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Should We Estimate Biological or Forensic Stature?

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ABSTRACT: Trotter and Gleser's stature regression equations were derived from partly incorrect measurements of long bones and antemortem measured statures (MSTATs). Forensic anthropologists have applied these equations to correctly measured bones and compared resulting estimates to a forensic stature (FSTAT), usually obtained from a driver's license. Forensic anthropologists have also used Trotter and Gleser's standard error as a stature prediction range, despite published warnings that it is not wide enough for this purpose. The combination of these factors has resulted in inaccurate and unrealistically precise estimates of stature from the long bones. Several factors decrease the accuracy of measured statures, and a reanalysis of Trotter's data reveals that estimating a biological stature is more imprecise than previously supposed. For FSTATs, these estimates are inaccurate as well. Using data from the Forensic Data Bank, new regression equations for predicting FSTAT were calculated, and in some cases are more precise than regressions based on Trotter's data using MSTATs. Confidence intervals for a single prediction, or prediction intervals, were calculated and are superior to standard errors for providing a range for stature estimations.

KEYWORDS: physical anthropology, human identification, stature estimation, forensic stature, linear regression, prediction intervals

Along with eye color and weight, the stature on a driver's license was a much more important piece of data for identification of the living when driver's licenses did not have a photograph. Driver's license stature (DLSTAT) is still valuable for the identification of human remains because it is the usual source for stature in the NCIC or missing person reports. These forensic statures (FSTATs) are most often compared to stature estimates using equations based on measured statures (MSTATs) provided by Trotter [*1*]. Trotter's equations may not provide correct estimates of FSTAT for several reasons. First, any estimations employing the tibia are questionable because Trotter's tibia measurements are incorrect [*2*]. Second, FSTATs are usually higher than MSTATs [*3*]. Third, MSTATs taken from the living or from cadavers are more variable and dynamic than has been assumed, and forensic anthropologists are using a range for stature estimations that is too narrow [*4–6*]. Finally, secular allometric increases in the long bones have made stature estimation equations based on earlier populations inaccurate [*7*]. While supposedly inaccurate, DLSTATs are on the whole accurate and highly correlated to MSTATs, though DLSTATs are less precise. Using modern populations from the Forensic Data Bank (FDB), new regression equations were calculated using correct bone measurements and FSTATs. These equations show prediction intervals (PIs) close to those derived using MSTATs.

Before examining the qualities of measured and forensic statures, a clarification of accuracy and precision is in order. Figure 1a illustrates accuracy without precision: The hits are near the center, and the average hit would be in the innermost region. Figure 1*b* shows greater precision than 1*a* but with less accuracy. This has been the usual outcome when forensic anthropologists estimate stature and compare it to an FSTAT. Figure 2 clarifies these points in the context of linear regression. Figure 2*a* is a regression with

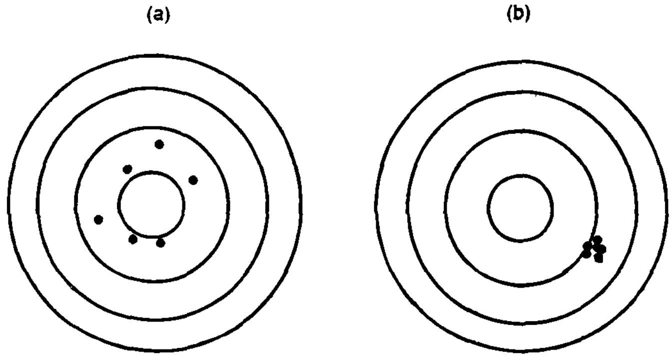

FIG. 1—*Target precision and accuracy.*

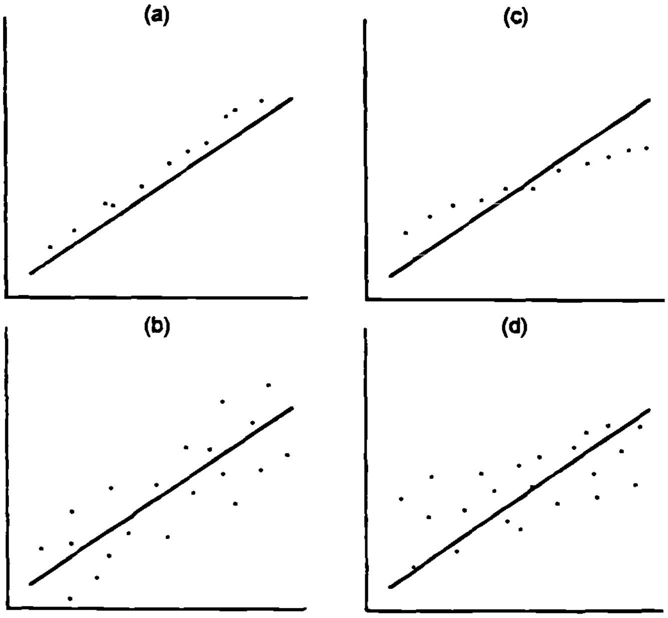

FIG. 2—*Regression precision and accuracy.*

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an incorrect intercept though the data are fairly uniform. Although inaccurate, a recalculated regression could be more accurate and precise in this case. This can happen when regression equations from one data set are applied to another data set, as when a regression based on living stature is applied to cadaver statures (CSTATs). The regression in Fig. 2*b* cannot be very precise, although it is more accurate on the whole. While the data points are relatively far from the regression line, the average least squares deviation will be zero. This is the general pattern of stature estimations using the long bones. Figure 2*c* illustrates changing accuracy depending on x values because an equation derived from another sample, with a different slope, was applied to this data. The mean difference between the predicted values and the actual values in this case may be near zero, but the predicted values are close to the actual values only near the mean of x. This situation occurs when applying Trotter's equations to FSTATs [*7*]. Assuming greater precision makes these estimations even more inaccurate because many actual statures are outside a prediction range that is too narrow. Notice as in 2*a* that a refitted regression equation *could* be more accurate. However, when combined with the actual inaccuracy of any stature estimation from the long bones, new equations derived from MSTATs applied to FSTATs produce the pattern seen in Figure 2*d*. This paper will illustrate that the precision of any stature prediction cannot be very great but the accuracy can be improved in predicting FSTATs, as in Figure 2*b*.

Measured Statures

Whether taken from a cadaver or the living, MSTATs should provide the best possible estimate of biological stature if they satisfy two criteria. First, they should be measured directly and not taken from photos. Second, they should be systematically measured following guidelines (for example, Lohman et al. [*8*]). There are several difficulties with measured statures in general (extensively summarized by Giles and Hutchinson [*9*]), and with Trotter's data and analysis in particular.

Interobserver error is the most serious problem of measured statures. Snow and Williams [*10*] reported statures taken on one criminal by police that differed by as much as 5″ and by medical staff as much as 2″. Several cases in the Forensic Data Bank illustrate this problem. One case (FDN 346) has statures collected by military technicians that varied as much as 4″. Another case (FDN 1212) has several sources for stature, two presumably measured and one estimated: Police had the decedent's height as 5′ 7″; medical personnel recorded his height as 5′ 8″; and his sister filled out a missing person report with his height as 5′ 9″.

CSTATs have been estimated to be 2.5 centimeters (cm) greater than standing stature [*11*], but it is doubtful that a constant can be applied to all cadavers regardless of age, body proportions, and height. In the Forensic Data Bank, one individual (FDN 1257) was photographed against a scale while alive, and after death his cadaver stature was 2″ greater than in the photograph. It is also uncertain in photographs if the shoes were removed. CSTATs collected at the University of Tennessee-Knoxville are quite variable compared to long bone lengths (see Results).

MSTATs on the living are also affected by time of day and age. Kobayashi and Togo [*12*] explored diurnal stature decreases due to compression of the intervertebral disks and heel pads. Stature is highest when one first rises and decreases soon after, but it increases when one naps or takes a bath. Stature loss (as much as 2 cm) is greatest after 6 to 7 hours without lying down, but a 2 hour nap can increase stature by at least 1 cm. Changes of this magnitude are greater than the estimated loss of height with age. Trotter and Gleser [*13*] arbitrarily estimated a small annual loss in stature beginning at age 30. Longitudinal studies indicate that height loss begins later and proceeds at a greater rate [*14,15*], and shows sex differences as well as a greater rate of loss with age [*16*]. Due to the loss of height with age, Galloway [*17*] recommended estimating a maximum height as well as an age-adjusted height for forensic reports.

There are also problems specific to the Trotter and Gleser stature regression equations [*1,11,18*]. As Meadows and Jantz [*7*] point out, they are inappropriate for estimating the stature of modern Americans because of secular allometric increases. Also, Trotter's mismeasurement of the tibia (her exclusion of the medial malleolus in measurements) has affected estimations involving the tibia [*2*].

There is a serious misunderstanding of Trotter's published standard errors and stature prediction ranges. Many forensic anthropologists have used Trotter's standard errors for the prediction range in stature estimation. The Forensic Data Bank receives copies of case reports, and most stature estimates based on femur and tibia measurements have a ± 1.5″ range, a rounded up conversion of Trotter's standard error of 2.99 cm. Trotter [*1*] and Stewart [*5*] recommended doubling the standard error to be correct 95% of the time, but these recommendations have not been followed. Giles and Klepinger [*4*] pointed out that doubling the standard error is not enough because the slope and intercept are also estimated and have their own error terms, which result in parabolic PIs that preclude rules of thumb for prediction ranges (Fig. 1 in [*4*]). In their example, the correct PI (± 11.35 cm) was almost 2 inches wider than the investigators' PI, 2 times the standard error (± 8.9 cm).

Forensic Statures

The main concern with forensic statures is their supposed inaccuracy. Willey and Falsetti [*3*] recorded driver's license statures (DLSTATs) and measured stature from over 500 college students. They found that on average, male DLSTATs are about half an inch greater than measured statures and female heights are less than 1/4 inch greater. These average differences are not large (especially when one considers diurnal variation) and are reasonably accurate on the whole. The greater problem with DLSTATs is their imprecision. Based on the mean and standard deviation of DLSTAT-MSTAT for males, a 95% confidence interval for DLSTAT is from 2 inches less than MSTAT to over 3 inches above MSTAT. Willey and Falsetti also warned that a source of error in DLSTATs may be due to failure to update DLSTAT after first issue despite subsequent growth. This is illustrated by a case in the Forensic Data Bank. A 24 year old male (FDN 1086) had a DLSTAT of 5′ 1″, but an estimate of his stature based on long bones is about 8″ greater. His family and the police knew he was in fact taller at death.

A more in-depth comparison of MSTAT and self-reported stature was performed by Giles and Hutchinson [*9*], who studied a large multiracial sample of military personnel. They found that reported statures, the statures the subjects believed themselves to be, are highly correlated to MSTATs. They also determined that taller people overestimate their stature less. This implies that FSTAT regressions would have a different slope from MSTATs, which would contribute to the imprecision of estimations.

Giles and Hutchinson also found that older people overestimate their stature more often, probably reflecting their maximum height at an earlier age. This is also reflected in their DLSTATs. Older persons, who are undergoing height reduction, do not change their

DLSTATs every year (if ever) [19]. Since both forensic statures and long bone lengths do not decrease with age, their relationship should not change over all adult age ranges: The same regression equation would apply to all ages, with no age adjustment needed. This is one advantage of FSTATs.

The main advantages of FSTATs are their abundance and ease of access. While finding out whether an MSTAT for a possible identification was recorded and where it is located can be difficult, everyone who has a driver's license has an FSTAT. There is also no diurnal variation in FSTATs. Given the potential shortcomings of MSTATs, a regression based on readily available FSTATs would seem to be much more valuable in a forensic context, since stature estimates are most often compared to the FSTAT of a possible identification.

To address these concerns, regressions based on MSTATs will be compared to FSTATs and evaluated in terms of accuracy and precision. Then, the precision of MSTAT estimation will be compared to FSTAT estimation. The value of MSTAT regressions for forensic applications is debatable if their accuracy and precision are not significantly greater than that of FSTATs.

Materials and Methods

Trotter's Terry and World War II data were acquired by Lee Meadows and made available to the author, and DL heights were available from 192 individuals in the Forensic Data Bank that also have long bone measurements. Most forensic data were collected in Tennessee, and the most numerous data are from white males.

Trotter's regression equations were first applied to long bone lengths and compared to FSTATs and CSTATs in the FDB to test for precision and accuracy. Next, Trotter's Terry and World War II data were reanalyzed using SAS [20] to measure the precision of MSTAT linear regression. Then, new regressions were calculated to estimate the precision and accuracy of FSTAT prediction.

The measure of precision will be based on the standard error and PI for a single prediction of Y based on the mean X value, well summarized in [4]. PIs reflect the precision of a prediction better than using the standard error because they take sample size into account and have an explicit probability: with a 90% PI, 10% of predictions will be outside this range. PIs are for a random variable, and thus are wider than confidence intervals, which are dependent on the regression distribution and parameter inferences [21]. Since the PIs at the mean have the smallest range, PIs from the mean, minimum, and maximum of several measurements were calculated to specifically address points raised by Giles and Klepinger [4].

Results and Discussion

Figure 3 is a plot of predicted stature using Trotter's [1] formula for femur + tibia length versus forensic stature with ± 1 standard error bands. Many cases are outside this range. Near the bottom center is the 24 year old male who did not update his DLSTAT. The overall trend is to underestimate FSTAT, especially the greater statures, suggesting that accuracy can be improved by adjusting the slope [22], as in Fig. 2*d*.

Table 1 shows the accuracy of applying Trotter's equations for femur + tibia length to cases in the FDB. While adjusted cadaver statures are slightly overestimated except for white females, forensic statures are underestimated except for black females. These patterns may be partly due to Trotter's exclusion of the medial malleolus, which increases the stature estimation using a correctly measured tibia. For FSTATs, the increase is not enough. On the whole, the Trotter equations would seem fairly accurate except for black females.

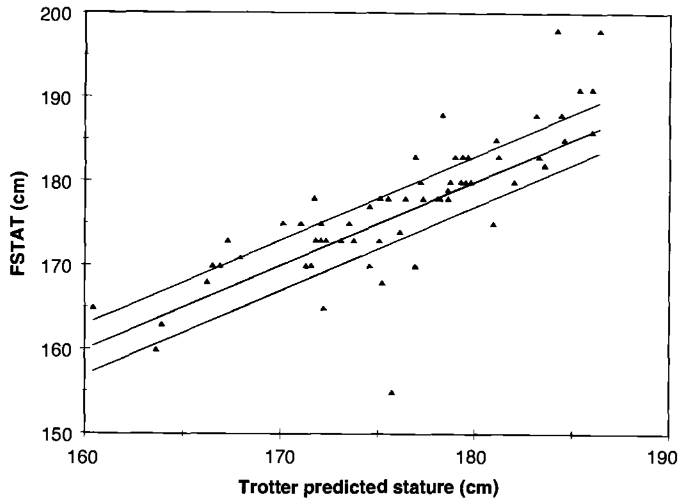

FIG. 3—*Predicted stature from the Trotter* [1] *formula for femur + tibia length compared to forensic stature with ± 1 standard error bands.*

TABLE 1—*Trotter* [1] *stature estimations using femur+ tibia applied to cases in the FDB.*

	Trotter Predicted Stature-Stature	
	Cadaver-2.5 *N*	Forensic *N*
White Males	1.6 cm (37)	−1.4 cm (63)
White Females	−1.2 cm (10)	−1.7 cm (42)
Black Males	.6 cm (17)	−1.9 cm (15)
Black Females	1.3 cm (14)	2.4 cm (13)

Table 2 shows the number of FSTATs falling outside one and two standard errors of Trotter [1] predicted values. On the whole, ± 1 standard error leaves out 40% of all cases, and ± 2 standard errors excludes 10% of all cases. In most cases, using one or even two standard errors for an estimation range is being unrealistically precise. The distribution of FSTATs meets the expectations of an appropriate equation only for white females, and the equation for black males is especially inaccurate. The aforementioned concerns of stature estimation using Trotter's equations and standard errors [2,4,7,22] are well justified by these results.

TABLE 2—*Forensic statures falling outside Trotter* [1] *estimation ranges.*

		FSTATs outside +/−1 se	FSTATs outside +/−2 se
White Males	(63)	26 (41%)	8 (13%)
White Females	(42)	10 (24%)	2 (5%)
Black Males	(16)	9 (56%)	3 (19%)
Black Females	(13)	6 (46%)	1 (8%)
Total	(134)	51 (40%)	14 (10%)

The Trotter estimations were compared to CSTATs in the FDB to see whether imprecision is merely a function of FSTATs (Table 3). CSTATs are even more variable than FSTATs, especially for white males. Nearly half of the estimates are greater than 1 standard error from the CSTAT.

Using Trotter's equations to predict forensic or cadaver stature may be fairly accurate on the whole but is inappropriate because of slope differences, resulting in inaccuracy for estimating an individual case, as in Fig. 2*d*. To put these results into perspective, the precision of stature estimation was calculated from Trotter's Terry Collection data. As Jantz et al. [*2*] have pointed out, Trotter measured long bones consistently if in part incorrectly. CSTATs from the Terry Collection were recorded to the nearest mm and should provide reliable statures, and the accuracy will be optimal since least squares regression was recalculated. Trotter's measurements of the tibia and femur for White Males in the Terry collection were reanalyzed and are plotted with a 90% PI in Fig. 4. For these data, a 90% PI is ± 6.1 cm, almost 5″ total. In this case, the PIs are only slightly parabolic. In contrast, Fig. 5 shows the PIs for black females from the Forensic Data Bank based on ulna length, showing how small sample size and greater variation around the regression line create PIs that are wider and more parabolic, as noted before [*4*]. Secular stature increases and the loss of height with age could affect the precision of estimates within the Terry Collection, which includes young and quite old adults. Using a subset of Trotter's Terry sample with ages between 20 and 50 did not improve the precision, however.

Trotter's World War II data, with a large number of white males in restricted age and birth year ranges, would appear ideal for stature estimation. Statures were recorded to the nearest 1/4″ by technicians at induction centers according to standardized procedures [*11*]. The regression plot is shown in Figure 6 with a 90% PI. This stature estimation, under the best circumstances, has a 90% PI of ± 5 cm, or 4″ in total. Some cases with nearly the same tibia and femur lengths differed in stature by at least 7 inches. Clearly, there are other significant factors contributing to measured stature besides long bone length, such as the length of the vertebral column (which shows a lower correlation than long bone lengths to stature [*22*]), innominate height, and skull height. Some interobserver errors are also likely. As a result, *no* available database can give a ± 1.5″ range for reliable predictions from long bone lengths.

Figure 7 shows a regression of tibia + femur length on FSTATs with a 90% PI. Table 4 is a comparison of the precision of the different stature regressions based on femur + tibia length. The highest accuracy was obtained using Trotter's World War II data. Forensic statures perform very well when one considers that there is some secular increase in the FDB, which also includes individuals from all adult age ranges. The figure of ± 6.4 cm for FSTATs is very close to the Terry figure and not much wider than that for Trotter's World War II data. CSTATs, most of which were collected

TABLE 3—*Adjusted cadaver statures falling within Trotter* [1] *stature estimations.*

		CSTATs outside +/−1 se	CSTATs outside +/−2 se
White Males	(37)	23 (62%)	13 (36%)
White Females	(10)	4 (40%)	1 (10%)
Black Males	(17)	5 (30%)	0
Black Females	(14)	6 (43%)	0
Total	(78)	38 (49%)	14 (18%)

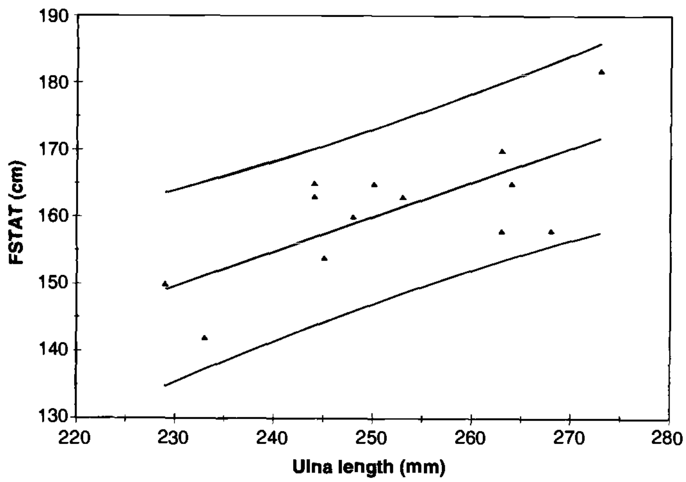

FIG. 5—*Regression of FSTAT on ulna length for black females in the Forensic Data Bank with a 90% PI.*

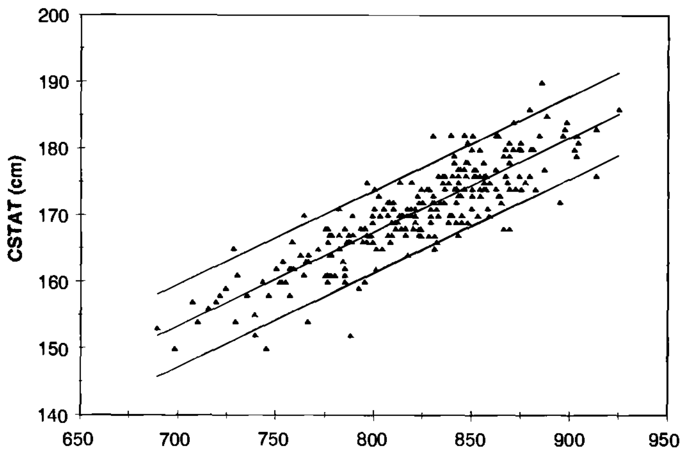

FIG. 4—*Regression of CSTAT on femur + tibia length from Trotter's Terry Collection data for white males with a 90% PI.*

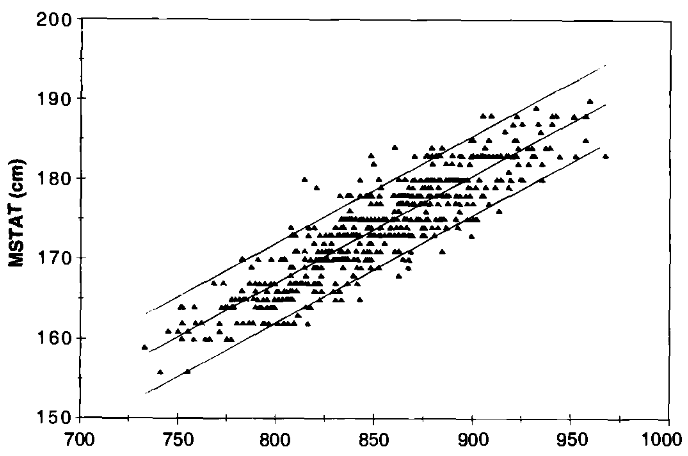

FIG. 6—*Regression of MSTAT on femur + tibia length from Trotter's WWII data for white males with a 90% PI.*

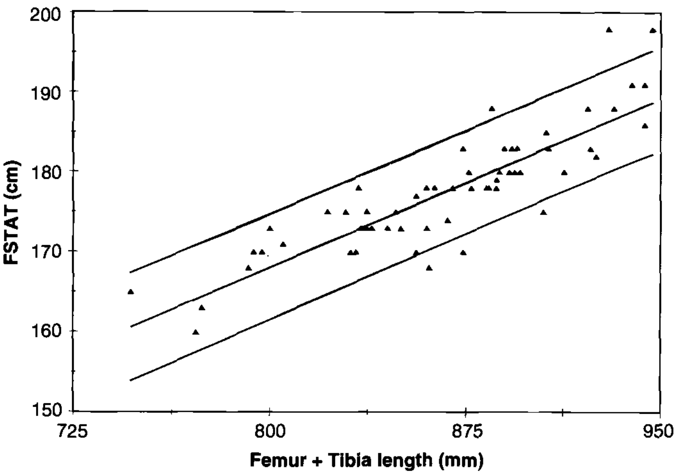

FIG. 7—*Regression of FSTAT on femur + tibia length for white males in the Forensic Data Bank with a 90% PI.*

TABLE 4—*Precision of recalculated stature estimation for white males using femur+tibia length, by sample.*

Sample	N	s.e.	90% C.I.	95% C.I.
Trotter WWII	255	3.02	±5.0 cm	±6.0 cm
Trotter Terry	545	3.70	±6.1 cm	±7.3 cm
Forensic	62	3.78	±6.4 cm	±7.7 cm
Cadaver	37	5.10	±8.7 cm	±10.5 cm

at Knoxville, show a larger PI. For females, Trotter's [*1*] published standard error of 3.55 cm based on femur + tibia length from 63 Terry collection white females (with CSTATs) is identical to the standard error in estimating 42 white female FSTATs. Using the femur alone, estimating FSTAT shows a lower s.e. (3.51 cm) than Trotter's published value (3.72 cm). Thus, some estimates of FSTATs from bone lengths can be as precise as Trotter's estimates based on CSTATs.

Table 5 shows regression equations to estimate FSTATs from long bone lengths with 90% PIs. Although the bone measurements should be in millimeters, all constants were converted to predict statures and prediction intervals in inches because most statures are recorded in inches. For example, if the maximum length of the femur from a probable white male is 454 mm, the forensic stature is estimated by: 0.10560 (454) + 19.39 = 67.33 ± 2.8. This person, if a white male, would have a roughly 90% chance of having a forensic stature between 64.5 and 70.1 inches (5 feet, 4-1/2″ and 5 feet, 10″). The 95% prediction intervals for these equations can be obtained by multiplying the ± figures by 1.2. The figures for Blacks are from small sample sizes, reflected in wider PIs than for Whites, and should be considered preliminary. Black females have sample sizes sufficient only for stature estimation based on femur length.

Since the PIs given in Table 5 were calculated based on mean bone lengths, where they are narrowest, PIs were calculated for the minimum and maximum of several bone lengths (Table 6). For Whites, with large sample sizes, the PIs are not substantially wider at the extremes. The PIs are at most ± .3″ wider only when estimating from male ulna length and female femur length. These increases may well disappear when stature estimates are rounded off in a forensic report. Blacks, with smaller sample sizes, show greater increases in the PI as well as generally less precise stature

TABLE 5—*Regression equations for estimating forensic stature.*

White Males				
Factor	*Bone measurement in mm*	*constant*	*90% PI*	*N*
0.05566	Femur Max L + Tibia L	21.64	±2.5″	62
0.05552	Femur Max L + Fibula L	22.00	±2.6″	54
0.10560	Femur Max L	19.39	±2.8″	69
0.10140	Tibia L	30.38	±2.8″	67
0.15890	Ulna L	26.91	±3.1″	62
0.12740	Humerus L	26.79	±3.3″	66
0.16398	Radius L	28.35	±3.3″	59
White Females				
Factor	*Bone measurement in mm*	*constant*	*90% PI*	*N*
0.06524	Femur Max L + Fibula L	12.94	±2.3″	38
0.06163	Femur Max L + Tibia L	15.43	±2.4″	42
0.11869	Femur Max L	12.43	±2.4″	48
0.11168	Tibia L	24.65	±3.0″	43
0.11827	Humerus L	28.30	±3.1″	45
0.13353	Ulna L	31.99	±3.1″	40
0.18467	Radius L	22.42	±3.4″	38
Black Females				
Factor	*Bone measurement in mm*	*constant*	*90% PI*	*N*
0.11640	Femur Max L	11.98	±2.4″	18
Black Males				
Factor	*Bone measurement in mm*	*constant*	*90% PI*	*N*
0.16997	Ulna L	21.20	±3.3″	14
0.10521	Tibia L	26.26	±3.8″	19
0.08388	Femur Max L	28.57	±4.0″	17
0.07824	Humerus L	43.19	±4.4″	20

estimates. The minimum femur length for black males has a PI that is 1″ wider than at the mean. In examining long bone lengths in the Forensic Data Bank, it was found that no adults had long bone measurements much greater than 3 standard deviations from the mean. While a bone measurement well away from the mean will necessarily have a wider prediction interval, it is debatable whether the additional calculations that Giles and Klepinger [*4*] recommend are necessary for adult bones, since they illustrated their point by estimating stature from a child's humerus that was over 6 standard deviations below the mean adult length for the humerus. If the presented estimates are used for probable whites with fused epiphyses, it is felt that the PIs can be used as rules of thumb without further calculations. Better estimates for Blacks can only come about with more data.

Conclusions

Forensic stature estimation is generally less precise than Trotter and Gleser stature estimation but is more accurate for modern forensic cases because a forensic stature is the only stature available for a missing person. Biological stature estimations based on long bone lengths are less precise than many have assumed, even under the best circumstances, as shown in a reanalysis of Trotter's World War II data. Because the vertebral column shows a lower correlation than long bones to stature [*22*], the best possible estimate of biological stature from the skeleton would be the Fully [*23*] method or a variation thereof, since it incorporates all skeletal components of stature. Once again, however, this estimate would most likely be compared to an FSTAT, which is usually higher than a person's MSTAT.

Prediction Intervals are more appropriate than standard errors for quantifying precision. Stature estimates using a 90% PI should be incorrect 10% of the time. With large samples and a somewhat restricted range of measurements, PIs are relatively constant from minimum to maximum values, allowing ± figures that can be

TABLE 6—*Comparison of 90% PIs at the mean and at extremes.*

Variable	N	Mean	s.d.	Min	Max	s.e.	PI at mean	PI at min/max
Femur L (White Males)	69	477.6	22.7	420	526	4.23	±2.80″	±2.93″/2.89″
Femur L (White Females)	48	444.7	19.0	398	507	3.51	±2.34″	±2.49″/2.59″
Femur L (Black Males)	17	489.6	28.1	429	528	5.62	±3.98″	±4.51″/4.21″
Femur + Tibia L (White Males)	62	868.3	45.9	747	947	3.78	±2.50″	±2.64″/2.56″
Femur + Tibia L (White Females)	42	807.7	37.2	718	916	3.55	±2.38″	±2.54″/2.61″
Radius L (White Males)	59	253.0	13.5	207	283	4.98	±3.30″	±3.62″/3.44″
Ulna L (Black Males)	14	289.7	17.2	266	322	4.50	±3.27″	±3.48″/3.65″

used as rules of thumb. In many cases, variation in PIs will disappear when rounding off estimates for forensic reports.

The equations in Table 5 can be used to be predictably accurate in estimating an expected forensic stature. Informing the police that a victim was a white male between 5′ 7″ and 6′ tall may not significantly narrow down possible identifications, but it will also avoid excluding other possible identifications. It also reflects a more realistic picture of the relationship of stature to long bone lengths. FSTAT estimates are also applicable to all adults with no need to compensate for age.

Finally, this paper illustrates the value of the Forensic Data Bank, namely, the integration of forensic and biological information. Some problems are also apparent, such as the paucity of skeletal data and other information from modern American Blacks. With the participation of the forensic community, we who work on the Forensic Data Bank hope to provide better tools to aid in the identification of skeletal remains.

Acknowledgments

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