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ORIGINAL ARTICLE

Sex estimation of the Cretan humerus: a digital radiometric study

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Abstract Sex estimation based on measurements of unidentified skeletal remains recovered in crime and death scenes can be accomplished with accuracy. In mass disasters, however, the remains are often fleshed, burned, and/or commingled. As a result, osteometric methods are difficult to apply. In such cases, radiography can be of great use during the examination process. A total of 101 (53 males and 48 females) adult humeri were radiographed using digital equipment (Technix TCA 4R PLUS). Specific measurements were taken on the radiographs and then analyzed. Multivariate discriminant function analysis was applied, and the results showed up to 89.1% classification accuracy. Single variables performed equally well for both epiphyses reaching 86.1% correct group membership. The method proposed here is successful, offering an alternative sex estimation technique applicable to the identification of deceased individuals whose remains are semi-fleshed, burned, mutilated, or otherwise unrecognizable. Specifically, this method is extremely useful when maceration of the remains is not an option.

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Introduction

The identification of an unknown body can be easily accomplished when fresh and relatively complete cadavers are recovered. Yet, death and crime scenes often involve disfigured and/or dismembered individuals exposed to scavengers and environmental conditions for an unknown amount of time. This significantly impedes the identification process. For instance, human remains recovered in mass disasters consist of comingled and charred body parts with fragmented and partially exposed skeletal elements. To apply standard osteometric methods for the reconstruction of the biological profile that will potentially lead to positive identification, maceration is indispensable. However, the amount of work and the time limitations in severe mass disasters preclude the maceration of the recovered remains. An alternative way to study such semi-fleshed remains is the application of image processing techniques such as radiography and computed tomography.

The application of imaging methods allows the visualization of the bones independently of the state of the remains (semi-fleshed, mummified, or charred), thus allowing immediate observation prior to autopsy. Moreover, radiographic equipment is routinely used in forensic departments. Recently, conventional radiographic machines have been replaced by digital ones, which have no additional cost for materials (e.g., film). Digital radiographic equipment can produce and store radiographs immediately, thus allowing a rapid evaluation of the skeleton in forensic cases. The objective here is to test the potential use of radiographs of the skeleton for the identification of sex.

Radiological identification was first introduced in 1926 by Culbert and Law, and since then, it has been extensively used in diagnosing skeletal pathology and trauma as well as in positive identification [1–5]. Nevertheless, the use of radiography in skeletal identification has been, until recently, limited to classical radiographic methods [6–8]. Lately, digital radiographs have been used in sex assessment of the femur [9, 10] and the humerus [11] achieving up to 93% accuracy.

The recovery of fragmentary skeletal remains in forensic investigations requires easy and rapid techniques for biological profiling and reconstruction of scene history. The use of radiographs instead of the actual bones allows the identification of semi-decomposed bodies without the need for special preparation (e.g., maceration), thus speeding up and facilitating the whole forensic investigation. The current study aspires to develop a sex estimation technique using metric variables taken on digital radiographs of humeral epiphyses for forensic purposes.

Materials and methods

Study population A total of 101 (53 males and 48 females) adult humeri were radiographed using a digital X-ray machine (Technix TCA 4R PLUS). The remains were selected from the exhumed skeletons of St. Konstantinos and Pateles Cemeteries, Heraklion, Crete. The assemblage consists of individuals who were born in Crete between 1867 and 1956, and died between 1968 and 1998. Mean age for males is 68. 57±13.52 (N=61) and for females is 72. 98±16. 90 (N=58).

Data acquisition Standard orientation of the bones was achieved by letting the humerus balance on the horizontal plane, with the anterior surface oriented towards the X-ray camera. Five landmarks (A–E) were selected on the radiograph of the proximal humerus (Table 1) and ten generated distances (PH1-PH10), representing all possible combinations of these marks, are calculated (Table 2). Seven landmarks (A–G) were selected on the radiograph of the distal epiphysis (Table 1) and 21 generated distances (DH1–DH21), representing all possible combinations of these marks, were calculated (Table 2). The selected landmarks for both proximal and distal humerus are illustrated in Fig. 1. TpsUtil [12] was used to create the databases from the radiographs. TpsDig2 was used to digitize the selected landmarks and to incorporate the scaling factor. Morpheus et al. [13] was used to generate the distances from the selected landmarks. Measurements were submitted to discriminant function analysis using SPSS subroutines.

Digitizing error For the quantification of intra-observer variation, standard procedures were followed [14, 15]. Five specimens were randomly selected, and each one was digitized five times. Principal components analysis was carried out, in order to test the relative position of the repeats in respect to each other and to the other individuals. This test evaluated the magnitude of error precision relative to the differences in shape between these five specimens and within the sample.

Discriminant function analysis A one-way ANOVA is used in order to calculate the means and the standard deviations for each measurement. Discriminant function analysis (DFA) was used to select the optimal combination of variables and to calculate specific formulae in order to classify cases in pre-existing groups according to the similarities between each case and the other cases belonging to the same group. In this analysis, (stepwise), F to enter is set to 3.84 and F to remove to 2.71. Single variables

Table 1 Definition of landmarks for both proximal and distal humerus

	Proximal humerus
A	The projection of the medial and inferior part of the head
B	The projection of the superior part of the anatomical neck
C	The sectioning point on the humeral head outline of the orthogonal projection of the middle point between landmarks A and B
D	The maximum curvature point of the greater tubercle
E	The most lateral point that defines the maximum distance from landmark A
	Distal humerus
A	The incision point between the medial epicondilus and medial part of the trochlea
B	The maximum curvature point projected in the distal surface of the medial trochlea
C	The incision point in the distal surface of the troclear groove
D	The maximum curvature point in the distal surface between the capitulum and the trochlea
E	The incision point of the capitulum and medial epicondylus
F	The most lateral point of the projection of the lateral epicondilus
G	The most medial point of the projection of medial epicondilus

Table 2 Definition of variables for the proximal and distal humerus

Proximal humerus		Distal humerus			
Variables	Distance	Variables	Distance	Variables	Distance
PH1	AB	DH1	AB	DH11	BG
PH2	AC	DH2	AC	DH12	CD
PH3	AD	DH3	AD	DH13	CE
PH4	AE	DH4	AE	DH14	CF
PH5	BC	DH5	AF	DH15	CG
PH6	BD	DH6	AG	DH16	DE
PH7	BE	DH7	BC	DH17	DF
PH8	CD	DH8	BD	DH18	DG
PH9	CE	DH9	BE	DH19	EF
PH10	DE	DH10	BF	DH20	EG
				DH21	FG

were subjected to direct discriminant function analysis to define the demarking point for separating the groups in the current population.

Cross-validation A "jack-knife" classification procedure is applied in order to demonstrate the accuracy rate of the original sample and the one created by cross-validation. The closer the cross-validated is to the original accuracy, the higher the reliability of the discriminant function would be.

Posterior probabilities The normal curve models of the predictor variables for each group was used to provide probability estimates of a particular score given membership in a particular group.

Results

Digitizing error

The five repeats were submitted to a principal components analysis, which showed that in all cases (proximal as well as distal epiphyses), the repeats are much closer to each other than to other individuals or their repeats. The percentage of variance, which is explained by digitizing error, was also calculated according to Cardini and Elton [16]. The ratio was computed for all repeats separately and the percentage varied from 0.75% to 3.1% for the proximal humerus (average of 1.9%) and from 3.3% to 8% for the distal humerus (average of 4.8%).

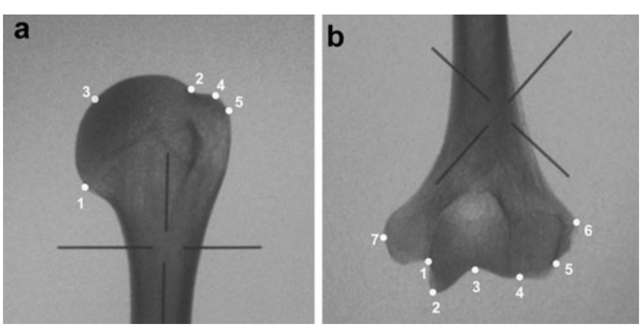

Fig. 1 Selection of landmarks. **a** Proximal **b** Distal humerus

Discriminant function analysis

Univariate statistics

Descriptive statistics and univariate differences between the sexes are calculated for each one of the ten dimensions of the proximal and 21 dimensions of the distal humerus. All but PH6 were found significantly different between the sexes at the level of $p<0.05$.

Table 3 presents the results of the discriminant function analysis for the single dimensions that performed better with over 80% accuracy of correct classification. F-ratios, cut-off values, and classification accuracy for both original and cross-validated data are also shown here. PH1, PH2, DH4, DH18, and DH20 are the best discriminatory variables with 86.1% accuracy.

Multivariate statistics

When all ten variables of the proximal humerus were used with a direct procedure, classification accuracy did not exceed 80%. PHF1 is the result of direct DFA using PF1, PF3, PF4, PH7, PH8, PH9, and PH10; PHF2 uses PF1–PF4 whereas PHF3 uses three measurements (PH1, PH3, and PH4). PHF2 is the formula that separates the sexes with the best accuracy (see Table 4). Stepwise procedure using nine variables that were found significantly different between the sexes, selected only one variable: PH4.

When direct DFA was applied to all 21 measurements of the distal humerus, seven of them were rejected automatically due to high co-variation with some of the remaining

Table 3 Univariate statistics for the measurements on the radiographs of the proximal and distal humerus

V	F-ratio	Cut-off value	Original					Cross-validated				
			Males		Females		Total	Males		Females		Total
			N=53	%	N=48	%	%	N=53	%	N=48	%	%
Proximal humerus												
PH1	121.05	44.17	43	81.1	44	91.7	86.1	43	81.1	44	91.7	86.1
PH2	91.32	28.25	45	84.9	42	87.5	86.1	45	84.9	42	87.5	86.1
PH3	94.69	48.33	42	79.2	43	89.6	84.2	42	79.2	43	89.6	84.2
PH4	126.71	49.8	44	83.0	43	89.6	86.1	43	81.1	43	89.6	85.1
Distal Humerus												
DH2	54.58	15.26	40	75.5	41	85.4	80.2	40	75.5	41	85.4	80.2
DH3	85.07	28.18	43	81.1	43	89.6	85.1	43	81.1	43	89.6	85.1
DH4	104.74	39.38	44	83.0	43	89.6	86.1	44	83.0	43	89.6	86.1
DH5	92.59	46.37	43	81.1	40	83.3	82.2	43	81.1	40	83.3	82.2
DH6	57.81	15.94	41	77.4	43	89.6	83.2	41	77.4	43	89.6	83.2
DH8	89.71	26.36	45	84.9	41	85.4	85.1	45	84.9	40	83.3	84.2
DH9	87.68	38.54	42	79.2	42	87.5	83.2	42	79.2	42	87.5	83.2
DH10	82.54	47.44	42	79.2	41	85.4	82.2	42	79.2	41	85.4	82.2
DH13	63.72	24.65	41	77.4	42	79.2	82.2	41	77.4	42	79.2	82.2
DH15	103.74	30.11	40	75.5	46	95.8	85.1	40	75.5	46	95.8	85.1
DH18	109.66	42.52	41	77.4	46	95.8	86.1	41	77.4	46	95.8	86.1
DH20	121.89	52.5	43	81.1	44	91.7	86.1	43	81.1	44	91.7	86.1
DH21	99.61	57.27	42	79.2	46	95.8	84.2	42	79.2	46	95.8	84.2

14 measurements. The combination of the 14 measurements gave a classification accuracy of 89.1% for the original data and 85.1% for the cross-validated sample. Table 4 presents DHF1 which is the one of the formulae with 11 variables and classification accuracy of 89.1%. Stepwise procedure selected only one variable (DH20) with classification accuracy of 86.1%. DHF2 is the result of a direct analysis using a combination of four variables (DH20, DH18, DH4, and DH 15). DHF3 is the result of a direct DFA using only DH20 and DH5. This formula has the minimum number of variables with the highest possible accuracy for the cross-validated data. Discriminant functions and accuracies for both original and cross-validated data are presented in Table 4. Sectioning point is set to zero in all cases.

Posterior probabilities

Univariate statistics

Posterior probabilities for the measurements taken on the radiographs of the proximal humerus resulted in grouping up to 42.6% of the specimens at a 0.95 threshold with 86.1% accuracy. For PH1, values over 45.3 mm for males and fewer than 39.6 mm for females classify the sample within 95% of confidence intervals. Similarly, PH4 classified over 73% of the sample at a 0.8 threshold, over 62% at a 0.9, and 42.6% at a 0.95 threshold with 86.1% accuracy (see Table 5).

In the case of distal humerus, 13 variables gave over 80% accuracy, and therefore posterior probabilities were calculated for each one of them (Table 5). The most reliable variable was found to be DH20 which classified correctly over 41% of the specimens at a 0.95 threshold with 86.1% accuracy. An individual with DH20>56.21 mm is classified as male within 90% of confidence intervals, whereas if DH20>57.49 mm, has 95% probability to be a male (Table 5).

Multivariate statistics

The best multivariate discriminant functions for the proximal humerus were PHF1, PHF2, and PHF3 with accuracies that reached 89%. All formulae classified over 70% of the sample with 80% probability. PHF1 performed better classifying over 67% of the specimens at 0.9 and over 57% of the specimens and a 0.95 threshold with 89.1% accuracy (Table 6).

The best multivariate discriminant functions for the distal humerus were DHF1, DHF2, and DHF3 with accuracies that reached 89%. DHF1 performed better

Table 4 Discriminant functions and classification accuracies for the proximal and distal humerus. Sectioning point is set to zero in all cases

	Proximal Humerus									Distal Humerus							
	F-ratio	Raw coefficients	Male		Female		Total			F-ratio	Raw coefficients	Male		Female		Total	
			N= 53	%	N= 48	%	%					N= 53	%	N= 48	%	%	
PHF1									DHF1								
PH1	46.82	0.211340	45	84.9	45	93.8	89.1	Original	DH20	56.11	-0.090012	45	84.9	45	93.8	89.1	Original
PH3	51.02	0.333786	44	83.0	44	91.7	87.1	Cross-validated	DH18	45.77	0.050562	44	83.0	43	89.6	86.1	Cross-validated
PH4	52.82	-0.148356							DH4	41.94	0.962343						
PH7	13.47	0.064807							DH15	32.26	0.290986						
PH8	35.76	-1.006738							DH21	61.24	0.039110						
PH9	41.66	0.958213							DH5	49.33	-0.117982						
PH10	7.88	-0.615780							DH8	28.45	0.778707						
Constant	-17.768589								DH9	41.01	-0.782126						
PHF2									DH3	30.37	-0.713853						
PH1	46.82	0.217321	45	84.9	45	93.8	89.1	Original	DH13	26.19	0.180293						
PH2	30.25	0.093335	44	83.0	45	93.8	88.1	Cross-validated	Constant	-15.559626							
PH3	51.02	-0.371965							DHF2								
PH4	52.82	0.479580							DH20	56.11	0.098027	43	81.1	46	95.8	88.1	Original
	-18.121070								DH18	45.77	0.046350	43	81.1	44	91.7	86.1	Cross-validated
PHF3									DH4	41.94	0.131566						
PH1	46.82	0.304936	44	83.0	45	93.8	88.1	Original	DH15	32.26	0.129463						
PH3	51.02	-0.408107	43	83.0	45	93.8	87.1	Cross-validated	Constant	-16.196080							
PH4	52.82	0.493376							DHF3								
Constant	-18.294018								DH20	56.11	0.279626	43	81.1	45	93.8	87.1	Original
									DH5	49.33	0.031957	43	81.1	46	95.8	86.1	Cross-validated
									Constant	-16.163374							

Table 5 Posterior probabilities (PP) of the measurements taken on the radiographs of the proximal (PH1-PH4) and distal (DH2-DH21) humerus

PP (%)	Males		Females		Total	Males		Females		Total	Males		Females		Total	Males		Females		Total
	DP>	%	DP<	%	%	DP>	%	DP<	%	%	DP>	%	DP<	%	%	DP>	%	DP<	%	%
	PH1					DH3					DH9					DH20				
>95	47.50	45.3	40.76	39.6	42.6	32.29	24.5	24.54	18.8	21.8	43.18	22.6	34.51	18.8	20.8	57.49	47.2	48.46	35.4	41.6
>90	46.80	64.2	41.43	56.3	60.4	31.30	37.7	25.45	33.3	35.6	41.95	34.0	35.65	37.5	35.6	56.21	56.6	49.56	52.1	54.5
>80	45.75	71.7	42.41	66.7	69.3	30.25	58.5	26.57	62.5	60.4	40.83	56.6	36.77	62.5	59.4	55.35	67.9	50.14	75.0	71.3
>50	44.17	81.1	44.17	91.7	86.1	28.39	75.5	28.39	89.6	85.1	38.78	79.2	38.78	87.5	83.2	52.86	75.5	52.86	91.7	86.1
	PH2					DH4					DH10					DH18				
>95	31.59	28.3	24.95	22.9	25.7	43.36	37.7	35.98	22.9	30.7	52.95	28.3	42.54	20.8	24.8	47.26	41.5	38.38	27.1	34.7
>90	30.87	37.7	25.77	43.8	40.6	42.43	47.2	36.92	50.0	48.5	51.60	39.6	43.68	39.6	39.6	46.16	62.3	39.51	45.8	54.5
>80	29.95	60.4	26.66	60.4	60.4	41.38	64.2	37.88	66.7	65.3	50.17	56.6	45.27	54.2	55.4	44.99	67.9	40.67	72.9	70.3
>50	28.25	84.9	28.25	87.5	86.1	39.63	83.0	39.63	89.6	86.1	47.73	79.2	47.73	85.4	82.2	42.84	77.4	42.84	87.5	86.1
	PH3					DH5					DH13									
>95	52.70	30.2	43.90	25.0	27.7	51.47	28.3	41.54	25.0	26.7	28.85	15.1	20.71	4.2	9.9					
>90	51.52	52.8	45.18	43.8	48.5	50.41	39.6	43.07	52.1	41.6	27.50	28.3	22.08	25.0	26.7					
>80	50.32	69.8	46.35	66.7	68.3	49.11	64.2	44.34	62.5	63.4	26.52	47.2	23.02	47.9	47.5					
>50	48.33	79.3	48.33	93.8	84.2	46.66	75.5	46.66	83.3	82.2	24.80	77.4	24.80	87.5	82.2					
	PH4					DH6					DH15									
>95	53.44	45.3	46.13	39.6	42.6	19.20	15.1		0.0	7.9	33.48	43.4	27.09	22.9	33.7					
>90	52.51	66.0	47.04	58.3	62.4	18.35	30.2	13.78	18.8	24.8	32.97	49.1	27.95	50.0	49.5					
>80	51.57	75.5	47.99	70.8	73.3	17.51	50.9	14.51	43.8	47.5	31.84	62.3	28.86	62.5	62.4					
>50	49.76	83.0	49.76	93.8	86.1	16.06	77.4	16.06	89.6	83.2	30.32	75.5	30.32	87.5	85.1					
	DH2					DH8					DH21									
>95	18.27	15.1	12.29	6.3	10.7	13.75	22.6	10.32	22.9	22.8	64.02	35.4	51.72	31.3	31.7					
>90	17.65	24.5	13.03	14.6	19.8	13.15	39.6	10.73	39.6	39.6	62.12	43.4	52.74	43.8	43.6					
>80	17.01	45.3	13.96	37.5	41.6	12.78	54.7	11.21	64.6	59.4	60.81	66.0	54.88	58.3	62.4					
>50	15.36	75.5	15.36	85.4	80.2	11.97	84.9	11.97	85.4	85.1	57.67	79.2	57.67	89.6	84.2					

DP = Demarking point

Table 6 Posterior probabilities (PP) of the multivariate functions for the proximal and distal humerus

PP (%)	Proximal humerus					Distal humerus				
	Males		Females		Total	Males		Females		Total
	DS>	%	DS<	%	%	DS>	%	DS<	%	%
	PHF1					DHF1				
>95	1.1903	62.3	-1.246	52.1	57.4	1.2957	47.2	-1.3454	43.8	45.5
>90	0.9785	67.9	-0.9144	66.7	67.3	0.9786	62.3	-0.9686	54.2	58.4
>80	0.3858	73.6	-0.8169	72.9	73.3	0.6366	71.7	-0.6434	77.1	74.3
>50	0	84.9	<0	93.8	89.1	0	84.9	0	93.8	89.1
	PHF2					DHF2				
>95	1.2496	58.5	-1.2454	50.0	54.5	1.3244	49.1	-1.3330	39.6	44.6
>90	0.9145	67.9	-0.9102	62.5	65.3	1.0052	58.5	-1.0222	58.3	58.4
>80	0.5943	75.5	-0.6494	70.3	73.3	0.7781	67.9	-0.6344	39.6	73.3
>50	0	84.9	<0	93.8	89.1	0	81.1	0	95.8	88.1
	PHF3					DHF3				
>95	1.264	54.7	-1.2911	45.8	50.5	1.3773	45.3	-1.3342	39.6	42.6
>90	0.9212	66.0	-0.9599	60.4	63.4	1.3114	56.6	-0.0283	52.1	54.5
>80	0.5705	75.5	-0.619	70.8	77.2	0.6552	69.8	-0.6658	72.9	71.3
>50	0	83.0	0	93.8	88.1	0	75.5	0	93.8	87.1

DS = Discriminant score

classifying over 58% of the specimens at a 0.9 and over 45.5% of the specimens and a 0.95 threshold with 89.1% accuracy (Table 6).

Discussion

Forensic radiology is a sub-specialization of forensic medicine, defined as the discipline that "utilizes the interpretation of medical radiological examinations to answer legal questions" [17]. The importance of radiographic methods has been long acknowledged in medico-legal practice [3–5, 18–20], and currently, it includes both clinical and postmortem radiology. Despite the fact that the most frequent applications survey positive identification (e.g., comparison of antemortem and postmortem dental X-rays), it has been widely used in biological profiling of the deceased, determination of cause and manner of death, medical negligence, non-accidental trauma, and smuggling [3, 5, 19].

Classical radiographic techniques can be helpful in assessing biological features from the different bones of the human skeleton. Age estimation using dental radiographs is reported extensively in the literature [18, 21–23]. Furthermore, the closure of the epiphyses in radiographs appears up to 6 months before it can be observed in the dry bones [24], which can be very helpful in cases of age estimation in juvenile individuals.

Radiography can be quite successful in sex identification as well. Brogdon [18] gives an example of what he calls "the absolute roentgenographic indicator of sex" in one of the victims of the Air India crash (Flight 182, July, 2000). Many of the recovered victims had viscera displaced into the thoracic cavity, resulting in the accidental discovery of an 18–22 week fetus in the chest radiograph of a young female. Anatomical features such as rib cartilage ossification [25] and dimensions of skeletal elements such as the bones of the cranium [26], sternum [27], calcaneus [6], patella, and foot [28] have been examined by means of radiography to assess sex. In addition, digital radiographs of the femur [9, 10] and humerus [11] have been more recently employed for the same purpose.

The latter study [11] addresses population specific sex estimation criteria based on quantified morphological features of digital radiographs of the humerus with the aid of geometric-morphometrics (GMM). The application of GMM techniques in humeral radiographs has proven to be successful, since it reveals shape differences that could not be assessed with conventional methods and allows for the combination of size and shape for the identification of sex with up to 90% accuracy. However, GMM is a method that requires a sophisticated mathematical background and complex statistical routines; thus, it is difficult to use [11].

The sex estimation method proposed here is an easy and simple technique based on linear measurements taken on radiographs of the humerus. Since the integrity of the recovered bones in forensic settings cannot be assured, this study considers fragmentary models. Therefore, each epiphysis of the humerus was radiographed separately. A certain number of landmarks were selected in each radiograph, and all inter-landmark distances were calculated. The landmarks were selected with the objective of being easily distinguished even by an inexperienced observer. The generated distances are the variables used to discriminate males and females with the aid of discriminant function analysis.

The radiographic machine that was employed is an accurate and flexible device used routinely in our department for diagnostic and scientific purposes. The radiographs taken are stored in digital form and can be transferred to a computer for further evaluation and therefore kept as evidence in case that they are needed in court. The advantage of such a machine relays on the rapid diagnosis and to the fact that there no additional costs for consumables (i.e., films, etc.).

It is commonly known that the overall reliability on sex estimation depends on the chosen method and the study population [2]. The computation of posterior probabilities for all functions allows the observer to evaluate each method for the particular case under consideration. The determination of sex using posterior probabilities and a threshold of 0.95 is highly reliable, and therefore, it was considered at the present study. Posterior probabilities at 0.9 and 0.8 thresholds were also calculated. According to this principle, the percentage of correctly assigned specimens based on formulae with over 80% accuracy was calculated.

According to the set of data employed here, the identification of sex using linear measurements on radiographs of the humerus was proved feasible. The classification accuracy reached 86% for single dimensions and 89% using multivariate approaches. Both epiphyses performed equally well. Single dimensions of the proximal (PH1 and PH4) and the distal (DH20) humerus classified correctly about 42% of the sample at a 0.95 threshold while at a 0.9 threshold. The single dimensions for the proximal epiphysis “performed” slightly higher (up to 62% compared with 54%). Similarly, multivariate functions for the proximal humerus classified a higher portion of the sample at a 0.95 threshold (up to 52%) compared with the ones for the distal humerus (up to 46%). These data indicate that functions for the proximal humerus are, overall, more accurate since they discriminate a larger amount of individuals within 95% levels of confidence. Yet, the true value of the method is tested in each individual case since the choice of method in forensic anthropology is always case-driven.

As in any osteometric study, the standards provided here should be treated as specific for the Cretan population, and caution should be taken when applying the formulae to other Greek or Balkan populations. However, to test the applicability of the formulae produced in this study to other populations, for both osteometric and radiometric data, several comparative samples are needed, an issue that needs to be explored by means of future research.

The lack of forensic anthropologists in Greece and other places around the world calls for the development of rapid and easy to use techniques that can be applied by the pathologists in order to reconstruct the biological profile of the individual in question and thus assisting positive identification. The method proposed here has proven to be successful as a sex estimation technique yielding high accuracies of correct assessment. Therefore, it is a useful alternative method, applicable to semi-decomposed, charred, or mummified remains like those recovered from mass disasters and forensic cases. Also, the use of digital radiographs in sex estimation can be advantageous when semi-fleshed or charred remains are recovered and maceration is not an option.

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References

1. Krogman WM, Sassouni V (1957) A syllabus in roentgenographic cephalometry. Philadelphia Growth Study, Philadelphia, pp 45–103
2. Krogman WM, İşcan MY (1986) The human skeleton in forensic medicine. Charles C. Thomas, Springfield
3. Kahana T, Hiss J (1997) Identification of human remains: forensic radiology. J Clin Forensic Med 4:7–15
4. Kahana T, Ravioli JA, Urroz CL, Hiss J (1997) Radiographic identification of fragmentary human remains from a mass disaster. Am J Forensic Med Pathol 18:40–44
5. Kahana T, Hiss J (1999) Forensic radiology. Br J Radiol 72:129–133
6. Riepert T, Drechsler T, Schild H, Nafe B, Mattern R (1996) Estimation of sex on the basis of radiographs of the calcaneus. Forensic Sci Int 77:133–140
7. Sağir M (2006) Estimation stature from X-rays of metacarpals in the Turkish population. Anthropol Anz 64:377–388
8. Petrovecki V, Mayer D, Slaus M, Strinović D, Skavić J (2007) Prediction of stature based on radiographic measurements of cadaver long bones: a study of the Croatian population. J Forensic Sci 52:547–552
9. Harma A, Karakas HM (2007) Determination of sex from the femur in Anatolian Caucasians: a digital radiological study. J Forensic Legal Med 14:190–194
10. Kranioti EF, Vorniotakis N, Galiatsou C, Iscan MY, Michalodimitrakis M (2009) Sex identification and software development using digital femoral head radiographs. Forensic Sci Int 189:113.e111–113.e117

11. Kranioti EF, Bastir M, Sánchez-Meseguer A, Rosas A (2009) A geometric-morphometric study of the Cretan humerus for sex identification. Forensic Sci Int 189:111.e111–111.e118
12. Rohlf, F (1997) tpsDIG, 1.08, Department of Ecology and Evolution, State University, Stony Brook, New York
13. Slice DE, Morpheus et al (1998) Software for morphometric research. Revision 01-01-00, New York, Department of Ecology and Evolution, State University, Stony Brook
14. Martinón-Torres M, Bastir M, Bermúdez de Castro JM, Gómez A, Sarmiento S, Muela A (2006) Geometric morphometric analysis of hominin lower second premolars: evolutionary implications. J Hum Evol 50:523–533
15. O'Higgins P, Jones N (1998) Facial growth in *Cercocebus torquatus*: an application of three-dimensional geometric morphometric techniques to the study of morphological variation. J Anat 193:251–272
16. Cardini A, Elton S (2008) Does the skull carry a phylogenetic signal? Evolution and modularity in the guenons. Biol J Linn Soc 93:813–834
17. Walsh M, Reeves P, Scott S (2004) When disaster strikes; the role of the forensic radiographer. Radiography 10:33–43
18. Brogdon G (1998) Forensic radiology. CRC Press, Brogdon G, LLC, Boca Raton, Florida
19. Brogdon BG (2006) Forensic aspects of radiology. In: Spitz WU, Spitz DJ, Clark R, Fisher RS (eds) Spitz and Fisher's medicolegal investigation of death: guidelines for the application of pathology to crime investigation. Springfield, Illinois
20. Evans KT, Knight B (1986) Forensic radiology. Br J Hosp Med 31:14–20
21. Kvaal SI, Kolltveit KM, Thomsen IO, Solheim T (1995) Age estimation of adults from dental radiographs. Forensic Sci Int 74:175–185
22. Thevissen PW, Pittayapat P, Fieuws S, Willems G (2009) Estimating age of majority on third molars developmental stages in young adults from Thailand using a modified scoring technique. J Forensic Sci 54:428–432
23. Maber M, Liversidge HM, Hector MP (2006) Accuracy of age estimation of radiographic methods using developing teeth. Forensic Sci Int 159:S68–S73
24. Paterson RS (1929) A radiological investigation of the epiphyses of the long bones. J Anat 64:28–46
25. McCormick WF, Stewart JH, Langford LA (1985) Sex determination from chest plate roentgenograms. Am J Phys Anthropol 68:173–179
26. Patil KR, Mody RN (2005) Determination of sex by discriminant function analysis and stature by regression analysis: a lateral cephalometric study. Forensic Sci Int 147:175–180
27. Torwald CR, Hoppa RD (2005) A test of sex determination from measurements of chest radiographs. J Forensic Sci 50:785–790
28. Abdel Moneim WM, Abdel Hady RH, Abdel Maaboud RM, Fathy HM, Hamed AM (2008) Identification of sex depending on radiological examination of foot and patella. Am J Forensic Med Pathol 29:136–140