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The Measure and Mismeasure of the Tibia: Implications for Stature Estimation

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ABSTRACT: Trotter and Gleser's stature estimation formulae, based on skeletons of the Terry collection and on WWII casualties, have been widely used in forensic work. Our work with the Terry and WWII data yielded tibia lengths too short compared to other data sets. Using Trotter's original measurements, we discovered that she consistently mismeasured the tibia. Contrary to standard practice and her own definitions, she omitted the malleolus from the measurement. Trotter's measurements of the tibia are 10 to 12 mm shorter than they should have been, resulting in stature estimations averaging 2.5 to 3.0 cm too great when the formulae are used with properly measured tibia.

We also examined tibia lengths of Korean War casualties, which were measured by technicians rather than by Trotter. Korean tibia measurements are also too short, but by a smaller amount than Terry and WWII. Since the Korean tibia are unavailable for restudy, it is unclear how they were measured.

Estimation of stature from Trotter and Gleser's tibia formulae is to be avoided if possible. If necessary, the 1952 formulae could be used with tibia measured in the same manner that Trotter measured, excluding the malleolus.

KEYWORDS: physical anthropology, tibia, stature estimation, measurement technique, Trotter

For over 40 years Trotter and Gleser's [*1*] stature formulae have been used, without, so far as we have been able to determine, any suggestion of a problem. Our work with Trotter's data, however, began to suggest that tibiae measured by her were relatively short when compared to those of modern people in the Forensic Data Bank [*2,3*]. We recently obtained Trotter's original data for the Terry collection and WWII casualties, upon which her 1952 formulae were based. Since the Terry collection skeletons are still available for study, a direct test of Trotter's measurements was possible. We carried out a preliminary test by remeasuring 67 randomly chosen individuals that Trotter had previously measured [*4*].

The results of the preliminary test revealed that Trotter's measurements average about 13 mm shorter than ours. Apparently, Trotter had omitted the malleolus from her measurement, although her definition indicates that it should be included. Trotter realized that something was amiss concerning the tibia when she conducted the Korean study [*5*]. In comparing the bone lengths of WWII and Korea, she makes the following observations [*5*]:

> ". . . the mean bone lengths, with the exception of the tibia, are approximately the same. However, the mean lengths of both the right and left tibia obtained in the present study are very significantly greater than those obtained in the previous study ($P < .001$). This difference is further emphasized by the fact that the tibia is longer on average than the fibula, whereas in the previous study the reverse relationship was found. Possibly this difference between the two studies may be accounted for by different technicians measuring the maximum length of the tibia . . . (p. 88).

Here it should be emphasized that Trotter personally measured WWII and Terry collection bones, but technicians measured the Korean sample, according to methods described in the earlier study.

The purpose of this paper is to carry out a more comprehensive test of Trotter's measurements and assess their implications for stature estimation using the tibia. We also evaluate, so far as is possible, the tibia measurements from the Korean war casualties, upon which the 1958 stature estimation formulae are based [*5*].

Materials and Methods

One of the authors (LM) obtained Trotter's original data for the Terry collection and WWII casualties from the Washington University Medical School Archives. The WWII bone lengths were written on 5″ × 8″ cards, which also contained the subject's age, height and weight at induction, birth place, and age at death. Most were killed in the Pacific Theater. The Terry collection data were available on old 80 column IBM punch cards. The 545 WWII individuals designated as WWII Complete in Trotter and Gleser [*1*] were also available on punch cards. We were able to read the cards onto the University of Tennessee VAX computer and download the data to a PC.

There were two Terry card decks; one contained only one measurement per bone, the average of right and left sides. The numbers by race and sex and the summary statistics agree exactly with what is presented in Trotter and Gleser's [*1*] Table 5 and hence must represent the cards used by Trotter and Gleser to compute their statistics. The second Terry deck contains a right and left measurement for each bone. The numbers in this deck agree only approximately with sample numbers given in Trotter and Gleser [*1*], and there are some missing data. For reasons we do not understand, the white male sample is mostly missing from this bilateral deck; there were only 27 white males. Most of the ID numbers in the two decks agree, as do the sex, race, stature and bone lengths. We use the data from the bilateral deck because they allow a direct, bone for bone comparison.

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Trotter's Measurement Definitions

Trotter provides definitions for the lengths of six long bones in her 1952 [*1*] and 1970 [*6*] papers. Her citations to measurement references appear unsystematic. For the maximum length of the humerus, radius, ulna and fibula and for bicondylar length of the femur, she cites "Hrdlicka '47" as her authority. For maximum length of the femur, she cites "Martin '28," although her definition states that it is taken in the same way as maximum length of the other bones. Curiously, for maximum length of the tibia, she cites no authority, and for "ordinary length" of the tibia she cites a personal communication from "Krogman '48." Trotter's definition of maximum length of the tibia is [*1*]:

> "Tibia. Maximum Length. End of malleolus against vertical wall of the osteometric board, bone resting on its dorsal surface with its long axis parallel with the long axis of the board, block applied to the most prominent part of the lateral half of the lateral condyle." (p. 473)

She cites no authority for this definition, but it conforms to Hrdlicka's maximum length [*7*], and Martin's tibia measurement No. 1, *Ganze Länge* [*8*]. Her definition of "ordinary length" of the tibia conforms to none we have found, although it is similar to Martin's tibia measurement No. 2, condylar-astragal length, differing only in using the lateral rather than the medial condyle.

Trotter's definitions seem to indicate clearly that the malleolus should be included in the measurement and we are unaware of any other interpretation. To test Trotter's measurement procedure one of the authors (DH) selected about 50 specimens from each race/sex group in the Terry collection, except white males where only 22 were available. He measured the maximum length of the femur and tibia according to Trotter's definition. He also measured the tibia omitting the malleolus, as shown in Fig. 1, the manner in which we believe Trotter actually measured maximum length of the tibia. The measurements were then sent to the first author for analysis.

Results

The 1952 Study

Table 1 presents the mean difference between Trotter's measurements and Hunt's for maximum length of the tibia. The differences between Trotter's and Hunt's measurements are significantly different from zero, Hunt's averaging 10 to 12 mm greater than Trotter's. This difference is beyond what one would expect if both observers were using the same technique and hence suggests use of different techniques. The F ratio also indicates that the Trotter-Hunt difference varies among groups; the difference is greater for blacks than for whites.

We assume that Trotter's shorter tibia lengths result from omitting the malleolus from her measurements. Table 2 presents the

TABLE 1—*Difference between Trotter's and Hunt's measurements of maximum length of the tibia. Hunt's measurements include the malleolus.*

Group	N	Mean	S.D.	t	Min	Max
White males	22	−10.18	2.28	−20.94*	−15	−5
White females	51	−10.84	2.69	−28.83*	−19	−4
Black males	52	−12.83	3.50	−26.41*	−21	−6
Black females	53	−11.28	2.55	−32.18*	−16	−3

NOTE: Test on means: $F(3,174) = 6.234$, $P = 0.00048$.

TABLE 2—*Difference between Trotter's and Hunt's measurements of the tibia. Hunt's measurements exclude the malleolus.*

Group	N	Mean	S.D.	t	Min	Max
White males	22	−0.36	1.05	1.63	−3	1
White females	51	−1.16	1.71	4.82*	−12	0
Black males	52	−0.87	1.34	4.65*	−3	5
Black females	53	−0.81	0.96	6.14*	−4	3

NOTE: Test on means: $F(3,174) = 1.875$, $P = 0.135$.

FIG. 1—*Measured tibia omitting the malleolus.*

difference between Trotter and Hunt, with Hunt omitting the malleolus from his measurement. The Trotter-Hunt differences are still significantly different from zero, but are much smaller, only white females exceeding 1 mm. The differences also tend to be both positive and negative, but the negative values of the mean differences indicate that Hunt's measurements are systematically longer than Trotter's. Nevertheless, the differences in Table 2 are what one would expect from two observers measuring the same bones using the same technique. The variation among groups in Trotter-Hunt differences among groups also disappears.

We have used femur measurements as a control, since the femur is easy to measure. Table 3 presents the Trotter-Hunt differences for maximum length of the femur. The largest mean difference is 1 mm for white females; all others are less. The ranges of the differences are instructive. For white females and black males the maximum Trotter-Hunt difference is 2 mm. For white males and black females maximum differences are greater. We have remeasured each of the larger differences and confirmed that Hunt's measurement is correct. The 10 mm difference is most likely a key punching error and the −5 and 7 mm differences are outliers in the distribution. Except for these three individuals, all the Trotter-Hunt differences are within 3 mm, what one would expect from different observers using the same technique.

It is curious that the Trotter-Hunt differences for the femur exhibit significant variation among groups. Why this should occur is not clear.

The 1958 Study

The 1958 study was based entirely on Korean War casualties, none of which are available for remeasurement. Hence it is not possible to conduct a direct test of the measurements as it was for the 1952 study using the Terry collection. We utilize an indirect assessment based on the relationship of the tibia to the fibula. Tibia and fibula lengths are closely related, and the fibula, unlike the tibia, is an easy bone to measure. We can therefore assume that the technicians measuring the fibula in the Korean study did so reliably. If the tibia were also measured reliably, it should exhibit a predictable relationship to the fibula.

Table 4 presents the tibia-fibula difference for Korea (calculated from Table 4 in [5]), for the Terry collection and for modern forensic cases from the Forensic Data Bank. For the Terry collection, we used Hunt's measurements of the tibia and Trotter's fibula measurements. The Forensic Data Bank tibiae were measured by different observers using Martin's tibia definition no. 1, [8], which corresponds to Trotter's definition.

It is apparent that the 1958 Korean tibia-fibula difference is considerably less than any of the other samples. The smallest difference in the comparative samples is 5.6 in forensic white males, substantially larger than the 1.7 seen in the Korean white males, and somewhat larger than the 3.6 in Korean blacks. Judging from the pattern seen in Table 4, blacks have greater tibia-fibula differences than whites and females greater than males. The Korean tibia-fibula difference for white males differs significantly from the Terry white male sample ($t = 3.98$; $P < 0.001$) and from the forensic white male sample ($t = 8.36$; $P < 0.001$). The Korean tibia-fibula difference for black males differs significantly from the Terry black male sample ($t = 5.41$; $P < 0.001$) and from the forensic black male sample ($t = 6.27$; $P < 0.001$).

TABLE 3—*Difference between Trotter's and Hunt's measurements of maximum length of the femur.*

Group	N	Mean	S.D.	t	Min	Max
White males	22	0.09	2.41	0.18	−1	10
White females	51	−1.00	0.85	−8.42*	−2	2
Black males	52	0.81	0.84	6.93	−1	2
Black females	53	−0.55	1.45	−2.75	−5	7

NOTE: Test on means: $F(3,174) = 17.933$, $P = 0.000$.

TABLE 4—*Difference between tibia and fibula lengths in the Korean, Terry and Forensic samples. Korean means and standard deviations were computed from Table 4 in* [5].

Group	N	Diff	S.D.	Min	Max
Korean White males	1265	1.70	5.559	—	—
Korean Black males	191	3.63	5.943	—	—
Terry White males	22	6.682	5.826	−2	18
Terry White females	51	7.510	5.442	−4	21
Terry Black Males	51	10.706	6.816	−8	26
Terry Black females	52	9.731	4.859	−7	21
Forensic White males	144	5.757	5.514	−7	20
Forensic White females	96	7.313	5.951	−6	26
Forensic Black males	70	8.486	5.386	−2	20
Forensic Black females	43	8.419	5.569	−6	18

Effect on Stature Estimation

Having shown that the WWII stature estimation formulae are based on incorrect, but consistent, tibia measurements, it remains to assess the effect of this error on stature estimation. We assess the effect by calculating stature for the subsample measured by Hunt, using both Hunt's and Trotter's measurements in Trotter and Gleser's [1] tibia equation. The results, shown in Table 5, indicate that including the malleolus yields stature estimates averaging 2.5–3.0 cm greater, but ranging from 0.74 to 5.5 cm.

Discussion

The results of our analysis raise issues of both historical and practical interest. The historical question is how could Trotter so seriously mismeasure the tibia? Trotter apparently had not received any formal instruction in measuring techniques, having been trained as an anatomist at Washington University School of Medicine. The only explanation we can offer at the moment is that she interpreted the "... end of malleolus against vertical wall of the osteometric board." phrase in her definition to mean that the malleolus should be placed against the side of the board, as shown in Fig. 1, rather than against its measuring surface.

If it is possible to imagine how Trotter might have misconstrued the measurement definition, it is almost impossible to understand her failure to pursue the inconsistence she pointed out in the 1958 study regarding the WWII-Korea difference in tibia length and

TABLE 5—*Stature predicted from Trotter's measurements and Hunt's measurements, and the difference between them.*

Group	N	Trotter	Hunt	Diff	S.D.	Min	Max
White males	22	172.02	174.59	−2.57	0.57	−3.78	−1.26
White females	51	159.12	162.26	−3.15	0.79	−5.51	−1.16
Black males	52	171.49	174.29	−2.81	0.77	−4.60	−1.31
Black females	53	160.08	162.85	−2.76	0.63	−3.92	−0.74

in tibia-fibula relationships. Her comments communicate genuine perplexity. She attributes the discrepancies to technicians, without further discussion of how the technicians' technique might have differed from hers. One has to wonder whether she realized her error by 1958 but did not wish to disclose it. Evidence that this may be the case is contained in a letter from Trotter to Henry McHenry. In it Trotter comments as follows on McHenry's [*11*] definition of tibia length:

> "Total length: from the most proximal point on the head to the distal extremity measured parallel to the shaft" (p. 330)

That definition leaves little doubt that the intercondylar eminence, as well as the malleolus, is included in the measurement. Trotter makes the following observation:

> "Under Materials and Methods, however, I note that you credit us with a definition of the length measurement of the tibia which you indicate as total length. I believe you are considering this definition as synonymous with ours listed as maximum length, but in ours the proximal extent of the tibia is measured from 'the most prominent point of the lateral half of the lateral condyle', which is quite different from your definition which implies, I believe, a measurement from the intercondylar eminence . . . and thus a longer total length. I hope this has not made a difference in your findings." [*12*]

Trotter could not have failed to notice that McHenry's definition includes the malleolus, yet she restricts her comments to problems with the proximal end. As far as we are aware, Trotter has never acknowledged that her measurement of the tibia departed from standard practice, even though she must have been aware of it, at least after 1958. Indeed, she becomes even more explicit in specifying that one measures to the "tip" of the malleolus [*13*], rather than merely specifying "end of malleolus against vertical wall . . ." [*1*].

Although Trotter was unable or unwilling to contribute to the solution of the problem, it is still somewhat surprising that its discovery took so long, considering how widely used the formulae have been. The omission of the malleolus from the measurement causes it to be shorter by 10 to 12 mm. This difference may not be enough to cause obvious problems for most who used Trotter's formulae, particularly forensic anthropologists applying them on a case by case basis. However, any application of the formulae to a sample would inevitably result in greater stature estimates from the tibia than from other bones.

A brief perusal of the literature reveals that this is the case. The investigators of the Spitalfields cemetery note that "Estimates for height derived from the tibia were greatest- an indication that the Spitalfields skeletons had relatively longer tibiae than had the reference sample of Trotter and Gleser" [*9*]. Boldsen's [*10*] analysis of Trotter's tibia data revealed a significantly greater intercept for females, where he used her Terry data, but not in males, where he used her Korean data. These observations make sense when we understand how Trotter measured. Apparently discrepancies such as these, though noticeable and significant, are too minor to engender much suspicion.

How the Korean tibiae were measured is uncertain. Unlike the tibiae measured by Trotter, there apparently was not a consistent pattern of omitting the malleolus. At this point we have no information about how the technicians were trained and by whom. Trotter only remarks that they used the definitions provided. The Korean tibiae are longer than the fibulae, but not by as much as they should be. This pattern could be explained if some of the technicians excluded the malleolus and some included it. An alternative explanation is that the intercondylar eminence was included and the malleolus excluded. Unless we are able to locate the original data or some documentation concerning how technicians were trained, we cannot resolve this question.

Our findings raise problems in the practical matter of predicting stature in forensic contexts. There appear to be two main choices available: 1) use the femur in preference to the tibia whenever possible; 2) if it is necessary to use the tibia, measure it in the same manner as Trotter apparently did, i.e., omit the malleolus from the measurement. We would not recommend using Trotter's 1958 formulae [*5*], since it is not clear how the tibia was measured. One may also choose to use adjustments presented in [*2,3*], which allow the tibia to be measured in the usual manner, that is, including the malleolus.

Acknowledgments

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