Available online at www.sciencedirect.com
ScienceDirect
Forensic Science International 175 (2008) 93–101
Forensic Science International
www.elsevier.com/locate/forsciint

Estimation of stature from footprint and foot outline dimensions in Gujjars of North India

Kewal Krishan *

Department of Anthropology, Panjab University, Chandigarh 160014, India

Received 7 September 2006; received in revised form 6 January 2007; accepted 17 May 2007
Available online 25 June 2007

Abstract

Estimation of individual's stature is an important parameter in forensic examinations. Examination of footprints provides important evidence in a crime scene investigation and helps in estimation of stature of a criminal. Analysis of bare footprints is often carried out in developing countries like India where the footprints are frequently recovered at the scene of crime. The present study attempts to reconstruct stature in a sample of 2080 bilateral footprints and foot outlines collected from 1040 adult male Gujjars of North India ranging in age from 18 to 30 years. Bilateral footprints and foot outlines of each individual were measured for ten and eight measurements, respectively. The results indicate that T-2 length (length of the footprint from heel to 2nd toe) and T-5 length in footprint and T-1 length, T-4 length and breadth at ball in foot outline show statistically significant bilateral asymmetry. Significant and positive correlation coefficients exist between stature and various measurements of footprint and foot outline ($P < 0.001$ and 0.01) except toe 1–5 angle of declination which shows insignificant correlation coefficient. The highest correlation coefficients were shown by the toe length measurements (0.82–0.87) indicating a close relationship between the stature and these measurements. Regression analysis presents smaller mean errors (2.12–3.92 cm) in estimation of stature than those of division factor method (3.29–4.66 cm), thus, gives better reliability of estimate than the latter. The regression equations were also checked for their accuracy by comparing the actual stature with estimated stature.

Keywords: Forensic science; Forensic anthropology; Personal identification; Stature estimation; Footprint; Foot outline; North Indian Gujjars

1. Introduction

Footprints are of immense value in establishing personal identity of the criminals in forensic examinations. They are found as a kind evidence at the crime site and link between the crime and the perpetrator. Although, footprints can be collected from almost all types of crime scenes but the possibility of their recovery at the scenes of sexual offences and homicides is relatively more. Examination of barefoot impressions is important especially in developing countries like India where majority of the rural population like to walk barefooted because of socio-economic and climatic reasons [1,2]. The partial or complete footprints can be found on rain covered surfaces, newly waxed floors, freshly cemented surfaces, moistened surfaces, in dust, mud, sand, oil, paint and can be left in blood at the murder scenes.

Analysis of footprints helps in estimation of an individual's stature because of existence of strong positive correlation between one's stature and foot size; the footprints are also considered as indicators of skeletal and body structure of a person. Gayer [3] was probably the first person to conduct a detailed study of footprints while working in the United Province of India and published his results in the form of a book. In the past, various other studies have been conducted on individualization [1,4–10] and estimation of stature from foot and footprints [11–21]. All these studies suggest different ways of utilization of footprints in forensic examinations. Earlier studies by Robbins [11,13], Barker and Scheuer [18], Topinard [22,23], Martin [24], Martin and Saller [25], Pales [26], Jasuja [27], provide a number of foot length/stature percentages for various populations ranging from 14.9 to 18.1. Some studies [13,27,28] have derived multiplication factors calculated by dividing stature by a foot/footprint measurement. However, these methods result in very high estimation error. Later on, various authors made use of regression equations [19,20,27–30] in estimating stature from foot/footprint dimensions.

* Tel.: +91 172 2534230/2541998.
E-mail address: gargkk@yahoo.com.

0379-0738/$ – see front matter © 2007 Elsevier Ireland Ltd. All rights reserved.
doi:10.1016/j.forsciint.2007.05.014

As most of these studies have been conducted on mixed populations throughout the world, no such study is available on an endogamous population. So, the present study attempts the estimation of stature from various dimensions of footprints and foot outlines in an endogamous group (in other words, genetically isolated population) of North India. The study includes every part of footprint and foot outline (rather than taking length and breadth only as in most of the studies), so that the study will be applicable not only to complete footprints but also to partial footprints in estimation of stature. The study further compares the reliability of stature estimation by division factor method and regression analysis.

2. Material and methods

2.1. Sample

The sample of the present study is based on 1040 adult male Gujjars inhabiting the Siwalik hills and adjoining plains in the Sub-Himalayan region near Chandigarh city in North India. The age of the sample ranges from 18 to 30 years with mean age 24.47 years. The Gujjars are an endogamous group strictly marrying within their own caste. As a part of Indian caste system, the Gujjars form a major caste group of North India. This population is sedentary and agriculturist having animal husbandry as a secondary occupation.

The data were collected from 16 villages namely Nada, Parachh, Kahne Ka Bara, Kraunde Wala, Jainti Majri, Gurha, Kasauli, Chhoti Naggal, Bari Naggal, Pallanpur, Gochar, Mirzapur, Tarapur, Majri, Sukho Majri and Prempura near Chandigarh city. All these villages are predominantly occupied by Gujjars along with a few other caste groups. The latitude and the longitude of the area are 76°40′–55′E and 30°47′–56′N, respectively. The climate of the region is hot in summers (minimum of 15 °C to maximum of 45 °C) and cold in winters (minimum of 2 °C to maximum of 21 °C).

2.2. Methods

2.2.1. Analysis of footprints and foot outlines

A total of 2080 footprints were obtained from left and right feet of 1040 male Gujjar subjects. As all the subjects were villagers and most of them are in the habit of walking bare feet, precautions were taken by asking the subject to clean the soles by washing with soap and water. After cleaning, cyclostyling ink was applied to the cleaned soles of the subjects who were asked to step on to white plain paper on flat surface and the left and right footprints were recorded one by one. Before the feet were lifted off the paper, following anatomical landmarks of the feet [12,24] were noted and marked on the paper (Fig. 1) close to the footprint by using a sharp pointed pencil:

(a) mid-rear heel point (pternion),
(b) medial metatarsal point (mt.m),
(c) lateral metatarsal point (mt.l),
(d) calcaneal concavity medial (cc.m), and
(e) calcaneal tubercle lateral (ctu.l).

With the subjects still standing on the paper, the foot outline was also drawn by a pointed lead pencil held vertically as close to the foot as possible and similar landmarks were marked on the foot outline as in case of footprints. Foot outline is defined as the line tracing around the outer margins of the fleshed foot (Fig. 2). The outline serves as a two-dimensional, intermediate foot form in going from the bare footprint to the shoe print. Tracing of the foot outline was one of the two features pertaining to the foot that received attention in the 1912 Geneva International agreement among physical anthropologists [31].

A total of ten measurements were taken on left and right footprints and eight measurements on left and right foot outlines. First of all, following Robbins [12], the designated longitudinal axis (DLA) and base line (BL) were drawn on the footprint and foot outline in an attempt to establish a definite axial

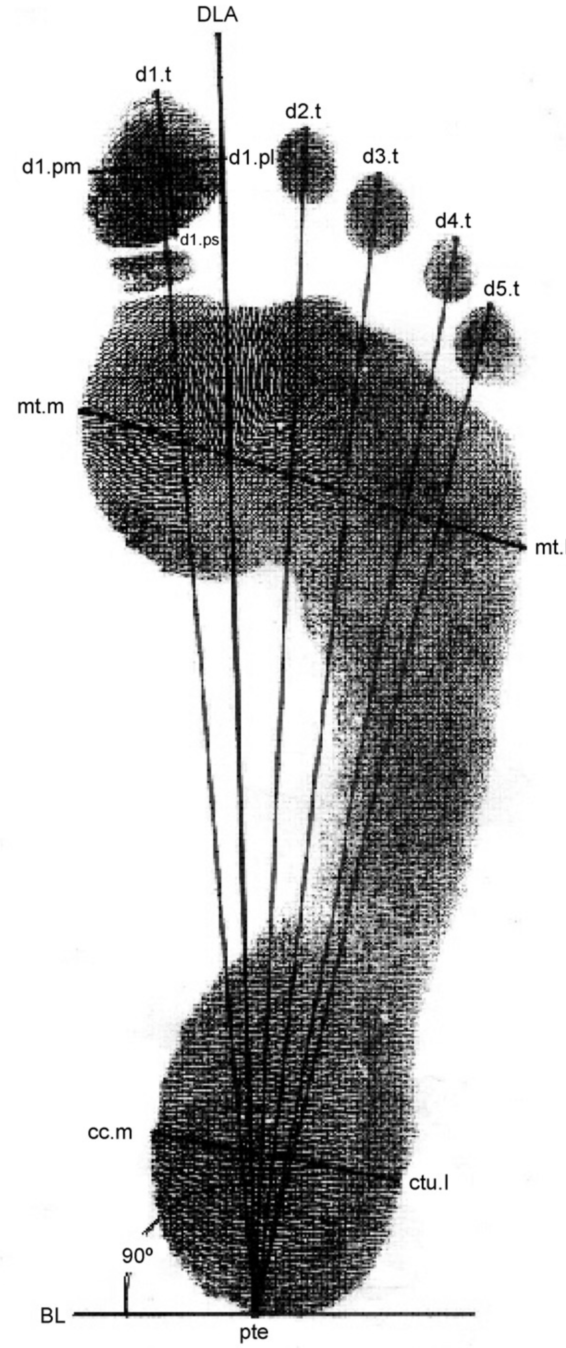

Fig. 1. Landmarks and measurements on footprint (modified after Robbins [12]).

orientation for length measurements. The DLA is from the pternion (pte.) landmark at the most posterior point of the rear heel margin to the lateral side of the toe 1 pad margin, the axial line touches the rim of the pad margin as it passes forward beyond the length of the foot. The DLA enables one to take foot length measurements from specific landmarks along the foot to the rear of the foot while keeping the line of measurement parallel to the DLA. Base line (BL) is drawn at the rear edge of the foot and perpendicular to the DLA. The BL extends from the landmark pternion at the rear of the heel in both the medial and lateral direction while maintaining its perpendicular alignment with the DLA. Its axis can be determined as marked on the footprint by using the protractor. With the 90° mark on the footprint placed on the DLA, and the midpoint of the protractor base at pternion, one automatically has the perpendicular BL by drawing a line through pternion along the base of the protractor.

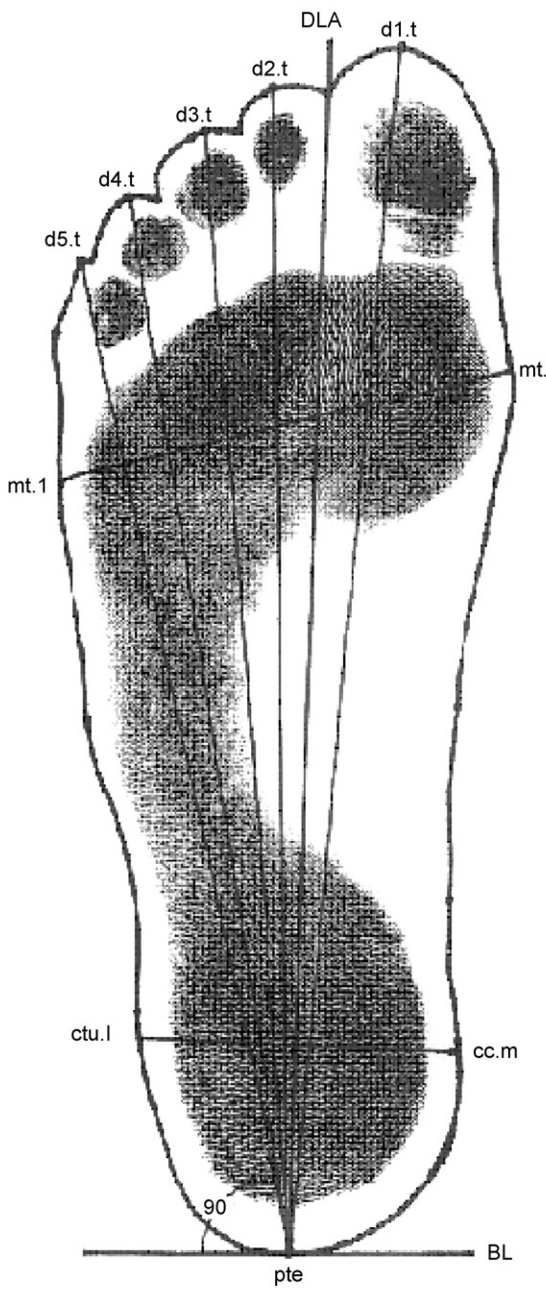

Fig. 2. Landmarks and measurements on foot outline [modified after Robbins [12]).

Following measurements were taken on footprints and foot outlines (Figs. 1 and 2):

- *Footprint/foot outline length measurements (T-1 length, T-2 length, T-3 length, T-4 length and T-5 length)*: These measurements were taken from the mid-rear heel point pternion (pte.) to the most anterior point of each toe, i.e. d1.t, d2.t, d3.t, d4.t and d5.t.
- *Footprint/foot outline breadth at ball*: Foot breadth was measured from metatarsal lateral (mt.l), the most lateral point on the metatarso-phalangeal joint of toe-5, and metatarsal medial (mt.m), the most medial point of the metatarso-phalangeal joint of toe-1.
- *Footprint/foot outline breadth at heel*: Foot breadth at heel was measured from calcaneal concavity medial (cc.m) to calcaneal tubercle lateral (ctu.l).
- *Big toe pad length of footprint*: This was measured from anterior terminal landmark (d1.t) to posterior terminal landmark (d1.ps) of the big toe.
- *Big toe pad breadth of the footprint*: This measures distance from d1.pm on medial side to d1.pl on lateral side on the big toe.
- *Toe 1–5 angle of declination in footprint/foot outline*: This is the angle of declination of toe-5 from the length of toe-1. This reveals the angulation that occurs between the medial and lateral sides of the toe region. Various other details of this angle are described in Robbins [12].

2.2.2. Technique involved in measuring stature

Stature of each subject was measured according to the standard procedures recommended by Weiner and Lourie [32] as follows:

The subject should stand on a horizontal platform with his heels together, stretching upward to the fullest extent, aided by gentle traction by the measurer on the mastoid processes. The subject's back should be as straight as possible, which may be achieved by rounding or relaxing the shoulders and manipulating the posture. The marked Frankfurt plane must be horizontal. Either the horizontal arm of an anthropometer, or a counter weighted board, is brought down on to the subject's head. If an anthropometer is used, one measurer should hold the instrument vertical with the horizontal arm in contact with the subject's head, while another applies the gentle traction. The subject's heels must be watched to make sure they do not leave the ground.

The data were entered into computer and analyzed using Statistical Package for Social Sciences (SPSS) on Widows Professional 2003.

Bilateral asymmetry (difference between the measurements on left and right side within an individual) was calculated for each of the measurement taken on footprint and foot outline. The significance of bilateral asymmetry was tested by applying a paired *t*-test.

Karl Pearson's correlation coefficients between various length/breadth measurements of the footprint and foot outline with stature were obtained separately.

Two methods were employed for estimation of stature, i.e. division factor method and regression analysis. The division factor was calculated by summing the measurement divided by stature value for each subject in the sample and dividing the sum by the sample size. The result so obtained is the average of foot measurement/stature percentages for 1040 adult male Gujjars. The division factor was calculated for each of the measurement on footprint and foot outline with stature separately. Regression analysis by least-square method was employed to calculate regression equations for estimation of stature from various measurements of footprints and foot outlines. Following Jasuja et al. [15], mean error was calculated by noting the difference between measured stature and stature estimated by the two methods.

3. Results

Tables 1 and 2 present the means, standard deviations, minimum and maximum values of left and right footprints and foot outlines in all the subjects. One can observe range of variation in the measurements of variables by examining the low and high figures of the minimum and maximum columns of the tables. Descriptive information emerges when the numerical data of the footprint and foot outline tables are examined together; one can sort out variables that exhibit greater or lesser changes in size between their footprint and foot outline measurements.

Table 3 displays means, standard deviations and values of '*t*' of bilateral differences (left–right) in measurements of footprint and foot outline in all the subjects. In the footprint, the minimum and maximum mean difference (left–right) values are indicated by T-3 length/breadth at ball (0.06) and T-5 length (0.69), respectively. Only T-2 length and T-5 length show statistically significant asymmetry and the values are larger on the left side. Other measurements, i.e. T-1, T-3 and T-4 lengths, footprint breadths, big toe pad length and breadth and toe 1-5 angle of declination do not show any statistically significant asymmetry.

Table 1
Descriptive statistics of footprint measurements in adult male Gujjars ($n = 1040$)

Measurement (cm)	Mean		S.D.		Minimum		Maximum	
	Left	Right	Left	Right	Left	Right	Left	Right
T-1 length (d1.t-pte)	24.05	24.13	3.23	3.26	19.6	19.3	27.9	27.3
T-2 length (d2.t-pte)	24.15	23.93	3.12	3.12	18.9	18.8	28.1	28.5
T-3 length (d3.t-pte)	23.45	23.51	2.93	2.99	18.1	18.3	26.8	26.3
T-4 length (d4.t-pte)	21.88	21.34	2.35	2.36	17.1	16.9	25.3	25.9
T-5 length (d5.t-pte)	20.78	20.09	2.30	2.23	16.2	16.5	23.3	23.4
Breadth at ball (mt.m-mt.l)	8.63	8.69	1.98	1.90	6.2	6.3	10.8	11.1
Breadth at heel (cc.m-ctu.l)	5.08	4.92	1.43	1.39	3.1	3.0	8.3	8.4
Big toe pad length (d1.t-d1.ps)	2.98	3.11	0.87	0.89	1.8	1.8	5.6	5.6
Big toe pad breadth (d1.t-d1.pl)	2.48	2.60	0.72	0.68	1.6	1.5	4.3	4.4
Toe 1-5 angle of declination	58°	60°	5.8	5.1	44°	43°	73°	71°

Table 2
Descriptive statistics of foot outline measurements in adult male Gujjars ($n = 1040$)

Measurement (cm)	Mean		S.D.		Minimum		Maximum	
	Left	Right	Left	Right	Left	Right	Left	Right
T-1 length (d1.t-pte)	25.82	25.43	3.23	3.25	20.2	19.9	28.8	28.3
T-2 length (d2.t-pte)	25.78	25.35	3.42	3.36	19.2	18.9	28.3	28.6
T-3 length (d3.t-pte)	24.97	25.07	2.91	2.82	18.8	18.5	27.3	27.3
T-4 length (d4.t-pte)	23.15	22.93	2.31	2.33	18.6	17.9	24.9	25.3
T-5 length (d5.t-pte)	22.08	21.81	2.29	2.28	16.1	16.4	22.6	22.7
Breadth at ball (mt.m-mt.l)	9.63	9.85	2.21	1.92	6.1	6.4	10.9	11.3
Breadth at heel (cc.m-ctu.l)	5.98	6.15	1.53	1.49	3.2	3.5	8.5	8.4
Toe 1-5 angle of declination	59°	60°	5.3	5.7	40°	40°	76°	72°

In the foot outline, the minimum and maximum mean difference (left–right) values are shown by T-3 length (0.10) and T-2 length (0.43), respectively. T-1, T-4 lengths and breadth at ball indicate statistically significant bilateral asymmetry and the values are larger on the left side except breadth at ball which indicates right-sided asymmetry. On the other hand, other measurements, i.e. T-2, T-3, T-5 lengths, breadth at heel and toe 1–5 angle of declination do not show any significant asymmetry.

Table 4 depicts the values of division factors and their corresponding mean errors for estimating stature from various measurements of footprint and foot outline in all the subjects. In the footprint, on the left side, the minimum and maximum values for division factor are given by big toe pad breadth (0.0145) and T-2 length (0.1425), respectively; the minimum and maximum mean errors in the estimation of stature are given by T-1 length (3.35) and big toe pad length (4.63), respectively. On the right side, big toe pad breadth (0.0151) and T-1 length (0.1427) indicate the minimum and maximum values for the division factor, respectively; the minimum and maximum mean errors are given by T-2 length (3.29) and big toe pad breadth (4.66), respectively.

In the foot outline, on the left side, the minimum and maximum division factor values are given by the breadth at heel

Table 3
Means, standard deviations and values of 't' of bilateral differences (left–right) in measurements of footprint and foot outline in adult male Gujjars ($n = 1040$)

Measurement (cm)	Footprint			Foot outline		
	Mean difference (left–right)	S.D.	t-Value	Mean difference (left–right)	S.D.	t-Value
T-1 length (d1.t-pte)	−0.08	1.12	−1.91	0.39	1.26	2.83*
T-2 length (d2.t-pte)	0.22	1.32	2.73*	0.43	1.51	1.78
T-3 length (d3.t-pte)	−0.06	1.56	−1.56	−0.10	−1.03	−1.35
T-4 length (d4.t-pte)	0.54	1.21	1.32	0.22	1.21	2.80*
T-5 length (d5.t-pte)	0.69	1.12	2.59*	0.27	1.40	2.10
Breadth at ball (mt.m-mt.l)	−0.06	1.07	1.92	−0.22	1.51	−2.57*
Breadth at heel (cc.m-ctu.l)	0.16	0.89	1.58	−0.17	0.79	−1.39
Big toe pad length (d1.t-d1.ps)	−0.13	0.76	−1.43	–	–	–
Big toe pad breadth (d1.pm-d1.pl)	−0.12	0.40	−1.16	–	–	–
Toe 1-5 angle of declination	−2°	0.26	−0.89	−1°	0.16	−0.78

* $P < 0.01$.

Table 4
Values of division factor for estimating stature from various measurements on footprint and foot outline in adult male Gujjars ($n = 1040$)

Measurement (cm)	Left footprint		Right footprint		Left foot outline		Right foot outline	
	Division factor	Mean error	Division factor	Mean error	Division factor	Mean error	Division factor	Mean error
T-1 length (d1.t-pte)	0.1424	3.35	0.1427	3.31	O.1512	3.25	0.1497	3.29
T-2 length (d2.t-pte)	0.1425	3.37	0.1413	3.29	0.1514	3.38	0.1496	3.31
T-3 length (d3.t-pte)	0.1379	3.41	0.1380	3.38	0.1467	3.32	0.1471	3.37
T-4 length (d4.t-pte)	0.1272	3.51	0.1254	3.47	0.1347	3.40	0.1340	3.45
T-5 length (d5.t-pte)	0.1213	3.46	0.1180	3.44	0.1285	3.41	0.1272	3.45
Breadth at ball (mt.m-mt.l)	0.0502	3.96	0.0508	3.98	0.0560	3.86	0.0574	3.97
Breadth at heel (cc.m-ctu.l)	0.0296	4.05	0.0288	4.09	0.0347	4.12	0.0358	4.19
Big toe pad length (dl.t-d1.ps)	0.0174	4.56	0.0179	4.59	–	–	–	–
Big toe pad breadth (d1.pm-d1.pl)	0.0145	4.63	0.0151	4.66	–	–	–	–

Table 5
Karl Pearson's correlation coefficients between footprint and foot outline measurements with stature ($n = 1040$)

Measurement (cm)	Left footprint/stature	Right footprint/stature	Left foot outline/stature	Right foot outline/stature
T-1 length (d1.t-pte)	0.87*	0.86*	0.85*	0.86*
T-2 length (d2.t-pte)	0.85*	0.87*	0.83*	0.85*
T-3 length (d3.t-pte)	0.86*	0.85*	0.84*	0.85*
T-4 length (d4.t-pte)	0.85*	0.84*	0.83*	0.83*
T-5 length (d5.t-pte)	0.82*	0.82*	0.84*	0.82*
Breadth at ball (mt.m-mt.l)	0.66*	0.64*	0.63*	0.66*
Breadth at heel (cc.m-ctu.l)	0.57*	0.55*	0.53*	0.52*
Big toe pad length (d1.t-d1.ps)	0.41*	0.43*		
Big toe pad breadth (d1.pm-d1.pl.)	0.32**	0.30**	–	–
Toe 1-5 angle of declination	0.09[a]	0.08[a]	0.04[a]	0.08[a]

[a] Values of correlation coefficients are not significant.
* Values of correlation coefficients are highly significant ($P < 0.001$).
** $P < 0.01$.

(0.0347) and T-1 length (0.1512), respectively; the minimum and maximum mean errors are given by T-1 length (3.25) and breadth at heel (4.12), respectively. On the right side, the minimum and maximum division factor values are shown by the breadth at heel (0.0358) and T-1 length (0.1497), respectively; the minimum and maximum mean errors are given by T-1 length (3.29) and breadth at heel (4.19), respectively.

Table 5 presents Karl Pearson's correlation coefficients of bilateral footprint and foot outline measurements with stature for all the subjects. All the correlation coefficients show positive relationship and show statistically significance ($P < 0.001$ and <0.01) except toe 1–5 angle of declination that indicates statistically insignificant correlation values in both footprint and foot outline data. Highly significant correlation coefficients exist between stature and footprint and foot outline lengths from toes (0.82–0.87, $P < 0.001$). Although, slightly higher correlation coefficients exist between stature and breadth at ball but breadth at heel indicates comparatively lower correlation coefficients with stature.

Tables 6 and 7 display the regression equations for estimation of stature from various footprint and foot outline

Table 6
Regression equations for estimation of stature through various length/breadth measurements of footprint in adult male Gujjars ($n = 1040$)

Measurement (cm)	Regression equations for left footprint	Mean error	Regressions equations for right footprint	Mean error
T-1 length (d1.t-pte)	3.689 × T-1 length + 84.013	2.12	3.510 × T-1 length + 87.214	2.16
T-2 length (d2.t-pte)	3.864 × T-2 length + 77.783	2.16	3.361 × T-2 length + 91.303	2.15
T-3 length (d3.t-pte)	3.520 × T-3 length + 89.146	2.27	3.613 × T-3 length + 84.953	2.30
T-4 length (d4.t-pte)	3.869 × T-4 length + 88.013	2.33	3.627 × T-4 length + 94.414	2.32
T-5 length (d5.t-pte)	3.985 × T-5 length + 87.753	2.35	3.869 × T-5 length + 94.572	2.31
Breadth at ball (mt.m-mt.l)	7.951 × BAB + 102.578	3.11	7.673 × BAB + 105.389	3.17
Breadth at heel (ccm.-ctu.l)	9.658 BAH + 122.802	3.64	8.781 × BAH + 126.093	3.68
Big toe pad length (d1.t-d1.ps)	12.056 × BTPL + 133.642	3.76	10.969 × BTPL + 133.402	3.75
Big toe pad breadth (d1.pm-d1.pl)	15.996 × BTPB + 131.361	3.92	15.064 × BTPB + 135.454	3.88

Table 7
Regression equations for estimation of stature through various length–breadth measurements of foot outline in adult male Gujjars ($n = 1040$)

Measurement (cm)	Regression equation for left foot outline	Mean error	Regression equations for right foot outline	Mean error
T-1 length (d1.t-pte)	3.255 × T-1 length + 88.458	2.18	3.289 × T-1 length + 87.385	2.17
T-2 length (d2.t-pte)	3.569 × T-2 length + 79.885	2.22	3.491 × T-2 length + 83.571	2.24
T-3 length (d3.t-pte)	3.621 × T-3 length + 90.467	2.23	3.583 × T-3 length + 80.972	2.24
T-4 length (d4.t-pte)	3.710 × T-4 length + 85.030	2.30	3.698 × T-4 length + 84.795	2.27
T-5 length (d5.t-pte)	3.993 × T-5 length + 83.894	2.28	3.915 × T-5 length + 85.582	2.20
Breadth at ball (mt.m-mt.l)	5.394 × BAB + 119.625	3.12	5.414 × BAB + 120.951	3.10
Breadth at heel (cc.m.-ctu.l)	8.810 × BAH + 118.376	3.61	8.735 × BAH + 120.265	3.58

measurements. The values of constants '*a*' and '*b*' were generated mathematically by the help of computer software; where '*a*' is the regression coefficient of the dependent variable, i.e. stature and '*b*' is the regression coefficient of the independent variable, i.e. any measurement of the footprint or foot outline. Hence, stature = $a + bx$, where, 'x' = a measurement of footprint or foot outline. The regression equations were calculated separately from various length/breadth measurements of the footprint and foot outline with stature by substituting the appropriate values of constants '*a*' and '*b*' in this standard equation of regression line. The table also depicts the mean error calculated by noting the difference between measured stature and stature estimated by regression method for each measurement.

4. Discussion

The results indicate that one can successfully estimate stature from different parts of the footprint and foot outline with a prescribed mean error using division factor method and regression analysis. However, it must always be kept in mind that precise prediction of stature from an individual's footprint or foot outline may be an unachievable and unnecessary goal, there would always be an estimation error of a few centimeters.

In the present study, the reason for taking the adult sample ranging in age from 18 to 30 years (average being 24.47 years) may be attributed to the fact that the average adult length of foot is attained by the age of 16 years in males [33,34]. According to Roche [35], generally stature at 18 years is accepted as adult, although there are small increments in stature after this. The median age for attaining height in males is 21.2 years with growth continuing in 10% of males until 23.5 years [36]. Although, loss of stature seen with increasing age is not accompanied by diminution of foot size and it is difficult to see how much variability could be incorporated into predictive calculation [18]. A study by Friedlaender et al. [37] suggests that a decline in stature does not commence until the fifth decade of life.

All the measurements of the footprints and the foot outlines (taken on diagonal axis) can be compared with those of Robbins [12] and Table 8 presents the comparison of various footprints and foot outline measurements separately for left and right sides. The footprint and foot outline dimensions of the present study Gujjars indicate somewhat larger values than that of the Robbins [12] who presented combines data for both male and female subjects ranging in age from 14 to 50 years in a Unites States population.

The length (T-1 length) and breadth of the footprint and foot outline in the present study can be compared with the studies by Philip [38] on South Indian subjects and Jasuja et al. [15] on Jat Sikhs of Punjab, India. The former used the same technique to measure the maximum length of the footprint and foot outline as used in the present study and the later used somewhat different technique to measure the foot size; however, the results are comparable. Present study Gujjars show somewhat smaller footprint and foot outline dimensions as compared to the South Indian subjects and Jat Sikhs of Punjab, however, the mean stature is slightly higher in the present study.

Table 8
Comparison of the means of various footprint and foot outline measurements of the present study with Robbins [12]

Measurement (cm)	Footprint data				Foot outline data			
	Present study		Robbins [12]		Present study		Robbins [12]	
	Left	Right	Left	Right	Left	Right	Left	Right
T-1 length (d1.t-pte)	24.05	24.13	23.68	23.59	25.82	25.43	25.10	25.06
T-2 length (d2.t-pte)	24.15	23.93	23.56	23.44	25.78	25.35	24.67	24.56
T-3 length (d3.t-pte)	23.45	23.51	22.71	22.56	24.97	25.07	23.79	23.64
T-4 length (d4.t-pte)	21.88	21.34	21.53	21.36	23.15	22.93	22.57	22.41
T-5 length (d5.t-pte)	20.78	20.09	19.94	19.75	22.08	21.81	20.99	20.81
Breadth at ball (mt.m-mt.l)	08.63	08.69	08.86	08.84	9.63	9.85	09.70	9.73
Breadth at heel (cc.m-ctu.l)	05.08	04.92	04.93	04.94	5.98	6.15	5.92	5.94
Big toe pad length (dl.t-dl.ps)	02.98	03.11	02.64	02.59	–	–	–	–
Big toe pad breadth (dl.pm-dl.pl)	02.48	02.60	02.39	02.42	–	–	–	–
Toe 1-5 angle of declination (°)	58	60	60.81	60.60	59	60	58.77	58.63

Results indicate that some of the measurements in footprint and foot outline show statistically significant asymmetry, however, the values of 't' are small. All the significantly asymmetric measurements, i.e. T-2 and T-5 lengths in footprint, T-1 and T-4 lengths in foot outline, are larger on the left side except breadth at ball in foot outline which shows right-sided bilateral asymmetry. This occurrence of the significant left-sided bilateral asymmetry in the footprint and foot outlines can be explained on the basis of the fact that majority of the persons put greater strain on the left lower limb than on the right in walking and in weight bearing as is shown by Singh [39] in his study. Although most of the persons kick and lift with the right foot, these functions are performed only occasionally, while weight bearing and walking have to be done by the limb for several hours every day. The feet that bear the whole weight of the body stabilize us as we run, twist or even dance. The simple act of walking is a huge strain, although one may not notice it. The Gujjars who are mostly engaged in the agricultural work all the time, put more strain on their feet while working in the fields. It is therefore, not surprising to note that the foot or limb that is more used for walking and weight bearing becomes physically better developed. This view is strongly supported by another study on limb bilateral asymmetry [19] in which the author finds significant left-sided asymmetry in the lower limbs of Gujjar population.

The findings of the present study are also supported by Rao and Kotian [40] by suggesting that the difference between the left and right footprints in the same individual is not a coincidence but may be explained on the basis of the "dominant foot". Most of the individuals have dominant foot, which always supports the body to a greater extent while in standing or in walking. The shoe of this foot wears off at a faster rate than the shoe on the other side. The bones in the dominant foot are regularly subjected to stronger stress forces like weight bearing pressures, than are the bones of the other foot. This in turn enlarges the bones of the dominant foot and therefore, produces a footprint or foot outline of larger dimensions.

Robbins [12] did not find significant bilateral asymmetry in various measurements of the feet of the U.S. population and stated, "Although not identical, the measurements of most variables in a person's left and right bare footprint are similar enough to permit either the right or left one being used for height and weight estimations." Similar views are expressed by Philip [29] that either of the feet can be used for the estimation of stature. He didn't find any significant asymmetry while working on the footprints of a South Indian population. Jasuja et al. [15] successfully tried to estimate stature separately from left and right side measurements of the foot but their study didn't show any significant asymmetry in the measurements of the left and right feet.

Every care was taken while measuring the subjects for stature and while taking measurements on footprints and foot outlines. To avoid inter-observer error, all the measurements were taken by the author himself. To calculate intra-observer error, all the measurements were taken twice on 30 subjects taken from the sample. The intra-observer error was calculated following Dangour [41] and Dangour [42]. The obtained values of the intra-observer error of the measurements fall within the prescribed limits [43] indicating that the measurements are reproducible without significant intra-individual error.

In the present study, division factors for estimating stature from various length/breadth measurements of footprint and foot outlines were calculated. Their corresponding mean error was also calculated which gives indication about the error occurring in the stature estimated. The mean errors calculated for the stature estimation from various toe length measurements (3.29–3.47) are small as compared to the other measurements of the footprint and foot outline (3.86–4.66) which means that the estimation of stature from the toe length measurements in a footprint and foot outline has more reliability of prediction than from other measurements like breadth at ball/heel and big toe pad length/breadth. In the present sample, it is further observed that the least reliability is found while estimating stature from big toe pad breadth. The findings of the present study are in consistent with that of Jasuja [27] because of the fact that the mean error was minimum when stature was estimated from foot length measurements and maximum when estimated from foot breadth measurements in Jat Sikhs. The division factors for estimating stature from footprint length (T-1 length) and foot outline length (T-1 length) have been compared with the stature ratio indices given by Robbins [13] and Philip [44] (Table 9). The results are found to be consistent with these studies.

In the present investigation, correlation coefficients of various measurements of footprint and foot outline separately with stature suggest a linear and close relationship between stature and these measurements. The correlations are quite high, one can estimate stature from either left or right side measurements of footprints and foot outlines. The correlations of stature with various length measurements from toes in both left and right footprints and foot outlines are extremely high (0.82–0.87) suggesting a close relationship with them. Similar results (0.80–0.85) were obtained by Robbins [12] on 550 subjects. Ozden et al. [30] on a Turkish sample of 294 males and Singh and Phookan [45] on four different ethnic groups of

Table 9
Comparison of the values of division factor/ratio index for estimation of stature with Robbins [13] and Philip [44]

Measurement (cm)	Present study (division factor)	Robbins [13] (stature ratio index) (%)	Philip [44] (stature ratio index) (%)
Left footprint length	0.1424	14.387	14.25
Right footprint length	0.1427	14.312	14.28
Left foot outline length	0.1512	15.199	15.25
Right foot outline length	0.1497	15.128	15.23

Table 10
Comparison of actual stature and estimated stature from left T-1 length of footprint using respective regression equations ($n = 1040$)

Value	Minimum estimated stature (cm)	Maximum estimated stature (cm)	Mean estimated stature (cm)
Mean estimated stature	156.31	178.56	172.73
Actual stature	150.81	186.30	172.68

India also showed that foot length gives better results than foot breadth in estimation of stature.

The regression equations obtained were checked for their accuracy. The minimum, maximum and the mean of the T-1 length were substituted in the regression equations and statures were calculated. With these data, an average height for both minimum and maximum values was now derived mathematically summing up the values of both sides. It was then compared with the actual minimum, maximum and mean stature recorded (Table 10). It is evident from the table that regression equation underestimates and underestimates the stature for minimum and maximum values of T-1 length, respectively. However, for mean values, the estimates are close to the actual stature. This is to be expected, since the regression equations are calculated from measures of central tendency.

In the present study, when mean errors occurring in the estimation of stature by division factor method were compared with that of regression method (comparison of Table 4 with Tables 6 and 7), it is observed that the values of mean error in the division factor method are quite higher than those in the regression method. Hence, the estimation of stature by means of regression method is more reliable than the division factor method. Robbins [12], based on her study recommended the use of percentage formula with a margin of variation instead of using regression equations for estimation of stature and she remarked that estimating height by means other than foot length as a percentage of height was 'unduly complicated'. The present study contradicts the opinion expressed by Robbins [12].

In the present study, better results are obtained in terms of correlation of stature with various measurements of footprints and foot outlines, accuracy and applicability of division factor method and regression analysis in estimating stature from measurements of footprints and foot outlines. This may be attributed to the larger sample size in case of present study (i.e. 2080 bilateral footprints from 1040 subjects) than most of the studies conducted in this context. Other reason may be that the current sample of Gujjar population from north India comprises an endogamous group, i.e. the members of this group are marrying within their own caste, thus making it anthropologically, genetically and forensically important population.

5. Conclusion

From the present investigation, it has been concluded that footprints and foot outlines are of utmost importance in estimating the stature in forensic examinations. Footprint and foot outline lengths are strongly correlated with stature and thus give better prediction of stature than the other measurements. It is further concluded that the reliability and prediction of stature by the regression method is better than that of the division factor method. In view of the significant bilateral asymmetry occurring in some of the footprint and foot outline measurements in Gujjar population, one should be careful in using the formula and the use of appropriate formula for the appropriate side is recommended. An important point to remember is that the people from different regions of India bear different morphological features depending upon their geographical distribution and primary racial characteristics hence a single formula cannot represent all parts of the country. It is, therefore, suggested that similar studies should be conducted on other endogamous groups living in different parts of the world so that effect of genetics and environment can be investigated in forensic terms.

Acknowledgements

I would like to thank my subjects for their excellent cooperation and participation in the study. My special thanks are due to Professor M.Y. Iscan for supplying related material and encouraging me to go ahead with my research project. I am also grateful to Dr. O.P. Jasuja, Professor, Department of Forensic Science, Punjabi University, Patiala, India and Dr T. Abraham Philip, Professor of Forensic Medicine, St. Johns Medical College, Bangalore, India, for providing me reprints of their valuable studies.

References

[1] S.R. Qamra, B.R. Sharma, P. Kaila, Naked footmarks—a preliminary study of identification factors, Forensic Sci. Int. 16 (1980) 145–152.
[2] B.R. Sharma, Forensic Science in Criminal Investigation, Central Law Agency, Allahabad, India, 1990, pp. 176–190.
[3] G.W. Gayer, Footprints, Government Publication, Lucknow, U.P., India, 1904.
[4] L.M. Robbins, The individuality of human footprints, J. Forensic Sci. 23 (1978) 778–785.
[5] W. Winkelmann, Use of footprints, especially forefoot prints, from the forensic viewpoint, Z. Rechtsmed. 99 (1987) 121–128.
[6] G.E. Laskowski, V.L. Kyle, Barefoot impressions—a preliminary study of identification characteristics and population frequency of their morphological features, J. Forensic Sci. 33 (1988) 378–388.
[7] R.B. Kennedy, I.S. Pressman, S. Chen, P.H. Patersen, A.E. Pressman, Statistical analysis of barefoot impressions, J. Forensic Sci. 48 (2003) 55–63.
[8] R.B. Kennedy, S. Chen, I.S. Pressman, A.B. Yamashita, A.E. Pressman, A large-scale statistical analysis of barefoot impressions, J. Forensic Sci. 50 (2005) 1071–1080.
[9] V.L. Naples, J.S. Miller, Making tracks: the forensic analysis of footprints and footwear impressions, Anat. Rec. B: New Anat. 279 (2004) 9–15.
[10] K. Krishan, Individualizing characteristics of footprints in Gujjars of North India—Forensic aspects, Forensic Sci. Int. 169 (2007) 137–144.
[11] L.M. Robbins, A method for analyzing footprints/shoeprints, in: Proceedings of the 10th Triennial Meeting of the International Association of Forensic Sciences, Oxford, England, 18–25 September, 1984.
[12] L.M. Robbins, Footprints—Collection, Analysis and Interpretation, Charles C. Thomas, Springfield, IL, USA, 1985.
[13] L.M. Robbins, Estimating height and weight from size of footprints, J. Forensic Sci. 31 (1986) 143–152.
[14] E. Giles, P.H. Vallandigham, Height estimation from foot and shoeprint length, J. Forensic Sci. 36 (1991) 1134–1151.

[15] O.P. Jasuja, J. Singh, M. Jain, Estimation of stature from foot and shoe measurements by multiplication factors: a revised attempt, Forensic Sci. Int. 50 (1991) 203–215.
[16] C.C. Gorden, J.E. Buikstra, Linear models for the prediction of stature from foot and boot dimensions, J. Forensic Sci. 37 (1992) 771–782.
[17] O.P. Jasuja, Manjula, Estimation of stature from footstep length, Forensic Sci. Int. 61 (1993) 1–5.
[18] S.L. Barker, J.L. Scheuer, Predictive value of human footprints in a forensic context, Med. Sci. Law 38 (1998) 341–346.
[19] K. Krishan, Limb bilateral asymmetry and footprints of male adult Gujjar population in parts of Punjab and Haryana, PhD Dissertation, Panjab University, Chandigarh, India, 2002.
[20] K. Krishan, R.N. Vashisht, Estimation of stature from foot-prints in adult male Gujjars, in: M.K. Bhasin, S. Nath (Eds.), Role of Forensic Science in the New Millennium, Department of Anthropology, University of Delhi, New Delhi, India, 2002, pp. 13–18.
[21] K. Krishan, A. Sharma, Estimation of stature from dimensions of hands and feet in a North Indian population, J. Clin. Forensic Med. 14 (2007) 327–332.
[22] P. Topinard, L' Anthropologie, C. Reinwald, Paris, 1876.
[23] P. Topinard, Anthropology, Chapman and Hall, London, 1876.
[24] R. Martin, Lehrbuch der Anthropologie, 1914, Gustav Fischer, Jena, 1928
[25] R. Martin, K. Saller, Lehrbuch der Anthropologie, Gustav Fischer, Stuttgart, 1959.
[26] L. Pales, Les Empreintes de Pieds Humains dans les Cavernes Archives de I'Institut de Paléontologie Humaine Mém. 36, 1976 (cited from [14]).
[27] O.P. Jasuja, Calculation of stature from foot and shoe impressions, PhD Dissertation, Punjabi University, Patiala, India, 1987.
[28] V.K. Sharma, R.K. Garg, P.K. Chattopadhyay, Calculation of stature from foot measurements: a study of Gaur Brahmins, Coll. Antropol. 2 (1978) 194–195.
[29] T.A. Philip, Formulae for estimating stature from foot size by regression method, J. Ind. Acad. Forensic Med. 12 (1990) 57–62.
[30] H. Ozden, Y. Balci, C. Demirustu, A. Turgut, M. Ertugrul, Stature and sex estimate using foot and shoe dimensions, Forensic Sci Int. 147 (2005) 181–184.
[31] J. Comas, Manual of Physical Anthropology, C.C. Thomas Springfield, USA, 1960, pp. 713–717.
[32] J.S. Weiner, J.A. Lourie, Human Biology—A Guide to Field Methods, Blackwell Scientific Publications, Oxford and Edinburgh, 1981.
[33] M. Anderson, M. Blais, W.T. Green, Growth of the normal foot during childhood and adolescence—length of the foot and interrelations of foot, stature and lower extremity as seen in serial records of children between 1–18 years of age, Am. J. Phys. Anthropol. 14 (1956) 287–308.
[34] M.M. Blais, W.T. Green, M. Anderson, Lengths of the growing foot, J. Bone Joint Surg. 38A (1956) 998–1000.
[35] A.F. Roche, Bone growth and maturation, in: F. Falkner, J.M. Tanner (Eds.), 2nd ed., Human Growth—A Comprehensive Treatise, vol. 2, Plenum Press, New York and London, 1986, pp. 25–60.
[36] A.F. Roche, G.H. Davila, Late adolescent growth in stature, Pediatrics 50 (1972) 874–880.
[37] J.S. Friedlaender, P.T. Costa Jr., R. Bosse, E. Ellis, J.G. Rhoads, H.W. Stoudt, Longitudinal physique changes among healthy white veterans at Boston, Hum. Biol. 49 (1977) 451–558.
[38] T.A. Philip, Foot size for predicting stature of males, J. Ind. Acad. Forensic Sci. 27 (1988) 30–39.
[39] I. Singh, Functional asymmetry in the lower limbs, Acta Anat. 77 (1970) 131–138.
[40] N.G. Rao, M.S. Kotian, Footprint ratio (FPR)—a clue for establishing sex identity, J. Ind. Acad. Forensic Med. 12 (1990) 51–56.
[41] A.D. Dangour, Growth of upper and lower body segments in Patamona and Wapishana Amerindian children (cross-sectional data), Ann. Hum. Biol. 28 (2001) 649–663.
[42] A.D. Dangour, Cross-sectional changes in anthropometric variables among Wapishane and Patamona Amerindian adults, Hum. Biol. 75 (2003) 227–240.
[43] S.J. Ulijaszek, D.A. Kerr, Anthropometric measurement error and the assessment of nutritional status, Br. J. Nutr. 82 (1999) 165–177.
[44] T.A. Philip, Reconstruction of stature from foot outline and footprint size, J. Ind. Acad. Forensic Med. 11 (1989) 15–20.
[45] T.S. Singh, M.N. Phookan, Stature and foot size in four Thai communities of Assam, India, Anthrop. Anz. 51 (1993) 349–355.