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PAPER

PHYSICAL ANTHROPOLOGY

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Secular Change in Morphological Pelvic Traits used for Sex Estimation*,†

ABSTRACT: This research evaluates secular change in Phenice's (Am J Phys Anthropol, 30, 1969 and 297) three morphological traits of the pubis, as described by Klales et al. (Am J Phys Anthropol, 149, 2012 and 104): medial aspect of the ischio-pubic ramus, subpubic contour, and ventral arc. Ordinal scores were collected for these traits and compared between a sample of innominates from the historical Hamann–Todd Collection (n = 170) and modern Bass Donated Collection (n = 129). Using the Freeman–Halton test, significant differences between temporal sample score frequencies were found for all traits in females and for the subpubic contour and ventral arc in males. Despite these findings, classification accuracy using logistic regression between the temporal periods remained low (68.7%). These results suggest that secular changes in trait expression are occurring; however, sex estimation methods using these traits and created with historical samples are still applicable to modern forensic cases. In fact, the secular changes occurring in these traits contribute to better classification accuracy between sexes in modern populations.

KEYWORDS: forensic science, forensic anthropology, secular change, pelvic nonmetrics, biological profile, sex estimation methods

Changes in the skeletal structure of Americans within the last two centuries have been well documented in the anthropological literature, especially in regard to changes in stature, weight, and cranial form (1–5). As Jantz et al. (6) noted, "only recently, however, have skeletal biologists had access to samples with adequate time depth and sample sizes and to more powerful statistical software necessary" to adequately study the phenomenon of secular change in modern populations. A recent symposium entitled *Examining the Big Picture: Working Towards a Holistic Understanding of Secular Change in Modern Populations* held at the 2012 annual meeting of the American Association of Physical Anthropologists engendered a discussion and synthesis of morphological and metric skeletal changes in the American population. Research presented within this symposium clearly demonstrated the presence of secular change over the last two centuries in many size dimensions and shape changes throughout the body. The myriad of factors contributing to the observed secular changes in skeletal form are complicated, but they are likely attributed to an increase in standards of living, social and economic improvements, and advancements in science and medicine within the United States.

Given the nature of secular change, questions have arisen regarding the applicability of methods developed using historic samples for use with modern populations, especially in forensic contexts. As Dirkmaat et al. (7) commented, historic populations "hardly represented the modern population from which forensic inferences were drawn. Estimates of sex, age, or stature obtained from those samples were biased when applied to modern populations due to secular changes." In light of the documented secular changes in modern Americans, biological profile estimation methods used within biological anthropology are being tested and refined to account for the skeletal changes occurring through time. Dirkmaat et al. (7) further noted that methodological improvements within forensic anthropology, specifically in regard to improved quantitative methods using modern samples, is one of the key developments within the field in the last 20 years and has contributed to the altered trajectory of forensic anthropology.

Phenice's (8) technique using three traits of the pubis, the ventral arc (VA), subpubic concavity (SPC), and medial aspect of the ischio-pubic ramus (MA), is overwhelmingly the most preferred method of morphological sex estimation in forensic and biological anthropology (9,10). The Phenice method was created using the historic Robert J. Terry Anatomical Skeletal Collection comprising individuals born from the 19th century to the early 20th century. Despite being developed using a historical sample, the method remains popular among today's forensic practitioners because of ease of use and high reported classification accuracy (95%). Multiple validation studies confirming the utility of Phenice's traits have also likely contributed to the popularity of the method (c.f. 11, Table 1 within). The subsequent Klales et al. (11) revision of the Phenice (8) method included ordinal scoring and robust statistical analyses. This revised method used the historical Hamann–Todd Osteological Collection and also achieved high classification accuracy (95%) (11). The Klales et al. revised method was further validated using an independent modern U.S. sample with sex classification accuracy of 86.2% (11). Both the Phenice and revised Klales et al. methods are currently being applied to active forensic cases in the

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United States and other countries worldwide; therefore, changes in the expression of the pubic traits through time need to be evaluated.

Size and shape changes in the pelvis, and specifically the innominates, between historical and modern samples, have been documented using metrics and geometric morphometrics (12–14); it therefore stands to reason that the morphological trait expressions may also be changing through time. The purpose of the present research was to evaluate secular change in the morphological expression of the ventral arc, the subpubic contour, and the medial aspect of the ischio-pubic ramus, as described by Klales et al. (11), through the comparison of trait scores between a historic and modern sample of human innominates. Furthermore, the utility of the Phenice traits (8) and the Klales et al. revised method (11) for use in modern forensic cases was examined in light of secular change in the innominate.

Materials and Methods

Sample and Scoring

The historic sample was derived from the Hamann–Todd Osteological Collection (HT) at the Cleveland Museum of Natural History. Individuals in the HT collection were born from the mid-19th century to early 20th century, with most born during the second half of the 19th century (15). The modern sample was derived from the William M. Bass Donated Skeletal Collection at the University of Tennessee, Knoxville (UT). Most individuals within the UT collection were born after 1940 (16). The total sample consisted of 136 female (HT $n = 83$, UT $n = 53$) and 163 male (HT $n = 87$, UT $n = 76$) adult innominates. Individuals with damage to the pubic region or with obvious pathological conditions were excluded from the samples. Two experienced observers scored the individual innominates on an ordinal scale from one to five for each of the three Phenice (8) traits using the Klales et al. (11) revision (Fig. 1). Scores one and two represent gracile expressions of the traits, score three represents an intermediate form, and scores four and five represent robust trait expressions (11). Previous research (11) found high levels of interobserver agreement for trait scoring between observers of varying experience levels; therefore, multiple observers should not bias the results obtained in the present research.

Statistical Methods

The median age for the entire Hamann–Todd Collection is 47.9 years, while the median age for the entire William M. Bass Donated Skeletal Collection is 60.2 years. Because of the apparent differences in the median ages between the two collections, an independent t-test was used to test for significant differences in the sex-specific temporal samples used in the present research.

Previous research revealed no significant differences in trait expression between ancestry groups (U.S. blacks and whites) (11,17); as a result, ancestral groups were pooled for each sex, in each temporal sample for all analyses. First, score frequencies for each trait were tabulated for each temporal sample and separated by sex. Next, trait frequencies by temporal group were subjected to a Freeman–Halton test, an extension of the Fisher's exact test, to determine whether significant differences existed between the two temporal samples for each of the three traits by sex. To determine which specific trait scores produced the significant differences between the two

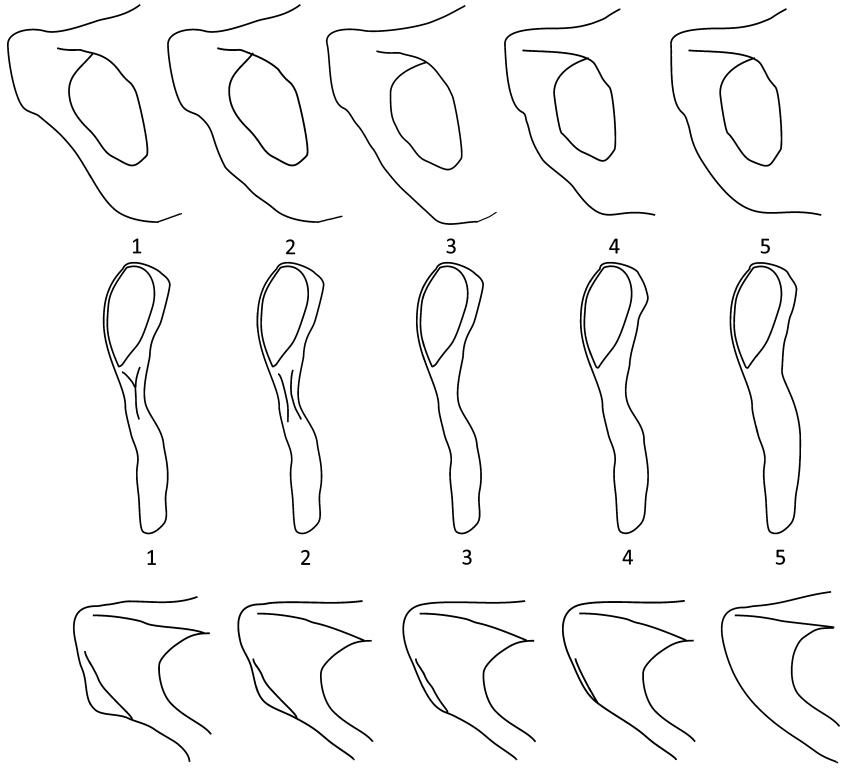

FIG. 1—*Klales et al. (11) morphological character states and ordinal scores of the pubic bone. From top to bottom: the subpubic contour, the medial aspect of the ischio-pubic ramus, and the ventral arc (from Klales et al., Am J Phys Anthropol, 2012, 149, 104–114, © Wiley).*

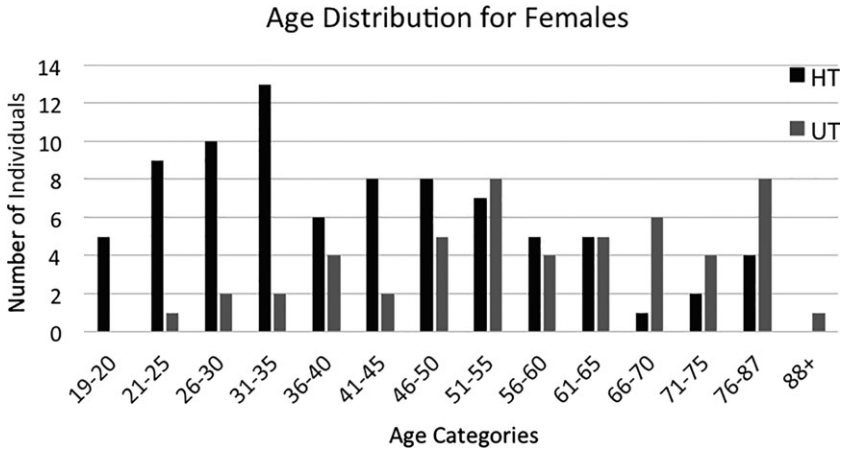

FIG. 2—*Age distribution for females in both temporal samples.*

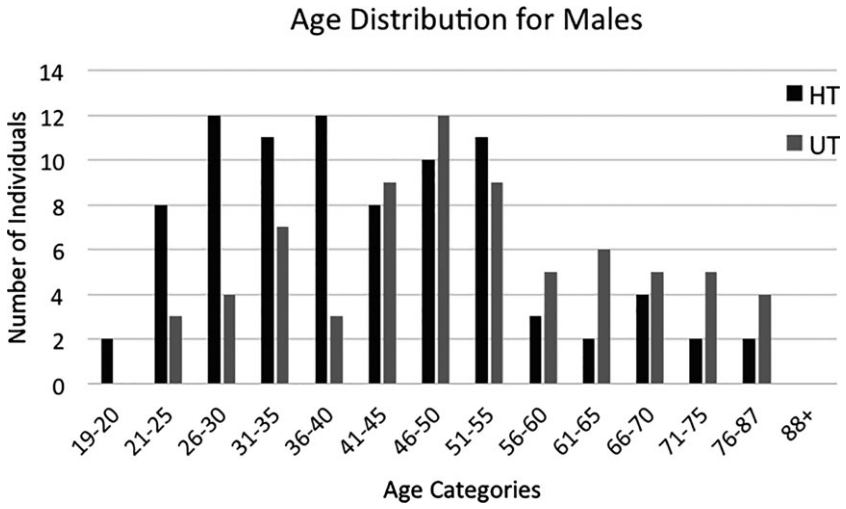

FIG. 3—*Age distribution for males in both temporal samples.*

temporal periods, the residual for each trait score produced from the Freeman–Halton test was converted into a *z*-score and compared to the appropriate critical value (1.96 for alpha = 0.05). Odds ratios were also calculated for each trait score to examine how traits were changing between temporal periods. Lastly, ordinal logistic regression (OLR) analysis was used to determine how well the traits were able to classify each of the sexes into the correct temporal period (historic or modern). Ordinal logistic regression was chosen because it does not assume normally distributed data or equal within-group variation (18). Previous research demonstrated that classification accuracy was highest and bias was lowest using all three traits in combination (11), for that reason, all three traits were included in the OLR.

Results

Age Distribution

The median female age was 42.3 years for the HT sample and 60.2 years for the UT sample used in this research (Fig. 2). The median male age was 42.8 years for the HT sample and 51.2 years for the UT sample used in this research (Fig. 3). The independent sample *t*-test revealed significant differences in the age distribution for both sexes between the two samples at the $p < 0.05$ level.

TABLE 1—*Score frequencies (%) for the medial aspect of the ischio-pubic ramus for both temporal samples.*

		Trait Score				
Sex	Sample	1	2	3	4	5
Females	HT	6.0	20.5	45.8	26.5	1.2
	UT	22.6	24.5	45.3	7.5	0.0
Males	HT	0.0	0.0	20.7	62.1	17.2
	UT	2.6	3.9	19.7	50.0	23.7

Frequencies

Score frequencies varied between the two temporal periods when controlled for sex. For the MA, modern females (UT sample) tended to have a higher percentage of low scores (1 or 2), while the historic females (HT sample) had a higher percentage of high scores (4 or 5) compared to the modern females (Table 1, Fig. 4). Both temporal samples had an equal number of the MA intermediate score three (~45%) for females. In males, the two samples were similar for the MA with most

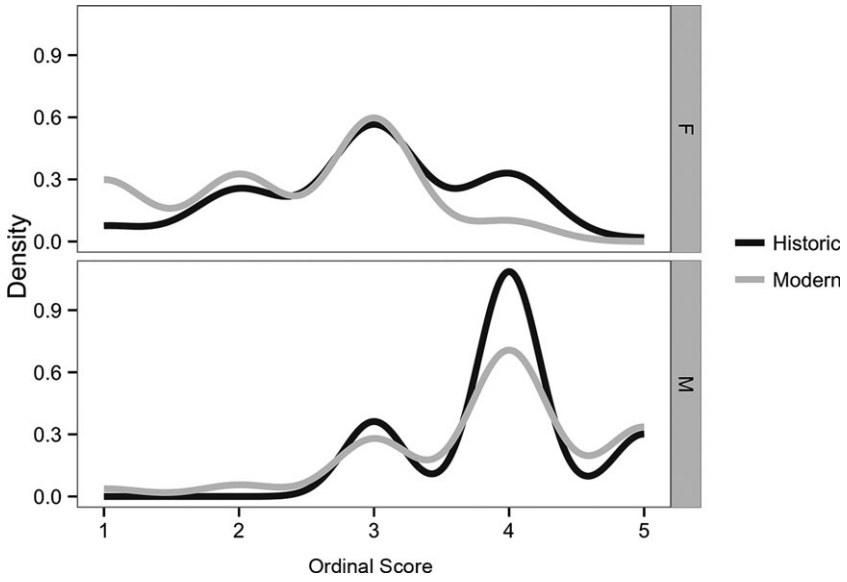

FIG. 4—*Density plots of the medial aspect of the ischio-pubic ramus scores for both temporal samples (M: males; F: females).*

TABLE 2—*Score frequencies (%) for the subpubic contour for both temporal samples.*

		Trait Score				
Sex	Sample	1	2	3	4	5
Females	HT	25.3	53.0	12.0	8.4	1.2
	UT	66.0	32.1	0.0	1.9	0.0
Males	HT	0.0	5.7	11.5	48.3	34.5
	UT	2.6	13.2	23.7	47.4	13.2

having higher scores (3 to 5); although, the modern sample was slightly more variable in score distribution (Table 1, Fig. 4). For the SPC, 98.1% of the modern females (UT sample) had low scores (1 or 2) (Table 2, Fig. 5). In contrast, the historic females showed more variability in score distribution. Males in the historic sample demonstrated consistently higher SPC scores (82.8% had a score of 4 or 5) than the modern males (60.5% had scores of 4 or 5) (Table 2, Fig. 5). Lastly, for the VA, 94.3% of the modern females (UT sample) had low scores (1 or 2), while only 71.1% of the historic females presented comparably low scores (Table 3, Fig. 6). Corresponding to the previously observed trend in SPC scores, the historic males had a higher percentage (80.4%) of extreme high scores (4 or 5) for the VA, while only 65.8% of the modern males exhibited high scores (4 or 5) (Table 3, Fig. 6). The odds ratios for each trait score in each sample revealed a similar pattern (Table 4).

Using the Freeman–Halton exact test, significant differences were found for all three traits in females between the two temporal samples, while in males significant differences were found only in the SPC and the VA (Table 5). Analysis of the residuals for the medial aspect revealed greater-than-expected "gracile" expression (i.e., narrow ischio-pubic ramus with sharp ridge of bone present/score 1) in the modern sample females (Table 6). Similarly in the modern sample, "gracile" expression of the subpubic contour (i.e., well-developed concavity/score 1) and of the ventral arc (i.e., angled arc present with triangular portion of bone inferiorly/score 1) were greater than expected, while the historic sample had lower-than-expected residuals for the same scores (Table 6). In males, the historic sample had a higher-than-expected "robust" expression of the SPC (i.e., large convexity/score 5), while in the modern sample, this same score was slightly lower than expected (Table 6).

Classification

Using OLR with all the three traits, 83.1% of the HT females correctly classified into the historic sample, while 85.1% of the HT males classified into the correct temporal period (Table 7). In the UT sample, 60.4% of the females correctly classified into the modern group, while only 46.1% of the males correctly classified (Table 7). Combined sex classification accuracy into temporal period was 84.1% for the historic HT sample and 53.3% for the modern UT sample (total combined accuracy of 68.7%).

Discussion

Significant differences in the age distributions for both samples were found in both sexes. The higher mean age in the modern sample may be a confounding factor impacting different trait score frequencies and may also account for the overall lower combined classification accuracy. Furthermore, the female mean for the modern UT sample is nearly a decade higher than the male mean. Lovell (19) advises that degenerative age-related changes to the pubis may impact expression of morphological traits. Specifically, Lovell (19) suggests that the identification of the ventral arc becomes more difficult in older individuals. In the current research, however, low VA scores (1 or 2 with clearly delineated ventral arcs present) were much more prevalent in the modern female sample, despite a higher mean age than the historic sample. High frequencies of ventral arc presence were also found in females up to 90 years of age by Sutherland and Suchey (20). The authors' (20) findings contradict Lovell's (19) and suggest that the VA is useful in females of all ages. Furthermore, Vollner (personal communication) found no correlation between an individual's age and trait expression score for each of the three traits. Therefore, while it is not possible to say with absolute certainty how the different age distributions between the samples may be impacting the differences in trait score frequencies through time, previous research (20) likely indicates that the different age

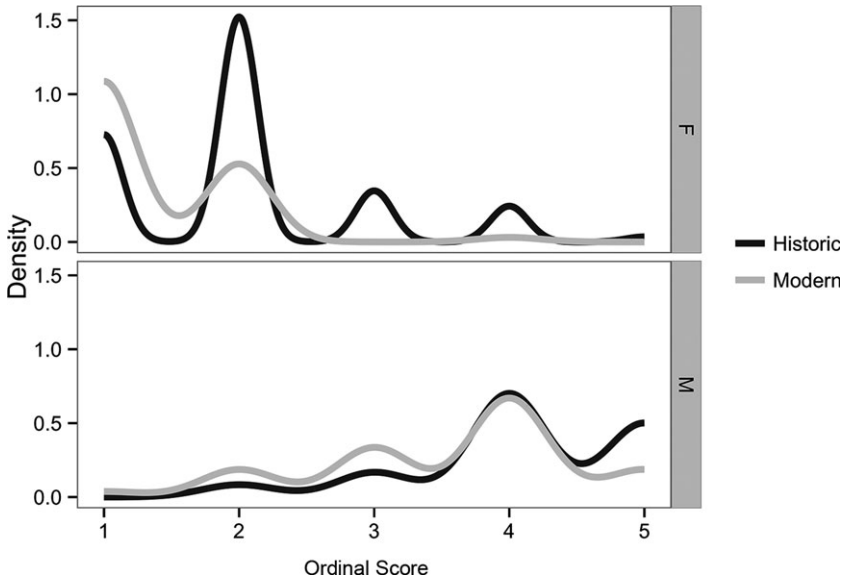

FIG. 5—*Density plots of the subpubic contour scores for both temporal samples (M: males; F: females).*

TABLE 3—*Score frequencies (%) for the ventral arc for both temporal samples.*

		Trait Score				
Sex	Sample	1	2	3	4	5
Females	HT	18.1	53.0	25.3	3.6	0.0
	UT	58.5	35.8	5.7	0.0	0.0
Males	HT	0.0	0.0	19.5	37.9	42.5
	UT	1.3	7.9	25.0	40.8	25.0

distributions does not have a significant impact on the results obtained in this study.

The score frequency distributions reveal that through time females are becoming more gracile in trait expression, while males trait scores have stayed relatively consistent through time, with robust expression being the most common. As in the original research (11), all grades of character expression were found in both temporal samples, thereby, also supporting the assertion that intermediate forms do frequently occur. An intermediate score (score 3) was the most common expression in females for the MA, yet intermediate SPC and VA scores for males and females were much less frequent in both samples. Males consistently had higher ordinal scores for each trait indicating more robust expression of the trait as compared to females in both temporal periods. Females in both samples were much more variable than the males. The historic females had greater variability in scores than the modern females, which tended to cluster more into the gracile score categories (1 or 2). Furthermore, none of the modern females exhibited a score five (most robust expression) for any of the three traits. Stull et al. (21) found a similar pattern using a modern South African sample, whereby females tended to have lower scores and none of the female individuals exhibited a score of five for any of the traits, while males consistently had more robust, or high, scores.

Analysis of the residuals revealed a trend toward more gracile females in the modern sample based on greater extreme low score trait expression. In all three traits, the modern females demonstrated greater-than-expected gracile expression (scores of 1 for each trait). Conversely, the historic females presented lower-than-expected residuals for score one of the SPC and MA. In historic males, only the SPC (score 5 only) had a residual near the critical value, which suggested a more masculine expression of this trait in the past. The general trend through time, as revealed by the residuals, is a tendency toward a morphologically more gracile appearing pubis region. The morphological gracilization found in these three traits parallels metric studies, which have suggested that an increase through time in pubis length "stretched" the region and resulted in a more gracile and thereby more feminine appearance (14). The metric findings likely correspond to a narrower ischio-pubic ramus, a wider area lateral to the symphyseal face, and a greater subpubic concavity.

Interestingly, after 1940, when most of the modern UT sample individuals were born, the "trend toward medically managed pregnancy and childbirth has steadily accelerated" (22:3). As of 2011, nearly one-third (32.8%) of all births in the United States were by Cesarean section (23). A higher incidence of Cesarean sections in modern populations would seemingly relax selection for a wider birth canal and a large subpubic concavity; however, we see a higher incidence of wider subpubic angles in the modern sample than in the historic sample. Results from this research support Delprete's (12:27) metric findings and contradict conclusions by Lehman et al. (24,25) that suggest female pelves are becoming more masculine in appearance or changing in a way that is "unfavorable for reproduction."

Given the abovementioned trends, it is apparent that secular change is occurring in morphological traits of the pubis. Specifically, modern females consistently had lower trait scores and thereby a more gracile appearance than historic females. Because of a more gracile appearance in modern females, sex differentiation in modern forensic cases using the three traits of the pubis should be higher than classification accuracy in historic samples. Despite the presence of secular change in trait expression, methods derived from these traits still appear to be applicable for sex estimation in modern forensic cases based on high classification accuracy and low, known error rates. When tested in an independent, modern U.S. validation sample, the Klales et al. (11) method (using the regression equation created with the historic HT collection) produced 86.2% classification accuracy between males and females. A similar study using a modern, South African

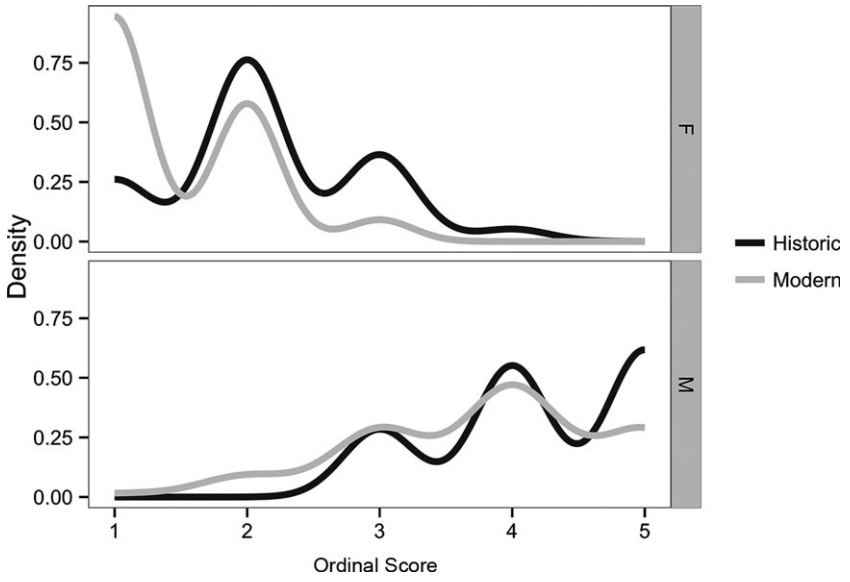

FIG. 6—*Density plots of the ventral arc scores for both temporal samples (M: males; F: females).*

TABLE 4—*Odds ratios for each of the three trait's scores by temporal period.*

		Trait Score									
		1		2		3		4		5	
Trait	Sex	UT	HT	UT	HT	UT	HT	UT	HT	UT	HT
MA	Females	3.76	0.06	1.20	0.38	0.99	0.51	0.28	2.73	0.00	–
	Males	–	–	–	–	0.95	0.54	0.81	0.69	–	–
SPC	Females	2.61	0.11	0.61	1.03	0.00	–	0.22	3.65	0.00	–
	Males	–	–	2.29	0.13	2.06	0.16	0.98	0.51	0.38	1.90
VA	Females	3.24	0.07	0.68	0.88	0.22	3.65	0.00	–	–	–
	Males	–	–	–	–	1.28	0.34	1.08	0.45	0.59	1.07

TABLE 5—*Results of the Freeman–Halton exact test for significant differences between the temporal periods for each trait.**

Trait	Females	Males
MA	**0.004**	0.102
SPC	**<0.001**	**0.002**
VA	**<0.001**	**0.008**

*Values significant at $p < 0.05$ are bolded.

TABLE 6—*Residual scores for each trait score for both temporal periods.**

		MA		SPC		VA	
Sex	Score	HT	UT	HT	UT	HT	UT
Females	1	−1.7	**2.1**	**−2.3**	**2.8**	**−2.5**	**3.1**
	2	−0.3	0.4	1.1	−1.4	0.9	−1.1
	3	0.0	0.0	1.6	**−2.0**	1.7	**−2.1**
	4	1.5	−1.9	1.0	−1.2	0.9	−1.1
	5	0.5	−0.6	0.5	−0.6	–	–
Males	1	−1.0	1.1	−1.0	1.1	−0.7	0.8
	2	−1.3	1.4	−1.1	1.1	−1.8	1.9
	3	0.1	0.0	−1.3	1.4	−0.5	0.5
	4	0.7	−0.7	0.1	0.0	−0.2	0.2
	5	−0.6	0.7	1.9	**−2.0**	1.3	−1.4

*Scores above the critical value are bolded.

TABLE 7—*Temporal period classification accuracy by sex using ordinal logistic regression.**

Sex	Sample		HT	UT
Females	HT	*n*=	69	14
		%	**83.1**	16.9
	UT	*n*=	21	32
		%	39.6	**60.4**
Males	HT	*n*=	74	13
		%	**85.1**	14.9
	UT	*n*=	41	35
		%	53.9	**46.1**

*Correct group classifications are bolded.

population by Kenyhercz (26) produced even higher classification accuracy (99.2%), as did another South African study by Stull et al. (21) (combined method average of 97.5% accuracy) when using a population-specific regression equation. The ongoing research by Kenyhercz and McCormick found similarly high classification accuracies when applying the method to a modern Thai sample. Lastly, a test of the method in positively identified, modern forensic cases achieved 90.9% classification accuracy (27). Each of these validation and recalibration studies suggest that the Klales et al. (11) revision of Phenice's (8) three traits for sex estimation remains accurate and reliable for use in modern forensic contexts despite secular change in pubic bone morphology.

Conclusion

As a discipline, biological anthropologists are aware that secular changes are occurring, which has previously called into question the utility of many methods, specifically in regard to those derived from historic samples, for biological profile estimation. The present research has shown that there are significant differences in pubic trait expression between historical and modern U.S. males and females, thereby indicating morphological secular change. Despite the observed changes, low classification accuracy for temporal period between the modern and historic sample using OLR suggests that the changes that are occurring may not necessarily negate the utility of biological profile estimation methods derived from these traits. Further, high sex classification accuracy between males and females using the Klales et al. (11) method in multiple modern samples suggests that this method is still reliable and valid for modern forensic cases, despite being developed using a historic sample and despite secular changes in trait expression.

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