JOURNAL OF FORENSIC SCIENCES

J Forensic Sci, September 2013, Vol. 58, No. 5
doi: 10.1111/1556-4029.12231
Available online at: onlinelibrary.wiley.com

TECHNICAL NOTE

ANTHROPOLOGY

Timothy P. Gocha,[1] M.Sc.; Giuseppe Vercellotti,[1] Ph.D.; Lara E. McCormick,[1] Ph.D.; and Traci L. Van Deest,[2] M.A.

Formulae for Estimating Skeletal Height in Modern South-East Asians*

ABSTRACT: Estimating stature in human skeletal remains of Asian ancestry is problematic for forensic anthropologists due to the paucity and uncertain suitability of regression formulae. To address this issue, our study analyzed 64 individuals from a modern skeletal collection of South-East Asian origin and developed population-specific ordinary least squares regression formulae to estimate skeletal height from each of the long bones of the upper and lower limbs, as well as from trunk length. Results indicate that the most accurate estimates of skeletal height from a single bone (as measured by standard error of the estimate—SEE) are from tibial length in males (SEE = 2.40 cm) and from humeral length in females (SEE = 2.59 cm), followed by femoral length (SEE = 2.84 cm). When multiple elements are considered, the combination of femoral and tibial length yields the best estimates in both sexes as well as combined sex samples (male SEE = 2.40 cm; female SEE = 2.77 cm; combined sex SEE = 2.54 cm).

KEYWORDS: forensic science, forensic anthropology, stature estimation, skeletal height, regression formulae, Asian

Estimating stature from human skeletal remains has a long history in physical anthropology; it may inform us as to the health and well-being in the past as well as highlight trends in growth and development at the population level. For the forensic anthropologist, however, the estimation of stature is chiefly important at the individual level. Stature, along with sex, age, and ancestry, is an important component of the biological profile, used in aiding law enforcement and medicolegal agencies to match an unknown set of human remains to a missing person's profile. As such, the accuracy of the demographic data ascertained through osteological analyses is of the utmost concern to forensic practitioners.

The two primary methods employed to reconstruct living stature from skeletal materials are the anatomical method (1–3) and mathematically with the use of regression formulae. The anatomical method provides more accurate estimates by summing the length of all skeletal elements contributing to height and a corrective factor for soft tissues. However, this method cannot be applied to incomplete skeletal remains. In such cases, living stature can be estimated from the length of one or a few skeletal elements through regression techniques. Regression formulae are mathematical models that allow stature prediction on the basis of its covariation with long bone length.

Since the earliest treatise on stature estimation, it has been recognized that the relationship between long bone length and stature varies among populations (4). Accordingly, population-specific methods have been deemed necessary throughout the last century (e.g., 5,6). Historically, the most widely utilized formulae for stature estimation among anthropologists in the United States have been the work of Trotter and Gleser (7,8), who address "White," "Negroid," and "Mongoloid" populations. However, the utility of these formulae in a modern forensic context has been called into question. Ross and Konigsberg (6) have demonstrated that significant heterogeneity exists within these broadly defined ancestral categories, while research by Meadows and Jantz (9) revealed that significant allometric secular changes in long bone length have occurred since the formulae were developed by Trotter and Gleser (7,8). This has led some authors (10) to conclude that the regional and temporal bias of Trotter and Gleser's work renders their formulae wholly inappropriate for modern forensic material.

Efforts to address these concerns have been made, offering updated approaches for stature estimation; at present, the most widely used tool among forensic anthropologists for stature estimation is FORDISC 3.0 (11). Utilizing the Forensic Anthropology Data Bank, FORDISC circumvents the secular problems with Trotter and Gleser's formulae by providing users with comparison data for 20th-century decedents. However, the availability of reference material has limited the realm of inquiry to populations of European American, African American, and Hispanic ancestry. Therefore, until recently, if a forensic anthropologist were to determine an unknown set of human skeletal remains to be of South-East Asian ancestry, stature would have to have been estimated from a Hispanic reference sample in

[1]Department of Anthropology, The Ohio State University, Columbus, OH 43210.
[2]Department of Anthropology, University of Florida, Gainesville, FL 32601.

*Supported in part by an appointment to the Student Research Participation Program at the Joint POW/MIA Accounting Command/Central Identification Laboratory administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and JPAC/CIL.

Received 20 Jan. 2012; and in revised form 3 Sept. 2012; accepted 30 Sept. 2012.

FORDISC, Trotter, and Gleser's "Mongoloid" formulae (7,8), or other outdated formulae that may not be readily available (e.g., 12–14). Fortunately, this deficiency has been recognized, and recent work on a population from northwest Thailand has provided formulae to estimate stature from long bone lengths (15). However, in light of the heterogeneity that has been demonstrated in other ancestral categories (e.g., 6), our study sought to develop formulae for the estimation of skeletal height and subsequently living stature, from a modern South-East Asian population from a different geographic region, as well as to evaluate the performance of our formulae along with other methods for the estimation of stature in remains of Asian ancestry.

Materials and Methods

Skeletal Material

Our study utilized material from the skeletal collection housed at Khon Kaen University in northeast Thailand. The collection comprises *c.* 800 skeletons, including both juvenile and adult individuals. Demographic information, as far as it was known, was recorded for each individual at the time of body procurement. Some of the earliest decedents included in the collection were born late in the 19th century, although most individuals were born during the 20th century. Some of the material is derived from individuals who were in the Thai military, monks, or unclaimed bodies; however, most of the remains are the result of a body donation program. The majority of the collection represents lifelong inhabitants of the rural Isaan Region of Thailand, an area of relatively low socioeconomic status. Some immigrants from both China and Laos are also present in the collection (R.W. Mann, pers. comm., 23 April 2011).

Due to time constraints during data collection, our sample consisted of 64 adult individuals (49 male; 15 female) all of whom died between 1994 and present. Average age at death in the sample was 62.2 years (SD = 16.2), with the sexes showing similar, nonsignificantly different age distributions (Mann–Whitney *U*-test, $p = 0.426$). Recorded information on sex and/or age for each individual was verified via standard osteological techniques, provided that the necessary elements were present (16,17). Documented living height was not available for the remains. While it is acknowledged that the small female sample size may be less than ideal, the inclusion of the female sample will allow for a comparison of methods for stature estimation in South-East Asian populations.

Osteometry and Living Stature Reconstruction

The osteometric measurements employed in the study include skull height (basion–bregma); vertebral column height (calculated as the sum of maximum anterior vertebral body heights from C2 to S1); maximum lengths of the humerus, radius, ulna, femur, tibia, and fibula; femur bicondylar length; tibia condylo-malleolar length; and foot height (measured as the height of talus and calcaneus in articulation using the method described by Raxter et al. [1]). Skeletal height of each individual was calculated as the sum of skull height, vertebral column height, bicondylar femoral length, tibia condylo-malleolar length, and foot height. When supernumerary vertebrae were present, they were included in the vertebral column height, as recommended by Raxter and Ruff (18). Living stature of each individual was consequently calculated from skeletal height using the regression equation developed by Raxter et al. (1,2).

Development of Population-Specific Regression Formulae

Population-specific ordinary least squares regression formulae for estimating skeletal height from incomplete remains were developed by regressing skeletal height on the length of several skeletal elements for male, female, and the combined sex subsample from the Khon Kaen collection. As the leg directly contributes to living stature, the femur and tibia typically produce better estimates and are therefore the long bones most desired for stature estimation. However, lower limb bones may not always be available for analysis. Our study therefore examined the utility of all long bones in isolation, as well as in combinations of different elements for the estimation of skeletal height as follows: (i) maximum femoral length; (ii) bicondylar femoral length; (iii) maximum tibial length; (iv) condylo-malleolar tibial length; (v) maximum fibular length; (vi) maximum humeral length; (vii) maximum ulnar length; (viii) maximum radial length; (ix) skeletal trunk height (C2-S1); (x) sum of bicondylar femoral length, condylo-malleolar tibial length, and combined lumbar segments of the vertebral column; (xi) combined bicondylar femoral length and condylo-malleolar length; (xii) combined humeral and radial length. Regression formulae and r^2 values, standard error of the estimate (SEE), residual mean square (s^2_{yx}), skeletal element(s) mean ($\bar{x}$), and variance (σ^2_x) are reported. In this study, we developed regression formulae for skeletal height rather than living stature, as the former is directly measured while the latter is computed from skeletal height and corrective factors for soft tissues thickness. For applications where living stature is desired, it can be easily calculated by employing the value of skeletal height calculated with our formulae in the methods developed by Raxter et al. (1,2):

$$\text{Living stature} = 1.009 \times \text{Skeletal height} - 0.0426 \times \text{age} + 12.1 \quad (1)$$

$$\text{Living stature} = 0.996 \times \text{Skeletal height} + 11.7 \quad (2)$$

The two different methods are used when age is known (1) or unknown (2), respectively. It should be noted, however, that Raxter et al. (2) recommend the use of age at death in the reconstruction of stature through the anatomical method to better account for age-related stature changes and avoid underestimating stature in younger individuals.

Comparison of Different Regression Methods

To investigate the accuracy of different regression methods in the Khon Kaen sample, skeletal height estimates obtained with our formulae were converted to estimates of living stature through the methods of Raxter et al. (1,2). Those estimates were then compared with living stature estimates produced by other formulae that have previously been used in South-East Asian populations (7,8,12–15). Sex-specific formulae based on the maximum length of limb long bones were used whenever available (Table 1). Given the existence of intrinsic methodological issues related to the mismeasure of the tibia in Trotter and Gleser's (1952) formulae (19), the formula for tibia length is not included in female comparisons. The performance of different regression methods was evaluated by calculating mean percent prediction errors (PPE) for male and female samples. All mean PPEs were calculated as 100 × [(regression estimate − anatomical estimate)/anatomical estimate]. Statistical analyses were performed using Microsoft Excel 2007 (Microsoft Corporation,

TABLE 1—*Regression formulae employed in the comparative analysis.**

Method	Femur	Tibia†	Fibula	Humerus	Radius	Ulna
Males						
Trotter and Gleser (1958)—"White"	2.38 × Fem + 61.41	2.42 × Tib + 81.93	2.60 × Fib + 75.5	2.89 × Hum + 78.10	3.79 × Rad + 79.42	3.67 × Uln + 75.55
Trotter and Gleser (1958)—"Mongoloid"	2.15 × Fem + 72.50	2.39 × Tib + 81.40	2.40 × Fib + 80.56	2.68 × Hum + 83.19	3.54 × Rad + 82.00	3.48 × Uln + 77.45
Sangvichien et al. (1985)	1.7289 × Fem + 88.13	2.7638 × Tib + 62.69	2.5992 × Fib + 71.04	—	—	—
Taik and San (1972)	2.227 × Fem + 68.10	3.063 × Tib + 53.82	3.237 × Fib + 50.34	3.904 × Hum + 45.97	4.313 × Rad + 61.49	4.415 × Uln + 49.90
Shitai (1983)	2.26 × Fem + 63.8	3.01 × Tib + 54.13	3.02 × Fib + 52.79	3.71 × Hum + 47.20	3.26 × Rad + 84.75	3.14 × Uln + 81.85
Mahakkanukrauh et al. (2011)	2.722 × Fem + 45.534	3.015 × Tib + 52.946	3.139 × Fib + 50.796	3.22 × Hum + 64.224	3.884 × Rad + 67.947	3.824 × Uln + 63.098
Females						
Trotter and Gleser (1952)—"White"	2.47 × Fem + 54.1	—	2.93 × Fib + 73.4	3.63 × Hum + 60.47	4.74 × Rad + 57.43	4.27 × Uln + 60.26
Sangvichien et al. (1985)	2.5815 × Fem + 49.24	2.9716 × Tib + 51.60	2.4256 × Fib + 71.49	—	—	—
Taik and San (1972)	2.34 × Fem + 58.46	3.436 × Tib + 36.92	2.922 × Fib + 58.46	3.00 × Hum + 67.22	2.864 × Rad + 88.70	3.043 × Uln + 79.67
Mahakkanukrauh et al. (2011)	2.778 × Fem + 40.602	2.620 × Tib + 63.089	2.629 × Fib + 64.562	2.911 × Hum + 69.424	3.459 × Rad + 75.275	3.323 × Uln + 72.792

*All formulae use the maximum length of the skeletal element, in centimeters.
†Trotter and Gleser's (1952) formulae for stature estimation from the tibia were not included in the comparison due to intrinsic methodological issues related to the mismeasure of the tibia by these authors (18).

Redmond, WA) and SPSS Statistics 18.0 (IBM Corporation, Armonk, NY).

Results

Descriptive statistics for the measurements included in the analysis, skeletal height, and reconstructed living stature for the Khon Kaen sample are reported in Table 2. Sexual dimorphism is apparent in all measurements, with female stature amounting to 94% of male stature in this sample. This follows the trend noted in previous studies of Thai sexual dimorphism, where the lengths of female femora and humeri were found to be approximately 93% of male elements (20,21).

Table 3 reports the ordinary least squares regression equations for calculation of skeletal height from single and multiple body segments in the male, female, and sex-combined Khon Kaen subsamples, along with r^2, SEE, s^2_{yx}, $\bar{x}$, and σ^2_x—these parameters can be used to calculate confidence intervals for individual stature estimates (22). The formulae based on femur + tibia and tibia length provide the best estimates in the male subsample, while formulae based on other long bones and the trunk are characterized by larger errors. In the female subsample, good estimates are provided by the formulae combining multiple elements or based on lower limb long bones; with the exception for humeral length, upper limb bones and the trunk are less preferable predictors of skeletal heights in females. When the sex-combined subsample is considered, the formulae employing tibia measurements (alone or combined with other skeletal elements) provide the best estimates. All other formulae for the sex-combined sample predict skeletal height with less accuracy, but still provide relatively better results than the same sex-specific formulae.

TABLE 2—*Descriptive statistics for the South-East Asian sample included in the study.**

Skeletal Element	*N*	Minimum	Maximum	Mean	Std. Deviation
Males					
Basion–Bregma	49	12.90	14.80	13.77	0.46
Vertebral column	49	43.80	54.40	49.56	2.23
Humerus	49	28.35	32.90	30.60	1.04
Radius	49	21.75	26.00	24.23	0.95
Ulna	49	23.25	27.70	25.88	1.00
Maximum femur	49	39.10	46.40	43.15	1.47
Bicondylar femur	49	38.85	46.00	42.84	1.47
Maximum tibia	49	32.85	39.05	36.14	1.39
Condylo-malleolar tibia	49	32.45	38.65	35.57	1.42
Fibula	49	31.90	38.25	35.37	1.37
Foot height	49	5.05	7.75	6.38	0.66
Skeletal height	49	137.40	158.05	148.12	4.68
Stature†	49	147.50	169.00	158.96	4.81
Females					
Basion–Bregma	15	12.50	14.50	13.37	0.57
Vertebral column	15	43.80	52.30	46.37	2.07
Humerus	15	25.05	30.75	28.54	1.54
Radius	15	19.55	23.75	22.23	1.19
Ulna	15	21.20	25.55	23.85	1.25
Maximum femur	15	35.05	43.45	40.38	2.15
Bicondylar femur	15	34.80	43.15	40.03	2.14
Maximum tibia	15	30.25	35.95	33.93	1.87
Condylo-malleolar tibia	15	29.75	35.70	33.39	1.85
Fibula	15	28.80	35.80	33.19	2.05
Foot height	15	4.75	7.10	5.87	0.73
Skeletal height	15	127.20	152.10	139.04	5.90
Stature†	15	136.60	162.10	149.68	5.98

*All measurements are reported in centimeters.
†Estimate obtained through the revised anatomical method (Raxter et al. 2006, 2007).

TABLE 3—*Regression formulae developed on the South-East Asian sample and relative statistical parameters.**

Skeletal Element	Formula	r^2	SEE	s^2_{yx}	N	$\bar{x}$	σ^2_x
Males							
Femur (max)	2.44 × FeMax + 43.1	0.586	3.043	9.263	49	43.146	2.166
Femur (bicondylar)	2.44 × FeBic + 43.4	0.587	3.039	9.235	49	42.840	2.156
Tibia (max)	2.88 × TibMax + 44.0	0.727	2.472	6.113	49	36.143	1.919
Tibia (condylo-malleolar)	2.85 × TibCM + 46.8	0.743	2.399	5.757	49	35.569	2.007
Fibula	2.67 × Fib + 53.5	0.610	2.955	8.730	49	35.371	1.868
Humerus	2.95 × Hum + 57.7	0.428	3.579	12.809	49	30.604	1.074
Ulna	3.65 × Uln + 53.6	0.608	2.963	8.779	49	25.876	0.999
Radius	3.88 × Rad + 54.0	0.616	2.931	8.589	49	24.234	0.895
Vertebral column	1.74 × Vert + 62.0	0.682	2.669	7.124	49	49.559	4.951
Femur + tibia + lumbar	1.42 × (FeBic + TibCM + Lumb) + 18.8	0.647	2.811	7.903	49	90.787	6.983
Femur + tibia	1.48 × (FeBic + TibCM) + 31.9	0.743	2.399	5.757	49	78.409	7.411
Humerus + radius	1.99 × (Hum + Rad) + 38.9	0.604	2.977	8.860	49	54.838	3.340
Females							
Femur (max)	2.43 × FeMax + 40.9	0.785	2.839	8.060	15	40.377	4.622
Femur (bicondylar)	2.45 × FeBic + 40.8	0.791	2.797	7.822	15	40.033	4.575
Tibia (max)	2.65 × TibMax + 49.2	0.708	3.305	10.926	15	33.927	3.513
Tibia (condylo-malleolar)	2.65 × TibCM + 50.4	0.695	3.383	11.444	15	33.393	3.429
Fibula	2.49 × Fib + 56.3	0.750	3.062	9.376	15	33.193	4.197
Humerus	3.46 × Hum + 40.1	0.821	2.590	6.709	15	28.543	2.379
Ulna	3.75 × Uln + 49.7	0.630	3.723	13.860	15	23.853	1.562
Radius	3.70 × Rad + 56.9	0.559	4.067	16.537	15	22.227	1.423
Vertebral column	2.17 × Vert + 38.2	0.583	3.955	15.638	15	46.373	4.289
Femur + tibia + lumbar	1.25 × (FeBic + TibCM + Lumb) + 31.5	0.778	2.885	8.324	15	86.267	17.407
Femur + tibia	1.36 × (FeBic + TibCM) + 39.1	0.795	2.771	7.677	15	73.427	14.934
Humerus + radius	1.91 × (Hum + Rad) + 42.3	0.740	3.124	9.760	15	50.770	7.086
Combined							
Femur (max)	2.72 × FeMax + 30.2	0.766	3.063	9.381	64	42.497	4.076
Femur (bicondylar)	2.72 × FeBic + 31.1	0.770	3.038	9.231	64	42.182	4.095
Tibia (max)	3.17 × TibMax + 33.1	0.799	2.837	8.050	64	35.623	3.138
Tibia (condylo-malleolar)	3.16 × TibCM + 35.1	0.800	2.831	8.016	64	35.059	3.154
Fibula	3.02 × Fib + 40.6	0.746	3.191	10.182	64	34.861	3.221
Humerus	3.61 × Hum + 37.2	0.701	3.462	11.987	64	30.121	2.121
Ulna	4.01 × Uln + 44.2	0.754	3.140	9.861	64	25.402	1.854
Radius	4.12 × Rad + 48.1	0.746	3.193	10.198	64	23.763	1.733
Vertebral column	2.11 × Vert + 42.8	0.744	3.201	10.249	64	48.813	6.575
Femur + tibia + lumbar	1.54 × (FeBic + TibCM + Lumb) + 7.79	0.776	2.997	8.980	64	89.727	12.913
Femur + tibia	1.57 × (FeBic + TibCM) + 24.9	0.839	2.542	6.460	64	77.241	13.490
Humerus + radius	2.07 × (Hum + Rad) + 34.2	0.778	2.984	8.904	64	53.884	7.136

*r-Squared value (r^2), standard error of the estimate (SEE), residual mean square (s^2_{yx}), sample size (N), skeletal element(s) mean ($\bar{x}$) and variance (σ^2_x).

TABLE 4—*Mean percent prediction errors (PPE)* for the regression formulae compared in this study.*

		Femur†		Tibia		Fibula		Humerus		Radius		Ulna	
Formula	Sample	F	M	F	M	F	M	F	M	F	M	F	M
Present Study	Thai	0.35	0.36	0.43	0.17	0.32	0.09	0.24	0.13	0.47	0.14	0.47	0.15
Trotter and Gleser (1952, 1958)	White	2.81	3.27	—	6.60	14.05	5.39	9.66	4.83	8.81	7.78	8.36	7.31
Trotter and Gleser (1958)	Mongoloid	—	4.01	—	5.62	—	4.13	—	3.99	—	5.60	—	5.41
Sangvichien et al. (1985)	Thai and Chinese	2.56	2.42	1.86	2.31	1.60	2.56	—	—	—	—	—	—
Taik and San (1972)	Burmese	2.22	3.33	2.56	3.52	3.88	3.73	2.16	4.12	1.88	4.46	1.80	3.28
Shitai (1985)	Southern Chinese	—	1.52	—	2.51	—	0.44	—	1.16	—	3.06	—	2.65
Mahakkanukrauh et al. (2011)	Thai	2.08	2.56	1.58	1.89	1.47	1.83	1.94	2.44	1.73	1.99	1.66	1.97

F, female; M, male.
*PPE was calculated as 100 × [(regression estimate−anatomical estimate)/anatomical estimate].
†All formulae reported here used maximum length of the skeletal element indicated.

Table 4 reports the mean PPEs for all regression methods employed. As expected, the results of the comparative analysis indicate that our formulae provided the best stature estimates in the Khon Kaen sex-specific samples, with mean PPE values between 0.09 and 0.36 for males and between 0.32 and 0.47 for females. In general, the formulae developed on specific Asian populations (12–15) provide estimates with lower mean PPEs than those of the formulae developed by Trotter and Gleser (7,8) on "Mongoloids" and "Whites." However, all of the other formulae examined show mean PPE values at least four times as large as for the present method, and their performance is inconsistent for different skeletal elements. It is particularly interesting that the equations for Thais recently developed by Mahakkanukrauh et al. (15) are characterized by relatively large mean PPEs, in line with the other equations for other South-East Asian populations. This result suggests that the body proportions of the population from Chiang Mai—on which Mahakkanukrauh et al. (15) developed their equations—may be significantly different from those of the individuals from Khon Kaen. This finding cautions from assuming that Thais from different parts of the country have similar body proportions and that the formulae developed on a specific sample may be applicable to all Thai remains regardless of geographic location. Clearly, future work is needed to determine the nature and extent of biological variation in stature and body proportions in Thailand. Such research should take into account a variety of different factors, including ethnic admixture, ecogeographic adaptations, and different life and population histories.

Conclusions

Accurate stature estimation from skeletal remains is an integral part of developing a biological profile for the identification purposes in forensic anthropology. When the anatomical method for stature estimation is not applicable, population-specific regression equations are the preferred method. In this study, we developed population-specific regression equations for estimating skeletal height in modern South-East Asians from several skeletal elements; these estimates can easily be converted into estimates for living stature through the formulae provided by Raxter et al. (1,2). Further, we compared the accuracy of our formulae with that of other methods commonly employed in South-East Asian populations. Results indicate that our formulae provide better stature estimates for the individuals in this sample than methods developed on other South-East Asian and Thai populations. The formulae developed in this study may be employed to more accurately estimate living stature from skeletal remains from Khon Kaen and possibly from northeastern Thailand, although due to the small sample size the formulae should be used with caution until the sample here can be supplemented. Future work by the authors will address this need, while further research should be conducted to test these formulae on other documented collections from Thailand and South-East Asia.

Acknowledgments

The authors would like to acknowledge the individuals who graciously donated their remains, known in Thai as "Ajarn Yai," meaning "Great Teacher," making this project possible. Thank you to Professor and Dr. Panya Tuamsuk of the Department of Anatomy at the Khon Kaen University Medical School for kindly providing access to the skeletal material utilized in this study. Thanks also to Dr. Robert Mann and Larry T. Boston for their suggestions and comments on the manuscript and to Mr. Brian Shottenkirk who helped in the collection of data.

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Additional information and reprint requests:
Timothy P. Gocha, M.Sc.
Department of Anthropology
The Ohio State University
4034 Smith Laboratory
174 West 18th Avenue
Columbus, OH 43210
E-mail: gocha.3@osu.edu