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Allometric Secular Change in the Long Bones from the 1800s to the Present

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ABSTRACT: Allometric secular changes in the six long limb bones for White and Black males from the mid 1800s to the present are examined. Long bone lengths are available from the Terry collection and WWII casualties. We conducted two types of analysis to reveal secular changes. First, allometry scaling coefficients were derived by regressing log bone length onto log stature. These showed that the femur, tibia and fibula were positively allometric with stature, while the humerus, radius and ulna were isometric. The lower limb bones were more positively allometric in the WWII sample than in the Terry sample.

Second, secular changes in length of femur and tibia and in the tibia/femur ratio were evaluated, using modern forensic cases in addition to the Terry and WWII samples. This analysis shows that secular increase in lower limb bone length is accompanied by relatively longer tibiae. Secular changes in proportion may render stature formulae based on nineteenth century samples, such as the Terry collection, inappropriate for modern forensic cases. The positive allometry of the lower limb bones argues against using simple femur/stature ratio, which assumes constant proportionality, as an alternative to regression equations.

KEYWORDS: physical anthropology, allometry, secular trend, long bones

Secular change in stature has been well documented [see *1–5*]. Figure 1 shows secular changes in height for White males from 1700 to 1930 (Fogel [*6*]). The slow gain in stature apparent prior to 1850 was interrupted by a marked secular decrease from 1850 to 1900, followed by recovery after 1900. We note that the time when stature is lowest corresponds to the birth dates of individuals in the Terry collection, the skeletal collection upon which significant Trotter and Gleser stature estimation formulae are based.

While secular change in stature has been well documented, secular change in long bone lengths has received little attention. Trotter and Gleser [*1*] investigated secular changes in femur and tibia length and height from 1840 to 1924 using Terry and WWII data. Our previous study [*7*] examined the secular changes in length of the long bones in the lower limb for White males only. We assembled a series expanding the time period, consisting of White males born between 1840 and 1960, and found that lower limb bone length has increased most markedly after 1900. Secular change in long bone proportions and its relationship to secular change in stature has not, as far as we are aware, been examined. The purpose of this study is to examine the allometric changes of the six long limb bones for White and Black males from the mid 1800s to the 1970s. We also examine the implications of proportional change for stature estimation. The use of stature estimation formulae in modern human identification requires that we examine any changes in the population that might alter estimates.

Materials and Methods

Long bone lengths and statures are available for White and Black males from the Terry collection and from WWII casualties. These data were obtained from the Washington University School of Medicine Archives where Mildred Trotter donated a large portion of her research materials. Measurements were made by Trotter and comprise the data employed in the 1951 [*1*] and 1952 [*2*] papers. The measurements include the maximum lengths of the humerus, radius, and ulna for the upper limb, and maximum and bicondylar lengths for the femur, maximum length and ordinary or physiological length of the tibia, and maximum length of the fibula. Definitions are given in Trotter and Gleser [*2*]. It should be noted that the definition of maximum tibia length includes the malleolus, but in fact the malleolus was excluded [*8*]. The stature measurements for the WWII sample were obtained at induction by military physicians and personnel. Trotter and Gleser describe the cadaver stature measurement of the Terry sample as well as how the adjustment is made [*2*].

We conducted two types of analysis to reveal secular changes. In the first we compared allometric scaling coefficients derived from the Terry and WWII samples. Allometric scaling coefficients were obtained by regressing log bone length onto log stature:

$$\ln(y) = b(\ln(x)) + \ln(a)$$

The regression coefficients show changes in long bone-height proportions with changes in height. Table 1 presents the date of birth statistics for these two samples. The two samples differ by thirty-five to forty-five years in mean or median birth dates, but the Terry sample has a broader range. The Terry Black sample is slightly later than the Terry White sample and overlaps slightly with the WWII sample on the later dates.

The second analysis is a direct test of secular change and proportion in the lower limb bones from 1840 to 1970. Here, in addition to Terry and WWII data, we use modern forensic cases, since they are the only source of bone length data after 1926. The Forensic Data Bank includes 106 White males, with dates of birth ranging from 1899 to 1973. The sample size for modern Black males was insufficient for use.

The test for secular change over time is based on the mean bone lengths for femur and tibia by birth decade. Since birth dates of

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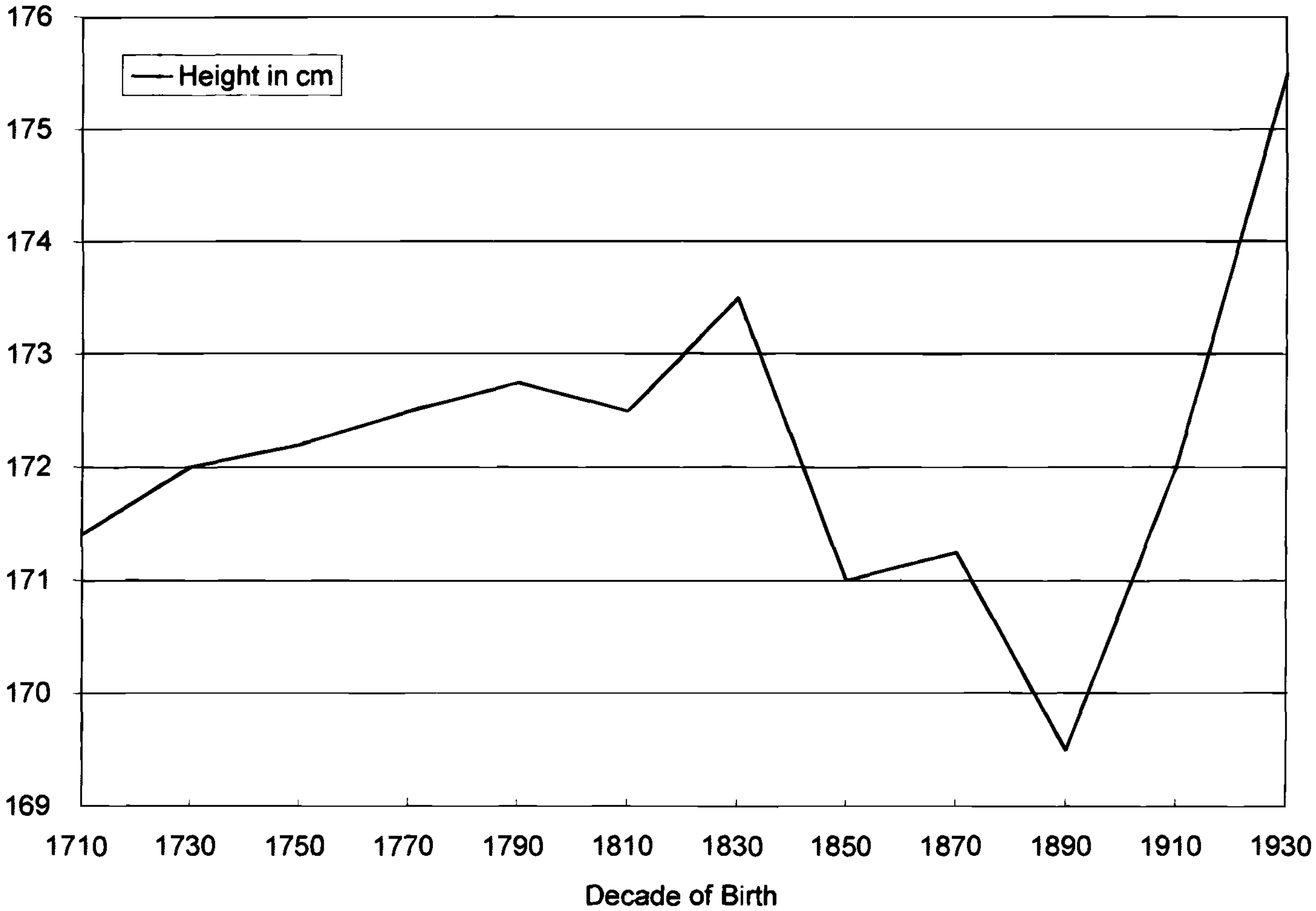

FIG. 1—*Secular change in White male stature from the 18th to the middle 20th century (redrawn after Fogel* [6].*)*

Terry individuals were unavailable, we used the mean bone lengths by decade presented in Trotter and Gleser [*1*]. Trotter and Gleser present only "ordinary" length of the tibia, which is available for the WWII sample but not the forensic sample. We therefore adjusted the forensic tibia length to Trotter's ordinary length by subtracting a constant, the average difference between maximum length and ordinary length. The mean femur and tibia lengths were added to assess secular change in combined length. Then, we calculated the tibia/femur ratio to ascertain whether the change in length is accompanied by a change in proportion. Secular changes were assessed by polynomial regression of bone length and ratio onto decade of birth midpoints, weighted by each decade's sample size.

Since Trotter's Terry data is a mean of the right and left bone lengths, we followed the same practice with WWII and forensic data. In instances where only one side was present, it was used.

Results

Tables 2 and 3 show the allometry coefficients for White and Black males from the Terry and WWII samples, and a t-test for the difference between them. The meaning of the allometry coefficients is as follows: if the coefficient is 1.0, it indicates that the bone maintains a constant proportional, or isometric, relationship with stature throughout the range of statures. If the coefficient is

TABLE 1—*Date of birth statitics for WWII and Terry samples.*

	WWII		Terry	
	White	Black	White	Black
N	465	53	255	360
Median	1921	1920	1875	1885
Mean	1920.6	1920.2	1872.2	1885.5
S.D.	3.05	3.24	12.60	15.71
Minimum	1915	1915	1840	1840
Maximum	1926	1926	1909	1919

TABLE 2—*Allometry coefficients for White males.*

Measurement	WWII	Terry	*t* Value for Diff
Humerus	1.059	0.961	1.577
Radius	1.009	0.942	0.996
Ulna	0.943	0.919	0.383
Femur	1.126	1.084	0.876
Maxfemur	1.136	1.095	0.849
Maxtibia	1.316	1.171	2.419[a]
Tibia	1.321	1.187	2.245[a]
Fibula	1.246	1.115	2.296[a]

[a] $P < .05$

TABLE 3—*Allometry coefficients for Black males.*

Measurement	WWII	Terry	*t* Value for Diff
Humerus	0.758	1.055	−2.431[a]
Radius	0.762	1.093	−2.241[a]
Ulna	0.726	1.016	−1.978[a]
Femur	0.983	1.152	−1.133
Maxfemur	0.979	1.168	−1.251
Maxtibia	1.311	1.278	0.242
Tibia	1.340	1.286	0.396
Fibula	1.221	1.237	0.128

[a] $P < .05$

TABLE 4—*Femur, tibia and tibia/femur ratio by decade of birth.*

Decade	*N*	Femur	Tibia	Ratio
1840	9	465.00	386.00	0.8301
1850	29	452.00	369.00	0.8164
1860	79	458.00	377.00	0.8231
1870	68	458.00	375.00	0.8188
1880	51	454.00	370.00	0.8150
1890	17	455.24	370.12	0.8130
1900	31	461.84	381.30	0.8256
1910	239	467.82	387.28	0.8279
1920	305	471.35	391.73	0.8311
1930	23	470.61	390.48	0.8300
1940	18	475.83	394.44	0.8287
1950	23	473.87	391.70	0.8266
1960	9	472.67	391.11	0.8274
1970	2	502.50	421.00	0.8378

less than 1.0, the bone is negatively allometric. Negative allometry implies that taller individuals have relatively shorter bones than shorter individuals. If the coefficient is greater than 1.0, the bone is positively allometric. Positive allometry implies that taller individuals have relatively longer bones than shorter individuals.

The allometry coefficients (Table 2) indicate that the WWII White males are positively allometric for the lower limb, with the femur being weakly positively allometric and the tibia and fibula being strongly positively allometric. Bones of the upper limb are very close to isometric. Terry males reflect a similar pattern of isometry for the upper limb and positive allometry for the lower limb. They differ from WWII males in having significantly weaker positive allometry for the tibia and fibula.

The results for Black males show a different pattern (Table 3). WWII Black males are negatively allometric in the arm bones, isometric for the femur, and positively allometric for the distal bones of the lower limb. Terry Black males are more similar to White males in their pattern of isometry for the upper limb and positive allometry for the lower limb. Like the White males, the Terry Black males are weakly positively allometric for the femur, while the tibia and fibula are strongly positively allometric.

Proportional, or allometric changes in limb bone lengths in Terry and WWII samples, based on the foregoing results, can be described as follows:

1. Upper limb bones are generally very close to isometric with stature. This can be interpreted to mean that the upper limb bones maintain a constant proportion to stature, regardless of height. The only exception to this is seen in WWII Black males. Why this occurs and its significance are unclear.
2. The lower limb bones are generally positively allometric with stature. This means that taller individuals have relatively longer lower limb bones than shorter individuals. Since the tibia and fibula are more strongly positively allometric than the femur, taller individuals should have relatively longer tibiae and fibulae than femora.

What do these observations imply about proportional changes associated with secular changes in height and lower limb bone length? We would expect that secular increases in height would result in femur and tibia lengths proportionately longer in relation to stature. We would also expect that tibiae would be relatively longer in relation to femora. Since we lack an extensive series of individuals with stature and bone lengths, we cannot directly test the stature-bone length expectations. But we can directly test femur-tibia proportions using Terry, WWII and Forensic Data Bank data. Table 4 shows the mean femur and tibia lengths and the tibia-femur ratio grouped by decade of birth from 1840 to 1970.

Figure 2 shows the mean lengths of the lower limb bones (tibia + femur) by decade of birth with a fitted regression line. Table 5 summarizes the polynomial regression statistics resulting from fitting linear, quadratic and cubic terms. All models are significant, but the only term resulting in significant reduction of the error sum of squares is the cubic. Hence the cubic provides the best fit, demonstrating that secular change in bone length is not a simple linear phenomenon. Interpreting the fitted regression line suggests little change prior to 1890, followed by gain until 1940, with change slowing thereafter.

Figure 3 shows the mean tibia/femur ratio by decade of birth with fitted regression line. Table 6 summarizes the polynomial regression statistics resulting from fitting linear, quadratic and cubic terms. All models are significant, but like the bone lengths, only the cubic term significantly reduces the error sum of squares. Hence the secular change in the tibia/femur ratio follows rather closely the pattern seen in lower leg length: When legs are shorter the tibia is relatively shorter and vice versa. In particular, the mid to late 1800s dip in stature seen in Fogel's [*6*] data and in the lower limb bone lengths is accompanied by a decrease in relative length of the tibia.

Discussion

Having shown that secular changes in height are associated with changes in limb bone proportions, it remains to determine the implications for stature estimation, particularly when formulae derived from earlier, shorter samples are applied to later, taller individuals.

Ideally, we would like to know what the biases are when formulae derived from the Terry collection or WWII casualties are applied to modern, mostly post-1940 forensic cases. We do not have reliable stature data for most of our forensic cases, so the question cannot be directly addressed. We can, however, assess the effect of applying Terry formulae to WWII data. We have seen that in both samples tibia length scales positively with height, but WWII is more strongly positive than Terry. From this observation we predict that Terry tibia equations underestimate the taller WWII sample. To assess this prediction, we estimated each WWII subject's stature using the tibia equation from the Terry data. Table 7 shows the results. To demonstrate the pattern of bias for individuals of different heights, we divided the WWII sample into quartiles and computed the mean residual (observed stature-predicted stature). If the Terry equation accurately predicts WWII stature, then the mean residual should be zero. It can readily be observed that

TABLE 5—*Tests for change in femur and tibia length with birth data from 1840 to 1970.*

Term	Source	df	R-sqr	F	P
Linear	Model	1	0.78	41.90	0.0000
Quadratic	Model	2	0.78	39.56	0.0000
	Reduction due to quadratic	1		0.26	0.6235
Cubic	Model	3	0.86	20.38	0.0000
	Reduction due to cubic	1		5.48	0.0413

TABLE 6—*Tests for change in femur-tibia ratio with birth data from 1840 to 1970.*

Term	Source	df	R-sqr	F	P
Linear	Model	1	0.54	14.05	0.0028
Quadratic	Model	2	0.54	6.47	0.0139
	Reduction due to quadratic	1		0.24	0.8787
Cubic	Model	3	0.76	10.28	0.0021
	Reduction due to cubic	1		8.77	0.0142

TABLE 7—*Terry tibia formula applied to WWII tibiae.*

Height Quartile	Mean Residual	S.D.	Bias
First	−1.669	2.622	Over
Second	−0.347	2.189	Over
Third	0.565	3.239	Under
Fourth	1.713	3.830	Under
Total	0.066	3.389	Over

NOTE: Quartiles are from shortest to tallest.

TABLE 8—*Estimation of stature from femur stature ratio (.2674)* [8] *applied to WWII White males.*

Height Quartiles	Mean Residuals	S.D.
First	−.309	4.207
Second	−1.425	4.240
Third	−2.471	4.717
Fourth	−2.305	4.542
Total	−1.620	4.500

NOTE: Quartiles are from shortest to tallest.

the bias of the entire sample is low, only .06 cm. It can also readily be seen that a significant bias exists for the shortest and tallest quartiles of the sample. Predicted stature for the shortest quartile is 1.7 cm greater than actual stature, while predicted stature for the tallest quartile is underestimated by 1.7 cm.

Our results also bear on a recent proposal for estimating stature using the femur-stature ratio [9]. The authors suggest that this simple ratio performs as well or better than Trotter and Gleser's equations and requires no prior knowledge of gender or race. Our results showing that the femur is positively allometric indicate that the femur-stature ratio varies with height. Using a constant ratio,

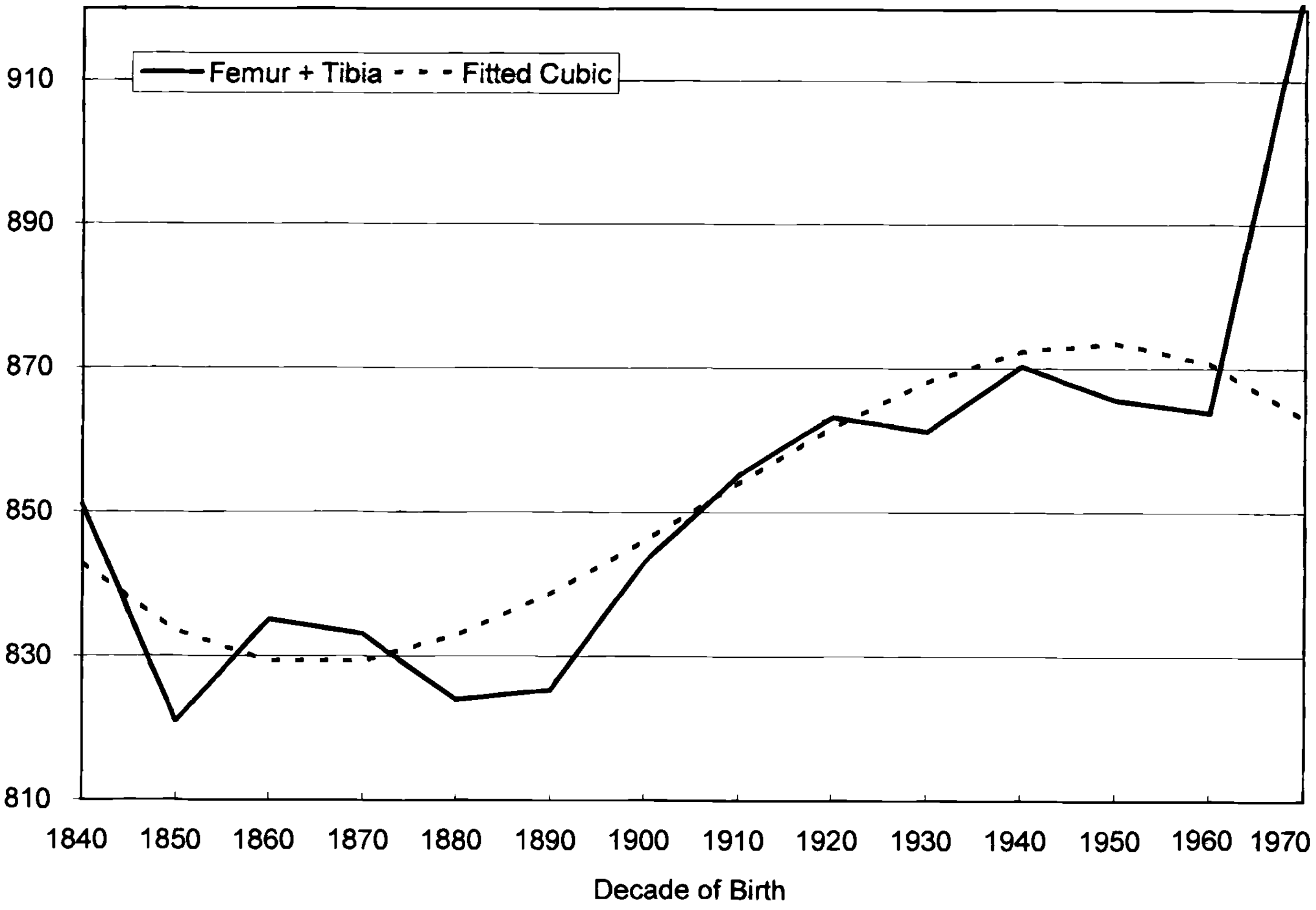

FIG. 2—*Secular change in lower limb bone length (femur + tibia) from 1840 to 1970 with fitted cubic regression line.*

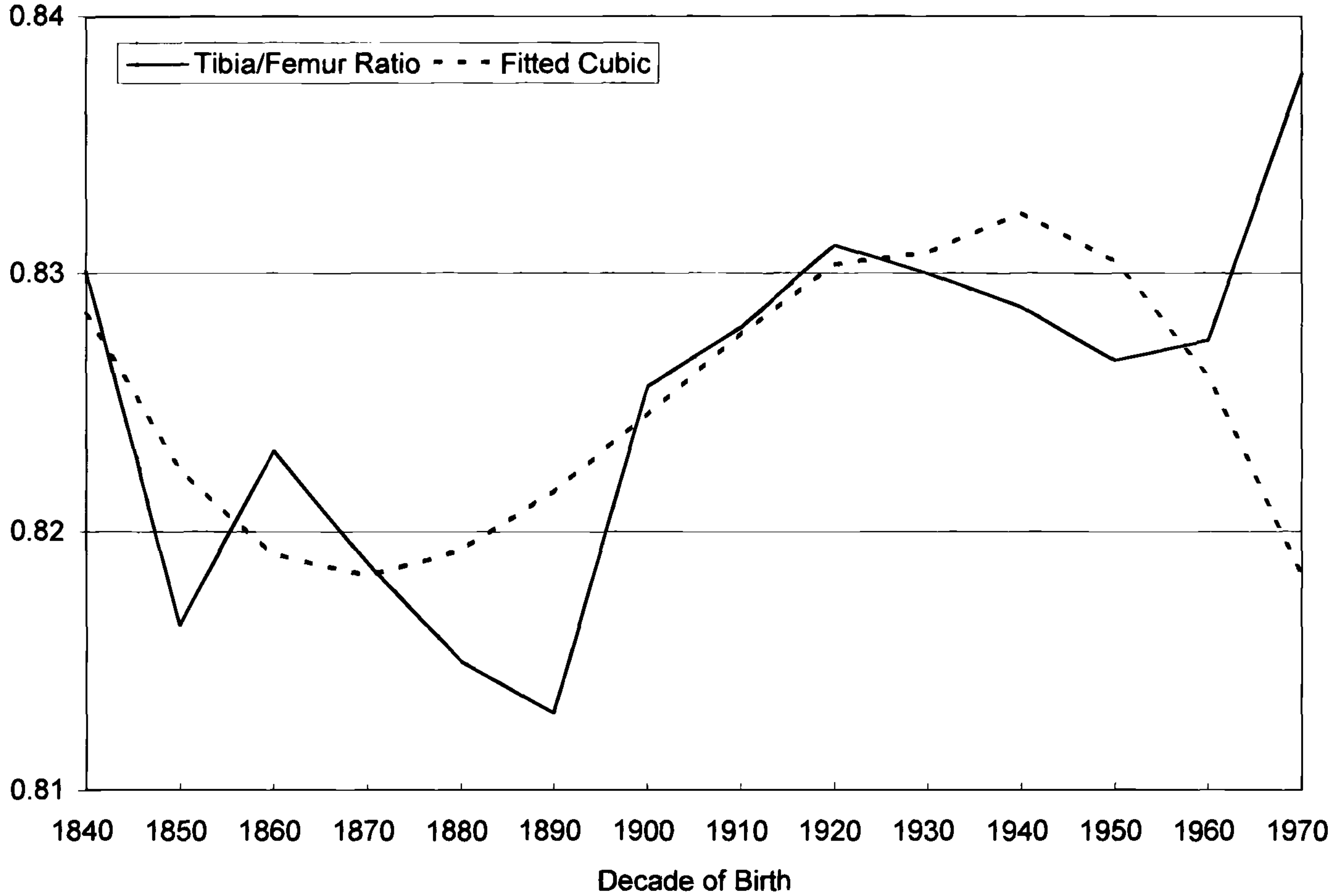

FIG. 3—*Secular change in tibia/femur ratio from 1840 to 1970 with fitted cubic regression line.*

we expect that taller individuals, with relatively longer femora would be overestimated. Table 8 shows the mean residuals from applying the Feldsman et al. [9] procedure to the WWII White male sample. It is clear that the entire sample is overestimated by 1.6 cm, and that the overestimation increases with taller stature. The top two quartiles are overestimated by 2.3–2.5 cm (ca. 1"). It is also clear that the residual standard deviation is substantially greater than the regression predictions (compare to Table 7), indicating a wider prediction interval.

Our results allow the following conclusions concerning stature estimation:

1. Since the lower limb bones are positively allometric with stature, it is generally inappropriate to apply regression formulae derived from earlier, shorter samples to taller later ones.
2. If this is to be done, the femur should be employed in preference to the tibia, since the latter exhibits greater proportional variation.
3. The upper limb bones are generally isometric with stature, and hence could be applied across samples from different times. The disadvantage is that upper limb bones generally yield less accurate estimations of stature than lower limb bones.
4. Since the lower limb bones are positively allometric with stature, simple ratios that assume constant proportionality are inappropriate for estimating stature.

Ideally, what is required are up-to-date stature estimation formulae derived from the contemporary population from which modern forensic cases are drawn. The Forensic Data Base is potentially a source of such regressions. The principal problem is that stature during life is difficult to obtain. The answer may well lie in statures derived from driver's licenses or other sources. These are the statures that are most often available and predicting them may well be more appropriate.

Acknowledgments

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