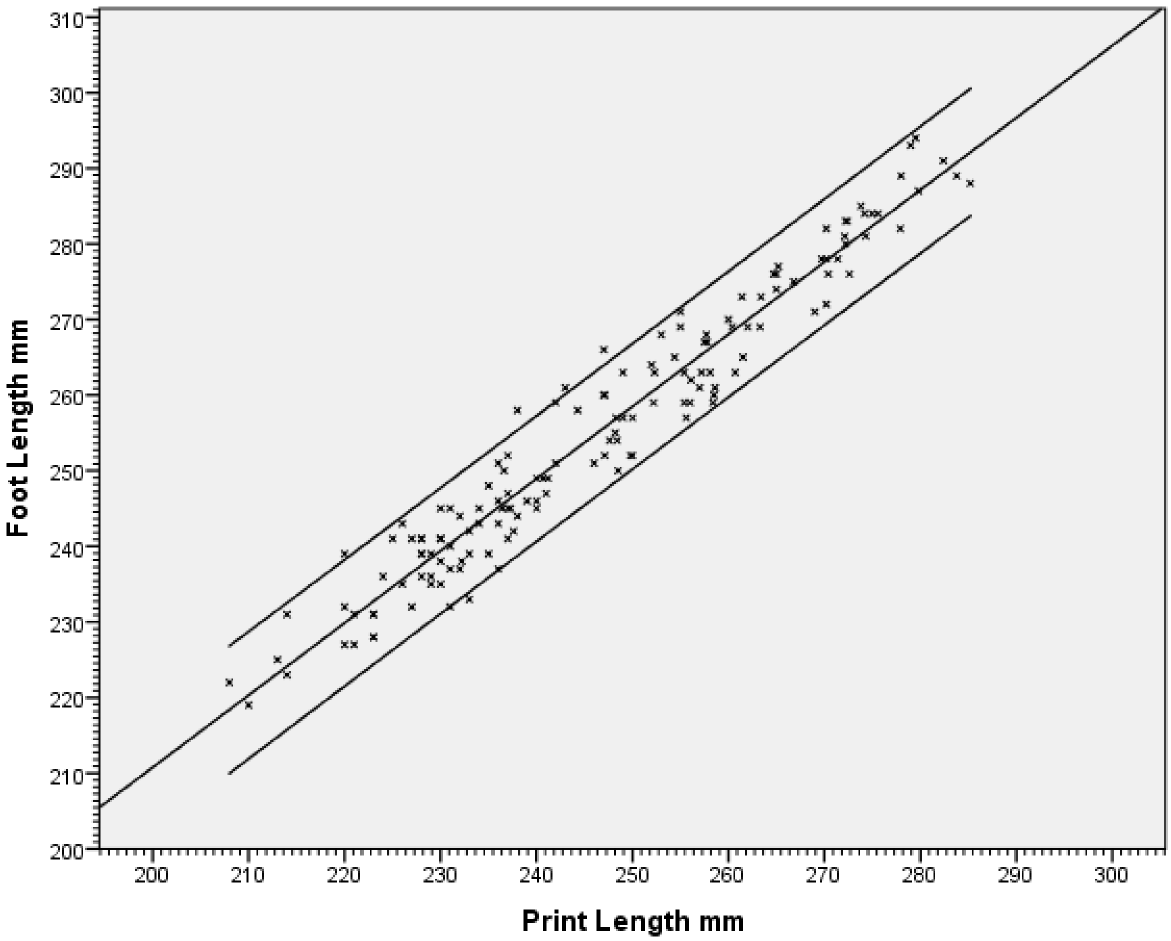

Figure 4: Regression estimates (centre line) and 95% prediction intervals (outer lines) of foot length from measured footprint length. Measured values used in the modelling are shown as crosses.

4) Discussion

When a bare footprint has been recovered from a crime scene, a forensic footprint examiner could be asked to investigate whether that bare footprint could be associated with a perpetrator of a crime. The footprint could be static or dynamic [2] [3] and Vernon [4] reports that experience has shown that the dynamic form of bare footprints typically presents with two features not usually seen in static prints; namely inner dark and outer ghosting areas at the posterior (heel) and various anterior (toe) areas. According to Di Maggio and Vernon [2] the Questioned print could be compared to the known print of a suspect or to their actual foot length.

The findings from this study, which focussed on static inked bare footprints, suggest that actual foot length can be related to static inked print length using a regression equation for the best estimate of the foot length. This is 19.89 + 0.95 x print length (in mm) with a 95% prediction interval of ±8mm. The use of this regression equation could lead to an estimate of the perpetrator's actual foot size from the static bare footprint, adding to the intelligence-gathering for association with a crime scene. This may be a much more accurate approach than adding a single, ad hoc length to static footprints that may vary considerably in their actual size. This regression equation was derived from a single sample of 146 white British adults. A larger sample would result in narrower prediction intervals and therefore improve the precision of the estimated foot length. Validation studies are needed to confirm these findings using other samples from the same population and from populations with differing characteristics to ensure its generalisability.

The findings from this study relate only to static bare footprints. It may be interesting to predict actual foot length from dynamic bare footprints. Reel [1] found that the difference between a static and dynamic bare footprint, within a sample of 31 men, on average was 17.41mm.

The measurements for this study were taken on a firm hard surface it may also be interesting to explore the effects of static and dynamic prints on soft surfaces such as carpet.

5) Conclusion

The study investigated whether a statistical model could be used to predict actual foot length from a static inked bare footprint. This may be used as an aid to associate or disassociate a person from a crime when only a static bare footprint is found.

The findings from the study found that the regression equation and 95% prediction interval for the best estimate of the foot length is 19.89+0.95 x print length ±8mm.

Although the findings from this study are an improvement over the existing method of adding an ad hoc length to a static bare footprint to obtain actual foot length, validation of the model using larger studies with more diverse sample characteristics are required to allow more accurate predictions and to be generalisable to a wider population.

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