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Original article

HEIGHT ESTIMATION FROM DIGIT LENGTHS AND HAND DIMENSIONS: AN ANTHROPOMETRIC STUDY ON THE SANTALS OF PURBA BARDHAMAN, WEST BENGAL, INDIA

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ABSTRACT

Introduction:
Variation in the strength of association between stature and hand dimensions across human groups necessitates the need for population-specific predictive models rather than the application of generalized equations. The present investigation aims to develop such a model for stature estimation among the Santal population of Purba Bardhaman district, West Bengal.

Methods:
Anthropometric data were collected from 177 adult males and 215 adult females, including stature, lengths of all digits on both hands, and hand length and breadth. Pearson's correlation coefficients were computed to examine the relationship between stature and each hand dimension, followed by stepwise backward multiple linear regression analyses conducted separately for each sex and hand to identify the most robust predictors of stature.

Results:
The correlation analysis indicates that, among males, right-hand length exhibits the strongest association with stature, whereas in females the right second digit demonstrates the highest correlation. Regarding digital measurements, the third digit of both hands correlates most strongly with stature in males; in females, right-hand length emerges as the next strongest correlate following the right second digit. Overall, male hand dimensions show stronger correlation relationships with stature compared to those of females. Regression analyses further reveal that, for males, left-hand length and breadth, as well as right-hand length, serve as the most effective predictors of stature. In females, left-hand length and the second and fifth digits of the right hand provide the greatest explanatory power.

Conclusion:
Consistent across sexes, predictive models derived from right-hand measurements yield higher adjusted R^2 values than those based on left-hand variables.

KEY WORDS: Forensic Anthropology, Forensics Science, Hand Anthropometry, Height Estimation, Regression Equation

INTRODUCTION

Estimation of stature remains a fundamental component of anthropometric research with applications across anthropology, human anatomy, and medico-legal practice (DiMaggio & Vernon, 2011; Breitinger, 1937; Numan et al., 2013). In both anthropological and forensic contexts, reliable stature prediction assists medical jurisprudence, forensic scientists, and medico-legal authorities (Jasuja & Singh, 2004). Within forensic anthropology, stature serves as

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one of the primary biological markers for human identification, especially in situations involving mutilated, decomposed, or fragmentary remains resulting from natural disasters such as earthquakes, floods, and cyclones, or human-induced events including mass accidents, terrorist attacks, and armed conflict (Ahmad et al., 2014). The need for accurate indirect methods of stature estimation is further heightened when dealing with incomplete skeletal remains, unknown bodies, or advanced decomposition. Because of these variables such as ancestry, geography, age, and sex influence growth and morphology, population-specific approaches remain essential (Patel et al., 2014).

Historically, scientific efforts to estimate stature from skeletal and soft-tissue measurements date back to Étienne Rollet (1880), who introduced a ratio-based method using long bones from male and female cadavers. Léonce Manouvrier (1892) subsequently refined this approach by developing tables that estimated stature from bone lengths, effectively moving toward regression-based prediction. Karl Pearson (1899) later formalized the use of linear regression for stature estimation from long bone measurements. Subsequent research—including the large German sample studied by Breitinger (1937), the interracial samples analyzed by Dupertui sand Hadden (1951), and the work of Trotter and Gleser (1952) comparing recorded statures of servicemen with measurements from their repatriated remains—confirmed that regression methods yield the most accurate stature estimates. In the present study, hand length, hand breadth, and lengths of all digits were used to develop regression equations for stature prediction.

In India, Athawale (1963) was among the first to construct population-specific regression equations, using forearm measurements from a Maharashtrian sample. Indirect stature estimation continues to be necessary for living individuals with mobility limitations—such as limb deformities, fractures, scoliosis, paralysis, lower-limb amputations, or age-related impairments—which make direct measurement unreliable (Supare et al., 2015; Hickson & Frost, 2003). Clinical measurement challenges also arise among bedridden or wheelchair-bound patients with osteoporosis or neurological deficits (Ter Goon et al., 2011). These circumstances highlight the continued forensic and clinical relevance of stature estimation from alternative anthropometric variables (Alam et al., 2016).

Hand anthropometry has gained particular prominence in recent decades. Studies among Bengali Post-Graduate male students (21-29 years of age) (Paul et al., 2018) and medical college students at Jodhpur (Agarwal et al., 2015) reported positive correlations between most hand measurements and stature, particularly hand length. Research in Upper Egypt found similar patterns in both sexes and both hands, leading to the development of generalized regression models (Abdel-Malek et al., 1990). Studies of cadaveric samples from Gujarat (Varu et al., 2015), university populations in Turkey (Uzun et al., 2018; Achikgoz et al., 2020), Malaysian adults (Nuratirah & Khairulmazidah, 2018), and large Indian cohorts (Charmode & Pujari, 2019) consistently report significant positive associations between hand dimensions and stature, with hand length typically emerging as the superior predictor.

A review of available literature reveals that most existing studies rely on selected hand measurements and do not incorporate a comprehensive set of hand dimensions—

including all digit lengths, hand lengths, and hand breadths—within the same sample. Consequently, the relative predictive value of these variables has not been systematically evaluated.

The present study aims to address these gaps by conducting an exhaustive assessment of hand anthropometry among Santal adults and examining its relationship with stature. By analyzing all major hand measurements and developing sex-specific regression models, this study seeks to identify the most reliable hand-based predictors of stature and contribute new population-specific data to the anthropometric and forensic literature. The objectives of this study thereby, can be presented as such:

(1) To establish correlation of height with hand length, hand breadth, digit lengths of both hands to understand the proportional relationship of this body part that contributes in determining the total body height.
(2) To create simple regression equations to successfully predict stature with all the measured parameters of both hands for both the sexes.
(3) To create multiple regression equations involving all dimensions of both hand and its digits.
(4) To create multiple regression equations involving a few of the best predictor variables for either hand through the backward method.

METHODS:

Study Area and Population: For this study, 177 males and 215 females of Santal tribe were sampled for the study from the various blocks within the district of Purba Bardhaman, West Bengal. The method of sampling was purely purposive and only individuals above the age of 25years were sampled since although long bone growth generally stops around 18±2 years, bone accrual may continue up to 25 years of age (Setiwati & Rahardjo, 2019) hampering any correlation between height and measured variables.

*Data Analysis:*14 measurements from the forelimbs were selected to examine each of their correlations with stature of an individual with a confidence level of 95 percent (i.e., for p- value < 0.05) and to verify if they could successfully estimate height of an individual and thereby a regression equation was determined consisting of stature and other measure parameters. The variables measured for this predictive model are the digit lengths of all ten digits in both hands, coded as Left Digit + n^{th} digit starting from the thumb and Right Digit + n^{th} digit starting from the thumb (LDn, RDn), hand lengths from both hands (RHL, LHL), hand breadths from both hands (RHB, LHB), and Height Vertex (Height) for every participant.

Data Collection: For the measurement of height, a stadiometer was used, whereas for the rest of the variables, including the hand dimensions a Martin's sliding caliper was used. All measurements were taken outdoors in adequate sunlight with each measurement being taken at least twice. All measurements were found to be at around 0.75 percent intra-observer percent TEM (Technical Error of Measurement), which is considered to be acceptable (Goto & Mascie-Taylor, 2007).

Statistical analysis: All data has been compiled in Statistical Package for Social Sciences (SPSS 26.0) by IBM for statistical analysis. The variable Height derived from Height Vertex has been determined as the dependent variable with which the variables LD1, LD2, LD3, LD4, LD5, RD1, RD2, RD3, RD4, RD5, RHL, LHL, RHB, LHB are correlated by calculating the Pearson's Co-efficient of Correlation (r) and co-efficient of determination (r^2) at $p < 0.001$ for both sexes. A regression analysis between the dependent variable: Height and all the other independent variables mentioned above are also done to derive multiple regression equations in the format:

$y=a+b_1x_1+b_2x_2+\ldots\ldots+c_nx_n$

Where, y=Height, a=constant, b_1, b_2.., b_n=co-efficient of independent variable and x_1, x_2.., x_n= value of the predictor variables.

For both hands, statistically significant ($p < 0.05$) predictor parameters are then taken to successfully form a multiple linear regression equation to better predict the height from the selected parameters. All of the measurements were separated based on sex and whether they are from the right or the left side. The best predictors for each hand were then put through backward stepwise multiple regression to make an even more robust regression equation.

RESULTS:

Table I displays the average height with Standard Deviation (SD) in the sample is approximately162.79±6.35cm, with height ranging from 145 to 183.2 cm for males, and 151.34 ± 6.18 cm, with a range from 136.9 to 170.2 cm for females. The mean left hand length (LHL) ±SD is around 17.99 ±0.82 cm for males and 16.82 ±0.81cm for females, whereas for mean right hand length (RHL) ± SD, it is around 17.88 ± 0.83 cm for males and 16.79 ± 0.79 cm for females. For LHB the mean ± SD is around 7.91 ± 0.42 cm for males and 7.25 ± 0.42 cm for females, and for RHB the mean ± SD is around 8.02 ± 0.46 cm for males and 7.41±0.40 cm for females.

Table I: Descriptive Statistics of Measured Variables

	Male (n = 177)					Female (n = 215)				
	Minimum	Mean	SD	Maximum	Excess Kurtosis	Minimum	Mean	SD	Maximum	Excess Kurtosis
Height*	145.00	162.79	6.35	183.20	0.76	136.90	151.34	6.18	170.20	0.22
LD1*	5.00	6.01	0.44	7.20	-0.26	4.40	5.51	0.42	6.80	0.08
LD2*	5.50	6.87	0.40	8.00	0.34	5.50	6.42	0.41	7.90	0.60
LD3*	6.40	7.56	0.43	8.80	-0.10	6.20	7.10	0.46	8.80	0.71
LD4*	5.80	6.92	0.47	8.10	-0.46	5.00	6.53	0.45	7.80	0.23
LD5*	4.60	5.59	0.42	6.70	-0.22	4.10	5.24	0.41	6.50	0.28
LHL*	16.10	17.99	0.82	20.70	0.06	15.00	16.81	0.84	19.70	0.33
LHB*	6.70	7.91	0.42	9.20	0.61	6.10	7.25	0.42	8.50	0.35
RD1*	5.10	6.03	0.38	7.10	-0.09	4.50	5.53	0.39	6.80	0.21
RD2*	5.50	6.81	0.42	7.90	-0.11	5.00	6.40	0.43	7.60	0.54
RD3*	6.40	7.46	0.46	8.70	-0.33	4.60	7.07	0.48	8.20	2.71
RD4*	5.60	6.87	0.50	8.10	-0.36	5.50	6.57	0.44	7.70	-0.20
RD5*	4.60	5.53	0.38	6.80	0.32	4.30	5.20	0.39	6.40	-0.05
RHL*	15.90	17.88	0.83	20.20	-0.01	15.00	16.78	0.81	19.50	0.70
RHB*	6.80	8.02	0.46	9.20	0.03	6.40	7.41	0.40	8.70	0.49

The mean LDR±SD and RDR±SD is 0.99±0.05 and 0.99±0.06 for males, and 0.98±0.05 and 0.97±0.05 for females respectively. Excess kurtosis of value greater than +2 is observed in RD3 among females suggesting leptokurtosis (George & Mallery, 2010), which points towards a non-normally distribution of the said variable necessitating non-parametric tests. Table II shows Pearson's correlation between height and other variables of the hand after a two-tailed significance correlation analysis. At $p<0.01$, RHL scores the strongest: 0.639 in terms of Pearson's r with height, making RHL correlated the strongest with height among males, followed by LHL with a Pearson's r score of 0.626 among hand dimensions. Among females, similarly RHL correlates the strongest with height with a Pearson's r score of 0.432, followed by LHL correlating with a r-score of 0.426 among hand dimensions. In case of digits, among males, LD3 correlates the strongest withar-scoreof0.528withheightandweakest with RD5 with a r-score of 0.319, and among females, RD4 correlates the strongest with a r-score of 0.430 and LD1 correlates the weakest with a r-score of 0.292.

Table II: Correlation of Measured Variables with Height

	Male (n = 177)		Female (n = 215)	
	Pearson's r	**p-value**	**Pearson's r/ Spearman's ρ**	**p-value**
LD1	0.359	<0.001	0.292	<0.001
LD2	0.423	<0.001	0.389	<0.001
LD3	0.528	<0.001	0.376	<0.001
LD4	0.456	<0.001	0.364	<0.001
LD5	0.376	<0.001	0.384	<0.001
LHL	0.626	<0.001	0.426	<0.001
LHB	0.464	<0.001	0.274	<0.001
RD1	0.389	<0.001	0.312	<0.001
RD2	0.467	<0.001	0.473	<0.001
RD3	0.508	<0.001	0.382*	<0.001
RD4	0.410	<0.001	0.430	<0.001
RD5	0.319	<0.001	0.387	<0.001
RHL	0.639	<0.001	0.432	<0.001
RHB	0.380	<0.001	0.314	<0.001

* Spearman's rho co-efficient

Table III and IV show backward stepwise multiple regression models with the measured variables as the independent variables and the height as a dependent variable. For males, for the left-hand digits, LD3 seems to be the most significant predictor variable, with an adjusted R^2 score of 0.275 and for the hand dimensions both LHL and LHB are significant, with an adjusted R^2 score of 0.408. For the right hand, both RD1 and RD3 were found to be significant predictors for the model with an adjusted R^2 score of 0.274 for the digits, and for hand dimensions, only RHL was found to be a significant predictor with an adjusted R^2 score of 0.404. For females, for the left-hand digits, LD2 and LD5 seems to be the most significant predictor variables, with an adjusted R^2 score of 0.167 and for the hand dimensions only LHL was found to be significant, with an adjusted R^2 score of 0.178. For the right hand, both RD2 and RD5 were found to be significant predictors for the model with an adjusted R^2 score of 0.236 for the digits, and for hand dimensions, only RHL was found to be a significant predictor with an adjusted R^2 score of 0.183.

DISCUSSION:

The present study provides a comprehensive assessment of the relationship between stature and hand anthropometry among the Santal population, yielding several important findings that contribute both novel and corroborative insights to the anthropometric and forensic literature. The major highlight of this research is the demonstrated effectiveness of hand length and selected digit measurements as predictors of stature in both sexes, with right-hand measurements consistently outperforming those of the left hand across most parameters.

Table III: Stepwise Multiple Linear Regression Models for the Digits and Hand Dimensions in Males

Predictors	Models											
	1	2	3	4	5	6	7	8	9	10	11	12
Intercept	102.413	102.175	102.231	102.495	104.351	67.822	100.609	100.659	99.387	101.582	71.791	74.909
LD1	1.285	1.262	1.104	1.168	—	—	—	—	—	—	—	—
LD2	–0.221	—	—	—	—	—	—	—	—	—	—	—
LD3	6.632	6.509	6.153	7.043	7.726	—	—	—	—	—	—	—
LD4	1.531	1.511	1.066	—	—	—	—	—	—	—	—	—
LD5	–1.175	–1.190	—	—	—	—	—	—	—	—	—	—
LHL	—	—	—	—	—	4.116	—	—	—	—	—	—
LHB	—	—	—	—	—	2.641	—	—	—	—	—	—
RD1	—	—	—	—	—	—	2.589	2.550	2.382	3.013	—	—
RD2	—	—	—	—	—	—	2.412	2.413	2.227	—	—	—
RD3	—	—	—	—	—	—	5.282	5.151	4.542	5.771	—	—
RD4	—	—	—	—	—	—	–0.186	—	—	—	—	—
RD5	—	—	—	—	—	—	–1.443	–1.464	—	—	—	—
RHL	—	—	—	—	—	—	—	—	—	—	4.623	4.915
RHB	—	—	—	—	—	—	—	—	—	—	1.039	—
R	0.537	0.537	0.534	0.532	0.528	0.644	0.544	0.544	0.540	0.532	0.642	0.639
Adjusted R^2	0.267	0.271	0.273	0.275	0.275	0.408	0.275	0.280	0.280	0.274	0.405	0.404
ΔR^2	0.288	0.000	–0.002	–0.002	–0.004	0.414	0.296	0.000	–0.004	–0.009	0.412	–0.004
SEE (cm)	5.438	5.422	5.416	5.408	5.409	4.889	5.407	5.392	5.392	5.411	4.899	4.902
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Table IV: Stepwise Multiple Linear Regression Models for the Digits and Hand Dimensions in Females

Predictors	Models											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Intercept	110.190	110.225	110.154	111.763	98.541	98.796	108.875	102.518	101.673	102.840	93.382	96.177
LD1	0.039	—	—	—	—	—	—	—	—	—	—	—
LD2	3.005	3.021	2.920	3.497	—	—	—	—	—	—	—	—
LD3	–0.211	–0.204	—	—	—	—	—	—	—	—	—	—
LD4	1.437	1.432	1.341	—	—	—	—	—	—	—	—	—
LD5	2.626	2.638	2.611	3.370	—	—	—	—	—	—	—	—
LHL	—	—	—	—	3.085	3.126	—	—	—	—	—	—
LHB	—	—	—	—	0.130	—	—	—	—	—	—	—
RD1	—	—	—	—	—	—	–0.602	–0.587	—	—	—	—
RD2	—	—	—	—	—	—	5.156	4.977	4.655	5.382	—	—
RD3	—	—	—	—	—	—	–0.470	—	—	—	—	—
RD4	—	—	—	—	—	—	1.528	1.247	1.276	—	—	—
RD5	—	—	—	—	—	—	2.320	2.310	2.210	2.703	—	—
RHL	—	—	—	—	—	—	—	—	—	—	2.922	3.288
RHB	—	—	—	—	—	—	—	—	—	—	1.207	—
R	0.423	0.423	0.423	0.418	0.426	0.426	0.497	0.497	0.496	0.493	0.437	0.432
Adjusted R^2	0.159	0.163	0.167	0.167	0.174	0.178	0.229	0.232	0.235	0.236	0.183	0.183
ΔR^2	0.179	0.000	0.000	–0.004	0.182	0.000	0.247	0.000	–0.001	–0.003	0.191	–0.004
SEE (cm)	5.669	5.655	5.643	5.642	5.618	5.605	5.428	5.416	5.406	5.403	5.588	5.588
p-value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

In males, the third digit of both hands emerged as the strongest correlating variable among the digital measurements, while in females the second digit—particularly of the right hand—showed the highest correlation with stature. Hand lengths in both sexes also showed stronger predictive potential than hand breadths, and regression models incorporating hand-length variables provided higher adjusted R^2 values than models based solely on digit lengths.

Several findings of this study corroborate previously published results. The moderate correlation between digit lengths and stature, as well as the stronger association with hand lengths, aligns with earlier findings in Indian populations such as those reported by Paul et al. (2018).

The observed pattern in which right-hand dimensions generally exceed left-hand dimensions in predictive strength also corresponds with studies conducted among other Indian groups (Agnihotri et al., 2008; Krishan & Sharma, 2007). Similarly, the weak-to-moderate correlation coefficients (r values between 0.1 and 0.5) for most digit variables are consistent with the interpretation proposed by Mukaka (2012), reinforcing the understanding that digit lengths alone are limited—but still useful—predictors of adult stature.

In contrast, this study also produced findings that diverge from earlier research.

Among females, the second and fourth digits of the right hand correlated more strongly with stature than did right-hand length, a pattern not commonly reported in related populations where hand length typically exhibits the strongest association (Pal et al., 2016; Agarwal et al., 2013). Furthermore, in males, the exceptional strength of the third digit as a predictor of stature—including its significant retention in the final regression models—is relatively unique in the existing literature and may represent a population-specific trait warranting further investigation. Additionally, while studies on non-Indian populations (e.g., Tang et al., 2012; Jee & Myung, 2015; Habib & Kamal, 2010) have generally found more symmetrical or left-hand dominant predictive patterns, the marked right-hand dominance observed in the Santal dataset among females stands in contrast to these earlier findings.

Several explanations may account for these population-specific patterns. The strong predictive value of the third digit in males and the second digit in females may reflect underlying sexual dimorphism in hand morphology linked to developmental, genetic, or biomechanical factors. The right-hand dominance seen in females may relate to population-specific functional asymmetry, occupational patterns, or differential usage of hands during growth, which could influence the maturation and relative lengths of digits. The superior performance of hand lengths over digit lengths in regression modeling is likely attributable to the integrative nature of hand length, which captures cumulative variation across multiple bones rather than a single phalangeal unit, thereby providing a more stable relationship with overall skeletal growth.

The results of this study offer several implications for future research and potential applied uses. From a forensic standpoint, the hand-based regression equations derived here may serve as valuable tools for stature estimation in cases involving incomplete remains, especially in regions with substantial Santal populations. Broader anthropological applications include refining population-specific growth models, exploring sexual dimorphism, and contributing to the understanding of morphological variation among Indian tribal groups. Future research should aim to validate these regression equations in independent Santal samples, extend the analysis to incorporate additional skeletal or soft-tissue markers, and compare hand-based models with those derived from foot or facial measurements. Longitudinal studies examining growth patterns and environmental influences may also help clarify the developmental basis of the observed asymmetries.

Finally, this study has notable strengths and limitations. A major strength is the comprehensive approach to hand anthropometry, including all digit lengths and hand-length and breadth measurements, enabling a more exhaustive examination of stature predictors than most of the earlier studies. The sizable and sex-balanced sample adds to the robustness of the findings. However, limitations include the reliance on a cross-sectional design, which restricts conclusions regarding developmental causality, and the focus on a single tribal population, which limits the generalizability of the equations to other ethnic or regional groups. Moreover, environmental and nutritional factors, which may influence hand morphology and stature relationships, were not assessed and warrant investigation in future work.

ETHICAL CONSIDERATIONS:

This study was conducted with compliance to the ethical guidelines set out in the World Medical Association 'Declaration of Helsinki' of 1975, as revised in 2008. All participants were made aware of the purpose and nature of the study along with how their data shall be used, whether there was any security concern for the participants and that no harm was being caused to participants, whether advertently or inadvertently, all according to the ICMR issued 'National Ethical Guidelines for Biomedical and Health Research Involving Human Participants', 2017. The participants who expressed consent, both verbal and written, after thorough understanding of the study's nature and purpose were then sampled for the study.

Conflict of Interest: No existence of potential or present conflict of interest has occurred.

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