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Radiometry versus osteometry in sex assessment

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Original research

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ABSTRACT

Sex estimation is vital for biological profiling, thus qualitative and quantitative methods have been developed for every skeletal part in humans. Amongst them the radius is somehow neglected. This study aims to develop a sex estimation method on radiographs of the radius applicable in situations when classical osteometry cannot be applied. A total of 103 left radii were used in this study. Three classical measurements (maximum length, head diameter and distal breadth) were taken on the dry bones. Digital radiographs of the same radii were taken using a portable X-ray machine (Technix TCA 4R PLUS). Eight landmarks are selected on the radiograph of the proximal and six on the radiograph of the distal radius generating in total 43 linear distances. ANOVA detected 3 osteometric and 24 radiometric variables that differed significantly between males and females ($p < 0.05$). Classical osteometry resulted in up

to 91% classification accuracy while the best multivariate formula of the radiometric method gave 88% correct classification. The study proposes a rapid and inexpensive alternative method for sex screening based on digital radiographs of the radius that can be particularly advantageous in cases of mass disasters with numerous mutilated and/or burnt bodies where maceration is not an option.

Key words: Forensic Anthropology, Sex estimation, Digital Radiography, Radius, Discriminant function analysis

1. Introduction

Sex estimation is the foremost crucial part of forensic identification when recovering human remains in extreme decomposition. Conventional methods of identification such as facial features, fingerprints, birthmarks or scars are useless when highly decomposed, mutilated, incinerated or skeletonized bodies are recovered¹. Consequently, forensic anthropologists are tasked to reconstruct the individual's biological profile to assist the identification process. Correct sex assessment guides forensic investigations of suspicious or complicated deaths towards the right direction while the opposite impedes the clarification of the circumstances surrounding the death of the individuals.

Classical osteometry has been widely used to develop sex estimation techniques for different populations in time and space ²⁻⁹. In addition, medical imaging techniques can be extremely useful in the estimation of sex. An excellent example of the use of conventional radiography in rapid sex estimation is given by Brogdon¹⁰ when describing the X-ray screening in one of the victims of Air India crash (Flight 182, 2000). The thoracic radiograph of a young female revealed a 18-22 week fetus displaced in her chest. In addition, conventional radiography and computed tomography have also been employed lately to develop digital methods of sex estimation for every bone of the

human skeleton¹¹⁻¹⁵. Amongst the bones that have been used in that aspect, the radius has received very little attention compared to the skull, the pelvis and other long bones.

Osteometric studies on the radius for sex estimation include a number of different populations. Berrizbeitia¹⁶ analysed radiographs of 567 paired radii from the Terry Collection, with respect to the minimum and maximum diameter of the radial head. A sample of 50 pairs was used for cross validation, resulting in up to 94% correct group membership. Among the five measurements taken from the forearm by Holman and Bennett¹⁷, maximum length and semistyloid breadth (SSB) of the radius are included. The SSB was measured from the most lateral point on the styloid process to the deepest point of the ulnar notch, at a right angle to the long axis of the bone. When only these two measurements were combined, classification accuracy yielded 72% for males and 92% for females. Mall and co-workers¹⁸, in a study of the upper extremity of a contemporary German population, included three radial dimensions (maximum length, maximum head diameter and distal width). The best discriminatory variable for the radius was found to be maximum length (89.1%), followed by maximum head diameter (88.6%) and multivariate analysis gave 94.9% classification accuracy. In a study by Safont and collaborators¹⁹ using the circumferences of long bones, radial tuberosity circumference was found to be the second most effective single dimension, with a classification accuracy of 92.8%. The radius has also been studied for Greeks using ROC analysis and resulted in up to 91% classification accuracy when considering single variables²⁰.

The aim of the current study is to explore the validity of digital radiographs of the radius for sex estimation in situations of extreme mutilation such as mass disasters when the time and limited resources do not allow for the maceration of the remains. A secondary goal of the study was to compare the efficiency of radiographic methods for sex estimation compared with classical osteometry techniques on the same sample and bone. For this reason the exact same sample was used to employ radiometric and osteometric techniques. Since the integrity of the recovered bones in forensic settings cannot be assured, this study considers fragmentary models in order to simulate real-life situations where the integrity of the skeleton is compromised due to post-mortem decomposition or mass disaster incidents.

2. MATERIAL AND METHODS

2.1 Study population

A total of 103 (53 males and 50 females) adult left radii were used in this study. The remains were selected from the Cretan collection, a modern reference collection comprising individuals who were born on the island of Crete, Greece between 1867 and 1956, and died between 1968 and 1998³.

2.2 Osteometric and radiographic equipment

Osteometric data were obtained using a sliding caliper. A digital X-ray machine (Technix TCA 4R PLUS), which constitutes part of the routine equipment in the forensic investigation of our department, was used for taking the radiographs of the radii. A more detailed description of the system can be found elsewhere^{13,21}.

2.3 Data acquisition.

Three classical measurements were taken on each radius: maximum length (ML), maximum head diameter (HD) and maximum distal breadth (DB) as defined by Martin and Seller²².

Standard orientation of the bones was achieved by letting the radius balance on the horizontal plane, with the anterior surface facing the X-ray camera. Eight landmarks (A-G) were selected on the radiograph of the proximal radius and 28 generated distances (PR1-PR28), representing all possible combinations of these points were calculated. Six landmarks (A-G) were selected on the radiograph of the distal epiphysis and 15 generated distances (DR1-DR15) representing all possible combinations of these landmarks, were calculated. The selected landmarks for both proximal and distal radius are defined in **Table 1** and illustrated in Figure 1 for 5 different specimens.

TpsUtil was used to create the databases from the radiographs. This software creates a sequence of images that can be used afterwards for digitizing landmarks on each consecutive image in an efficient and rapid way. TpsDig2²³ is a second program that was used to digitize the selected landmarks and to incorporate the scaling factor. Morpheus et al.²⁴ was used to generate the distances from the selected landmarks. Combining the eight selected landmarks on the proximal radius, 28 distances (PR1-PR28) were generated. Combining the six selected landmarks, on the distal radius, 15 distances (DR1-PR15) were generated. All radiometric variables can be seen in Table 2.

Table 1. Definition of landmarks for both proximal and distal Radius

Landmarks	Proximal Radius
A	Point under the end of the lateral projection of radial tuberosity in the long axis of the radial shaft as seen in the radiograph.
B	Point so that the distance AB is perpendicular to the axis of the radial shaft.
C and D	Points on the radial neck so that the distance CD represents the minimum radial diameter on the radiograph
E and F	Points on the radial head so that the distance EF represents the maximum radial diameter on the radiograph.
G	Point on the most lateral projection of the radial tuberosity
H	Point on the radial shaft so that the distance GH is perpendicular to the radial shaft.
	Distal Radius
A	Point on the most medial projection of the distal radial epiphysis
B	Point on the most distal projection of the styloid process
C	Point on the most lateral projection of the styloid process
D	Point on the most inferior and medial border of the lunar articular facet and the inferior projection of the ulnar notch.
E	Point of intersection between the posterior and inferior border of the scaphoid articular facet medially.
F	Point of insertion of brachioradialis. It corresponds to the most lateral projection near the lateral end of the epiphyseal line as seen in the radiograph.

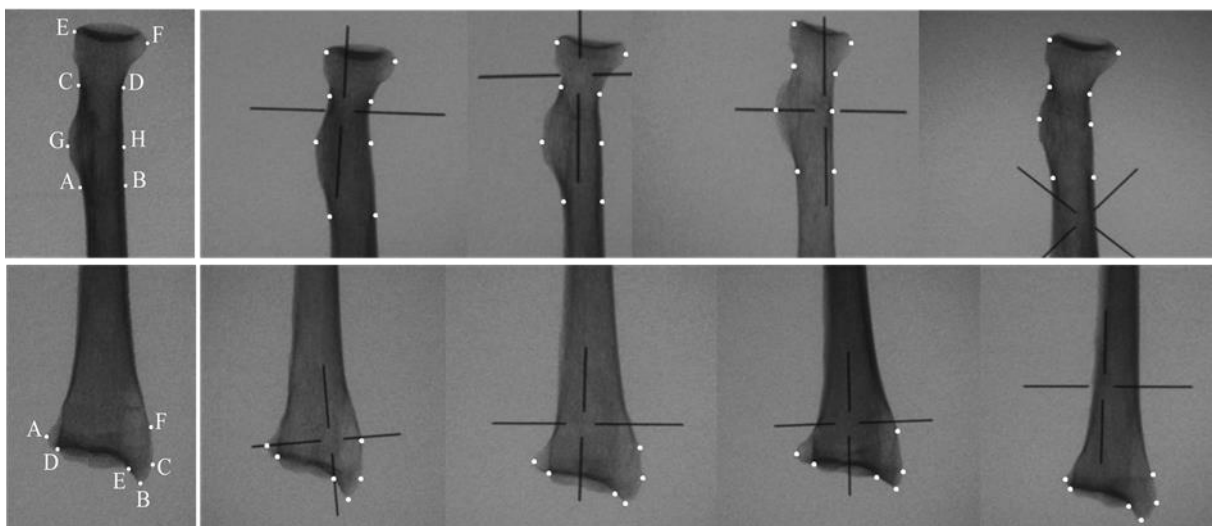


Figure 1. Position of the landmarks on the proximal and distal radius in 5 random specimens

2.4 Statistical analysis

2.4.1 Error estimation

Intra-observer variation was quantified for osteometric variables according to Ulijaszek and Kerr²⁵ and for landmark data according to O'Higgins and Jones²⁶.

2.4.2 ANOVA and discriminant function analysis

Measurements were submitted to discriminant function analysis using SPSS 22. Descriptive statistics were used to present the study sample. A one-way ANOVA was used to test the mean differences between males and females for each measurement. All subset discriminant function analysis 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. The accuracy rate of the original sample was always compared to the one created using a “leave one out” approach.

Table 2. Definition of variables for the proximal and distal Radius

Proximal Radius (28)				Distal Radius (15)	
Variables	Distances	Variables	Distance	Variables	Distances
PR1	AB	PR16	CF	DR1	AB
PR2	AC	PR17	CG	DR2	AC
PR3	AD	PR18	CH	DR3	AD
PR4	AE	PR19	DE	DR4	AE
PR5	AF	PR20	DF	DR5	AF
PR6	AG	PR21	DG	DR6	BC
PR7	AH	PR22	DH	DR7	BD
PR8	BC	PR23	EF	DR8	BE
PR9	BD	PR24	EG	DR9	BF
PR10	BE	PR25	EH	DR10	CD
PR11	BF	PR26	FG	DR11	CE
PR12	BG	PR27	FH	DR12	CF
PR13	BH	PR28	GH	DR13	DE
PR14	CD			DR14	DF
PR15	CE			DR15	EF

2.4.3 Posterior probabilities

The normal curve models of the discriminatory variables for each group were used to provide estimates (posterior probabilities) of a particular score given membership in a particular group. Posterior probability is a statistical term referring to the conditional probability of the individual being of a particular sex given that a particular value of discriminant score or linear measurement was observed. For sex estimation three thresholds were considered (PP \geq 80%, PP \geq 90% and PP \geq 95%).

95%. In order to evaluate the accuracy of the given formulae posterior probabilities were calculated for all functions that resulted in more than 80% classification accuracy.

Table 3. Intra-observer error was quantified by calculating TEM, rTEM and R for each variable.

	TEM	rTEM	R
ML	1.05	0.46	0.99
HD	0.22	1.42	0.96
DB	0.37	1.22	0.97

3. RESULTS

3.1 Error estimation

Error of the osteometric variables was estimated using Technical Error Measurement (TEM), relative TEM (rTEM) and R (coefficient of reliability) in a sample of 10 randomly selected radii. The error estimates can be seen in Table 3.

Table 4. Means, Standard Deviations and F-ratios for all osteometric (Vost) and radiometric (Vrad) variables

Osteometry-Radius						Radiometry-Proximal Radius					
	Males (N=53)		Females (N=50)				Males (N=53)		Females (N=48)		
Vost	Mean	SD	Mean	SD	F-ratio	Vrad	Mean	SD	Mean	SD	F-ratio
ML	119.03	10.59	215.17	11.70	242.36	^d PR1	13.21	1.3	12.08	3.9	4.05
HD	99.76	1.63	19.94	1.27	5.51	PR2	27.82	3.9	27.17	7.8	0.28
BD	58.82	2.61	26.45	3.07	70.61	PR3	29.58	3.9	28.3	7.9	1.1
Radiometry-Distal Radius						PR4	42.36	4.3	40.31	9.5	2.05
	Males (N=53)		Females (N=48)			^d PR5	43.68	3.9	40.42	10.0	4.64
Vrad	Mean	SD	Mean	SD	F-ratio	PR6	15.07	3.3	14.73	4.9	0.17
^a DR1	31.13	2.54	28.05	1.99	45.72	PR7	19.42	2.5	18.23	5.5	2.05
^a DR2	32.98	2.54	29.53	1.94	58.43	PR8	30.01	3.4	29.07	8.2	0.58
DR3	4.22	1.38	4.06	1.1	0.44	PR9	25.6	3.8	24.82	6.6	0.54
^a DR4	25.14	2.35	23.15	2.0	20.91	PR10	43.9	3.9	41.52	9.9	2.62
^a DR5	32.19	2.68	28.18	1.75	78.6	^d PR11	38.51	3.8	35.8	8.6	4.38
^a DR6	10.25	1.6	7.89	1.22	68.65	PR12	21.86	2.6	21.14	6.8	0.51
^a DR7	27.08	1.95	24.2	1.66	63.45	PR13	13.4	3.0	13.14	4.0	0.14
^a DR8	6.51	1.45	5.24	1.13	23.9	PR14	13.13	1.4	12.07	4.4	2.85
^a DR9	17.66	2.11	15.37	2.2	28.59	^d PR15	14.61	3.0	13.17	2.8	6.36
^a DR10	29.24	2.09	26.08	1.65	70.65	^b PR16	22.91	2.1	20.43	5.8	8.54
^a DR11	10.3	1.19	8.37	1.03	76.01	PR17	13.83	3.6	13.86	4.5	0.00
DR12	8.15	1.95	8.31	2.21	0.15	PR18	18.84	2.7	17.71	5.5	1.81
^a DR13	21.12	1.82	19.38	1.75	23.96	^c PR19	21.51	1.9	19.39	5.5	6.97
^a DR14	29.00	2.14	25.45	1.53	90.51	^b PR20	14.17	2.4	12.27	3.3	11.3
^a DR15	15.26	1.64	13.34	1.76	32.04	PR21	20.75	3.1	20.04	6.7	0.48
^a Significantly different at the level of $p < 0.001$ ^b $p < 0.005$						PR22	12.22	3.3	11.71	3.4	0.61
						^d PR23	21.56	1.8	19.35	6.1	6.3
						PR24	27.93	4.2	26.56	5.9	1.85

Five specimens were randomly selected, each one was digitized five times and principal components analysis was carried out for the whole sample and the repeats. The relative position of the repeats in respect to each other and to the other individuals was tested in an effort to evaluate the magnitude of error relative to the differences in shape between these five specimens and within the sample. Figure 2 shows a plot of principal component 1 and 2 where the repeats of test specimens 1,2,3 and 5 cluster much closer to themselves than to other individuals. This indicates small intra-observer error. In the case of the repeats of test specimen 4 other individuals also cluster very close. This can be attributed to perhaps the fact that many individuals were a similar size to this particular individual and the two components cannot differentiate easily between them.

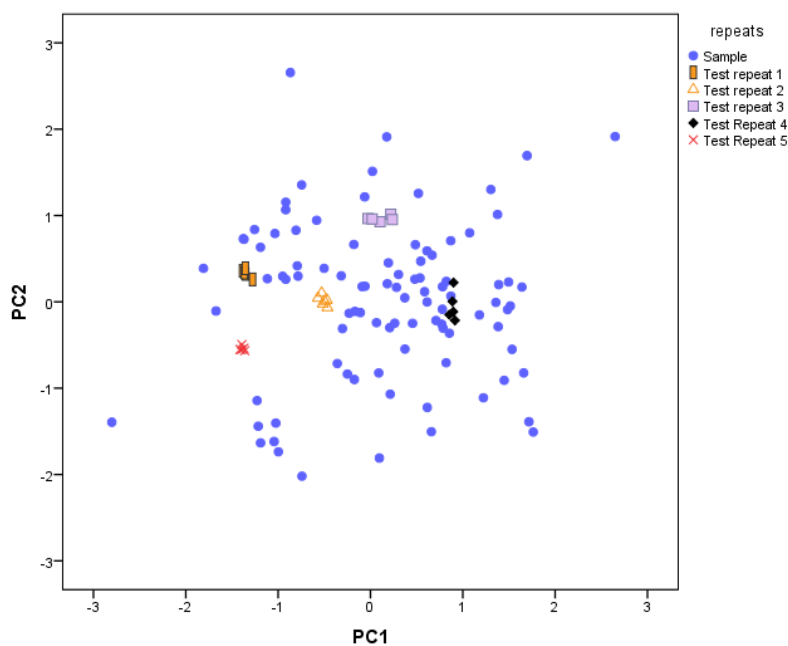


Figure 2. Plot of Principal components 1 and 2 using radiometric measurements for 5 test specimens and the whole sample.

3.2 Osteometry

3.2.1 Univariate analysis

All osteometric variables were found to differ significantly ($p < 0.001$) with respect to their means after ANOVA was carried out. Descriptive statistics can be found in **Table 4**. Univariate equations were created for ML, and HD and BD sectioning points were calculated accordingly (see **Table 5**). The best discriminatory variable was found to be

ML (88%) followed by HD (86%) for cross-validated data. Interestingly HD classifies strikingly higher females compared to males and the other two variables.

Table 5. F-ratios, cut-off values and classification accuracies for the Osteometric (V_{ost}) and the Radiometric (V_{rad}) variables.

	V	F-ratio	Cut-off value	Original			Cross-validated		
				Males %	Females %	Total %	Males %	Females %	Total %
V_{ost}	ML	119.03	227.3	88.7	87.5	88.1	88.7	87.5	88.1
	HD	99.76	21.39	83	91.7	87.1	81.1	91.7	86.1
	BD	58.82	28.62	84.9	79.2	82.2	84.9	77.1	81.2
V_{rad}^1	Proximal Radius								
	PR16	8.54	21.67	75.5	90	82.5	75.5	90	82.5
	PR23	6.3	20.17	77.4	94	85.4	77.4	94	85.4
	Distal Radius								
	DR5	78.6	30.18	75	85.7	80.2	75	85.7	80.2
	DR11	76.01	9.34	78.8	81.6	80.2	78.8	79.6	79.2
	DR14	90.51	27.22	75	91.8	83.2	75	91.8	83.2

¹Only variables with over 80% accuracy are included

3.2.1 Multivariate analysis

Multivariate formulae for all possible combinations of the three variables were created and classification accuracy was calculated for both original and cross-validated data. Function R1 (ML, HD, BD) gave the best classification accuracy for cross-validated data (96%) while R4 (HD, BD) performed the worst with 86% for cross-validated data. **Table 6** presents all multivariate functions (R1-R4) and classification accuracies.

3.3 Radiometry

3.3.1 Univariate analysis

Descriptive statistics of the 43 dimensions and univariate differences between the sexes are shown in **Table 4**. Ten variables (PR1, PR5, PR11, PR15, PR16, PR19, PR20, PR23, PR25 and PR27) of the proximal radius were found to be significantly different between the sexes at the level of $p < 0.05$. Of them only PR 16 (82.5%) and PR23 (85.4%) resulted in over 80% classification accuracies (see **Table 5**). Thirteen variables of the distal radius were found to differ significantly between the sexes at the

level of $p < 0.001$ (**Table 4**). Of them only three exceeded 80% classification, thus they are listed in **Table 5**.

Table 6. Multivariate discriminant functions and classification accuracies for the radius for osteometric and radiometric variables.

	V	Raw coefficients	Males %	Females %	Total %	Classification accuracy
Osteometric Variables	Function R1					
	ML	0.06	98.1	95.8	97	Original
	HD	0.30	98.1	93.8	96	Cross-validated
	BD	0.12				
	Constant	-22.83				
	Function R2					
	ML	0.06	96.2	93.8	95	Original
	HD	0.40	96.2	93.8	95	Cross-validated
	Constant	-22.38				
	Function R3					
	ML	0.07	96.2	89.6	93.1	Original
	BD	0.19	94.3	89.6	92.1	Cross-validated
	Constant	-21.71				
Function R4						
HD	0.52	84.9	89.6	87.1	Original	
BD	0.15	83.0	89.6	86.1	Cross-validated	
Constant	-15.36					
Radiometric Variables	Function DRF1					
	DR1	2.70	84.6	91.8	88.1	Original
	DR2	0.02	79.8	89.8	84.2	Cross-validated
	DR4	-3.47				
	DR5	0.69				
	DR6	0.43				
	DR7	0.67				
	DR8	-3.27				
	DR9	0.67				
	DR10	-0.24				
	DR15	-0.76				
	Constant	-13.19				
	Function DRF2					
	DR14	0.37	80.8	87.8	84.2	Original
	DR6	0.36	80.8	87.8	84.2	Cross-validated
	Constant	-13.28				
	Function DRF3					
DR6	0.24	80.8	91.8	86.2	Original	
DR14	0.33	78.8	89.8	84.2	Cross-validated	
DR11	0.23					
Constant	-13.29					

3.3.2 Multivariate analysis

Various formulae were produced using direct and stepwise discriminate function analysis of various combinations of the 10 variables for the proximal radius, however, none exceeded the cut-off of 80% that was set as a limit in this study; therefore no multivariate formula is presented herein. Similarly, various different combinations of the 13 variables for the distal radius resulted in higher classification. The combination of 9 measurements (DRF1) gave a classification accuracy of 88.1% for the original data

and 84.2% for the cross-validated sample. When a stepwise procedure was applied (DRF2), only two variables (DR6 and DR14) were selected. Many different combinations gave similar classification results for the original data but worse for the cross-validated ones. Some of the best formulae for separating the sexes along with classification results for both original and cross-validated data are presented in **Table 6**. Sectioning point is set to zero in all cases. DRF3 is the result of a direct DFA using the three more effective single variables (DR6, DR11 and DR14). Classification accuracy reached 86.1% for the original whereas classification for the cross-validated data was only slightly lower.

3.4 Posterior probabilities

3.4.1 Univariate statistics

3.4.1.1 Proximal radius

Posterior probabilities for the measurements taken on the radiographs of the proximal radius resulted in grouping all the specimens under a 0.8 threshold, suggesting that there is a considerable degree of overlap between the two groups.

3.4.1.2 Distal radius

Posterior probabilities for the measurements taken on the radiographs of the distal radius classified up to 29% of the specimens at a 0.95 threshold. More specifically DR14 classified 43% of the sample at a 0.9 and 29% of the sample at a 0.95 threshold with 83% accuracy. The cut-off values for this formula at a 0.95 threshold are 30.26mm for males and 16.3mm for females (**Table 7**).

3.4.2 Multivariate statistics

3.4.2.1 Proximal radius

Multivariate discriminant functions using different number of variables of the proximal radius did not exceed the cut-off of 80% accuracy that was set in this study. Therefore, posterior probabilities for the multivariate functions of the proximal radius are not presented here.

3.4.2.2 Distal radius

The best multivariate discriminant function for the distal radius (DRF1) classified over 76% of the sample at a 0.8, over 64% at a 0.9 and over 50% at a 0.95 threshold

exhibiting 88% correct group membership. For this function discriminant scores over 1.2501 classify males and under -1.2378 classify females at a 0.95 threshold. DRF3 classified over 60% of the sample with 90% probability and over 40% with 95% probability of correct group assignment with 86.1% accuracy. For this function and individual with $DS > 1.4316$ has 95% probability to be a male while if $DS < -1.3826$ it has 95% probability to be a female. Posterior probabilities for all multiple discriminant functions of the distal radius are shown in Table 7.

Table 7. Posterior probabilities for univariate and multivariate functions for the radiometric variables

PP (%)	Males		Females		Total	Males		Females		Total
	>	%	<	%	%	>	%	<	%	%
	DR5					DRF1				
>95	34.00	28.9	25.93	14.3	21.8	1.25	51.9	-1.24	49.0	50.5
>90	33.14	42.3	27.27	28.6	35.6	1.07	59.6	-0.92	69.4	64.4
>80	32.46	55.8	28.37	57.1	56.4	0.58	67.3	-0.63	85.7	76.2
>50	30.18	75.0	30.18	85.7	80.2	0	84.6	0	91.8	88.1
	DR11					DRF2				
>95	11.35	21.2	7.40	18.4	19.8	1.45	48.1	-1.43	28.6	38.6
>90	10.76	32.7	7.80	36.7	34.7	1.19	51.9	1.04	63.3	57.4
>80	10.26	55.8	8.44	55.1	55.5	0.65	65.4	-0.65	77.6	71.3
>50	9.34	78.9	9.34	81.6	80.2	0	80.8	0	87.8	84.2
	DR14					DRF3				
>95	30.26	42.3	24.24	16.3	29.7	1.43	46.2	-1.38	34.7	40.6
>90	29.52	51.9	24.97	32.7	42.6	1.06	59.6	-1.02	61.2	60.4
>80	28.84	61.5	25.82	55.1	58.4	0.69	69.2	-0.71	77.6	73.3
>50	27.26	75.0	27.26	91.8	83.2	0	80.8	0	91.8	86.1

An example of the applicability of the method is illustrated in Figure 3. A radiograph of the wrist from the hospital's archives was randomly selected with unique criterion the

preservation of the distal epiphysis of the radius and was used to apply the method. Landmarks were placed according to the instructions (see materials and methods) and measurements were calculated using taking under account the scale (corresponding to 6 cm). For this case DRF1 was found to be -0.9718, which according to Table 7 classifies the individual as female with over 90% probability. Demographic information of the patient confirmed the X-rays belonged to a female.



Figure 3. Example of application of the method in a randomly selected radiograph from the hospital's archive.

4. Discussion

Sex can be identified through direct observation, osteometry or medical imaging techniques by the shape and the size of the pelvis, the cranial features and the size of the long bones. In the case of severe mass incidents resulting in mass destruction, disfigurement and mutilation of human bodies, classic identification techniques

(facial recognition, fingerprints) become problematic while osteological methods for biological profiling are often deemed unfeasible as they require maceration of the body parts, which would be time consuming under the circumstances of a mass incident. In these cases, medical imaging techniques, including classical radiography could be of extreme help if radiometric standards of biological profiling were available. Taking these under consideration the current study aspires to use radiographs of the radius, a relatively neglected bone in medical imaging studies, to develop a sex estimation method for a modern Greek population.

Indeed, there are hardly any radiographic studies dealing with sex estimation of the radius. One of the early radiographic studies using portable X-ray equipment is that of Allen and colleagues in 1987 recording 3 measurements on the radius ²⁷. Most recent studies from radiographs and CT scans include the correlation of maximum length and distal width using radiographs of the radius ²⁸ but mostly focus on developing age ²⁹ and stature estimation methods ^{30,31}. The present study created and tested 43 new metric variables from the proximal and distal epiphyses of the radius to explore statistically significant differences between the sexes. The best function for the proximal epiphysis involved a single variable (PR16, 85.4%) while different combination of variables gave poor results for cross-validated data. For the distal epiphysis the best variable was DR14 (83.2%) while three multivariate formulae gave over 84% accuracy for the cross-validated data (see **table 6**).

Comparing the classification accuracy of the radiometric method to classical osteometry on the same sample, the latter performs better with 81-96% classification accuracy for cross-validated data. The best single variable was found to be ML (88%) followed by HD (86%) and DB (81%). The best single radiometric variables for the upper and lower epiphysis are PR23 (85%) and DR14 (83.2%) respectively. These results are comparable with the results of the osteometric method. In the case of the multivariate functions, the osteometric methods the best function (R1) achieved 96% accuracy which is 10% higher than the best radiometric functions for cross-validated data. This can be attributed to the inclusion of total length in the functions R1-R3 which is the most important single sex indicator. Function R4 (which only includes HD and BD) achieved lower classification accuracy (86%) compared to R1-R3. The radiometric method considered separately each epiphysis and gave similar

results (up to 84% for cross-validated data) to R4, which makes it valuable in cases of mutilated bodies where the radius may not be found intact.



Figure 4. Human arm found away from the rest of the body, due to animal scavenging, in a forest in Rethymnon, Crete. This is an excellent example of a case that would benefit from the radiometric method.

Digital radiographs have been proven to be useful in developing sex estimation methods for Greeks on several occasions. Studies of radiographs from the upper epiphysis of the Cretan femur yielded up to 93% accuracy while osteometric methods on the same sample did not exceed 87%³². A similar study on femoral radiographs of living individuals from Egypt³³ followed the same protocol on data acquisition and reported similar and in some occasion higher classification accuracy compared to the Kranioti et al. ³² study. In addition, studies of the radiographs of the Cretan humerus using traditional¹³ and geometric morphometric approaches³⁴ resulted in high classification accuracies (up to 90%) making the use of radiographs an excellent alternative when other methods are unavailable.

Medical imaging techniques have been increasingly used by forensic practitioners not only for diagnostic purposes but also for the development of standards for biological profiling. Amongst the obvious advantages is the availability of large samples from hospital archives, which allows for data collection without the existence of modern skeletal collections. For example, in Muslim countries the creation of modern skeletal collections is an impossible task due to the religious prohibition of exhuming human remains after their burial¹⁴. Another example is the strict legislation regarding the use of modern human remains for research that

currently applies in the UK (see Human Tissue Act, 2004; 2006). This work eliminates the abovementioned problems with the use of portable X-ray machines in the examination of skeletal remains and presents an example of developing a sex estimation technique from fragments of the radius under X-rays. The classification results are comparable to the classical osteometric method applied on the epiphyses of the bone, and thus it can be used as an alternative method for cases of dismembered bodies. Figure 4 illustrates a human arm that was found away from the body due to animal scavenging in a forest in the area of Rethymnon, Crete, which would be an excellent example of applicability of this method. The same X-ray machine that was used for this study is always available at the morgue for a quick scan of the remains and the application of the method would not take more than 5-10 minutes depending on the experience of the operator. It must be stressed that the data was derived from a documented sample of a modern Greek population from Crete thus, it should not be considered applicable to other populations without further testing.

Conclusions

Radiometric techniques are valuable alternative tools to classical osteometry for building a biological profile of unknown remains. They become especially advantageous in cases of semi-decomposed, incinerated or postmortem scattered remains that maceration cannot be done due to restrictions in time or resources. The current study presents a method of sex estimation based on the radiographs of the radius, which classifies the study sample almost as well as the classical osteometric technique. Thus, it is recommended for use in forensic cases if the specifics of the case dictate, bearing in mind that the method is population specific and not appropriate for wider use without validation.

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References

1. Brogdon BG. Forensic aspects of Radiology. In: Spitz WU, Spitz DJ, Clark R FR, ed. Spitz and Fisher's Medicolegal Investigation of Death: Guidelines for the Application of Pathology to Crime Investigation. 4th ed. Chicago, IL: Springfield; 2006:1092-1135.
2. Krüger GC, L'Abbé EN, Stull KE. Sex estimation from the long bones of modern South Africans. *Int J Legal Med.* 2016;1-11. doi:10.1007/s00414-016-1488-z.
3. Kranioti EF, Michalodimitrakis M. Sexual Dimorphism of the Humerus in Contemporary Cretans—A Population-Specific Study and a Review of the Literature*. *J Forensic Sci.* 2009;54(5):996-1000. doi:10.1111/j.1556-4029.2009.01103.x.
4. Curate F, Coelho J, Gonçalves D, et al. A method for sex estimation using the proximal femur. *Forensic Sci Int.* 2016;266:579.e1-579.e7. doi:http://dx.doi.org/10.1016/j.forsciint.2016.06.011.
5. Spradley MK, Anderson BE, Tise ML. Postcranial Sex Estimation Criteria for Mexican Hispanics. *J Forensic Sci.* 2015;60:S27--S31. doi:10.1111/1556-4029.12624.
6. Kranioti EF, Apostol MA. Sexual dimorphism of the tibia in contemporary Greeks, Italians, and Spanish: forensic implications. *Int J Legal Med.* 2015;129(2):357-363. doi:10.1007/s00414-014-1045-6.
7. Franklin D, O'Higgins P, Oxnard CE, Dadour I. Discriminant function sexing of the mandible of Indigenous South Africans. *Forensic Sci Int.* 2008;179(1):84.e1-84.e5. doi:http://dx.doi.org/10.1016/j.forsciint.2008.03.014.
8. Navega D, Vicente R, Vieira DN, Ross AH, Cunha E. Sex estimation from the tarsal bones in a Portuguese sample: a machine learning approach. *Int J Legal Med.* 2015;129(3):651-659. doi:10.1007/s00414-014-1070-5.
9. Papaioannou VA, Kranioti EF, Joveneaux P, Nathena D, Michalodimitrakis M. Sexual dimorphism of the scapula and the clavicle in a contemporary Greek population: Applications in forensic identification. *Forensic Sci Int.* 2012;217(1-3):231.e1-231.e7. doi:http://dx.doi.org/10.1016/j.forsciint.2011.11.010.
10. Thali, M.J., Viner, M.D., Brogdon BJ, ed. Brogdon's Forensic Radiology. 2nd ed. Boca Raton, Florida: CRC Press, LLC; 2010.
11. DeSilva R, Flavel A, Franklin D. Estimation of sex from the metric assessment of digital hand radiographs in a Western Australian population. *Forensic Sci Int.* 2014;244:314.e1-314.e7. doi:http://dx.doi.org/10.1016/j.forsciint.2014.08.019.
12. Osipov B, Harvati K, Nathena D, Spanakis K, Karantanas A, Kranioti EF. Sexual Dimorphism of the Bony Labyrinth: A New Age-Independent Method. *Am J Phys Anthropol* 2013;151:290-301. doi:10.1002/ajpa.22279.

13. Kranioti EF, Nathena D, Michalodimitrakis M. Sex estimation of the Cretan humerus: a digital radiometric study. *Int J Legal Med.* 2011;125(5):659-667. doi:10.1007/s00414-010-0470-4.
14. Ekizoglu O, Er A, Bozdog M, et al. Sex estimation of the tibia in modern Turkish: A computed tomography study. *Leg Med (Tokyo).* 2016;23:89-94. doi:10.1016/j.legalmed.2016.10.004.
15. Franklin D, Flavel A, Kuliukas A, et al. Estimation of sex from sternal measurements in a Western Australian population. *Forensic Sci Int.* 2012;217(1-3):230.e1-230.e5. doi:http://dx.doi.org/10.1016/j.forsciint.2011.11.008.
16. Berrizbeitia EL. Sex determination with the head of the radius. *J Forensic Sci.* 1989;34(5):1206-1213.
17. Holman DJ, Bennett KA. Determination of sex from arm bone measurements. *Am J Phys Anthropol.* 1991;84(4):421-426. doi:10.1002/ajpa.1330840406.
18. Mall G, Hubig M, Büttner A, Kuznik J, Penning R, Graw M. Sex determination and estimation of stature from the long bones of the arm. *Forensic Sci Int.* 2001;117(1-2):23-30. doi:http://dx.doi.org/10.1016/S0379-0738(00)00445-X.
19. Safont S, Malgosa A, Subirà ME. Sex assessment on the basis of long bone circumference. *Am J Phys Anthropol.* 2000;113(3):317-328. doi:10.1002/1096-8644(200011)113:3<317::AID-AJPA4>3.0.CO;2-J.
20. Kranioti EF, Tzanakis N. Estimation of Sex from the Upper Limb in Modern Cretans with the Aid of ROC-Analysis: A Technical Report. *Forensic Res Criminol Int J Forensic Res Criminol Int J.* 2015;1(12). <http://medcraveonline.com>.
21. Kranioti Elena F, Vorniotakis N, Galiatsou C, Y IM, Michalodimitrakis M. Sex identification and software development using digital femoral head radiographs. *Forensic Sci Int.* 2009;189(1-3):113.e1-7. <http://www.elsevier.com/copyright>.
22. Martin, R., Seller K. *Lehrbuch Der Anthropologie in Systematischer Darstellund.* München: Gustav Fischer Verlag; 1957.
23. Rohlf F. TPSDig 1.08 Department of Ecology and Evolution, State University, Stony Brook, NY. 1997.
24. Slice DE, Morpheus et al.: Software for morphometric research. Department of Scientific Computing, The Florida State University, Tallahassee, Florida, USA. 2013.
25. Ulijaszek SJ, Kerr DA. Anthropometric measurement error and the assessment of nutritional status. *Br J Nutr.* 1999;82(3):165. doi:10.1017/S0007114599001348.
26. O'Higgins P, Jones N. Facial growth in *Cercocebus torquatus*: an application of three-dimensional geometric morphometric techniques to the study of morphological variation. *J Anat.* 1998;193 (2):251-272. doi:10.1046/j.1469-7580.1998.19320251.x.
27. Allen JC, Bruce MF, MacLaughlin SM. Sex determination from the radius in humans. *Hum Evol.* 1987;2(4):373-378. doi:10.1007/BF02436498.
28. Baumbach SF, Krusche-Mandl I, Huf W, Mall G, Fialka C. Linear intra-bone geometry dependencies of the radius: Radius length determination by maximum distal width. *Eur J Radiol.* 2012. doi:10.1016/j.ejrad.2011.02.030.

29. Baumann U, Schulz R, Reisinger W, Heinecke A, Schmeling A, Schmidt S. Reference study on the time frame for ossification of the distal radius and ulnar epiphyses on the hand radiograph. *Forensic Sci Int.* 2009;191(1-3):15-18. doi:<http://dx.doi.org/10.1016/j.forsciint.2009.05.023>.
30. Rodríguez S, Miguéns X, Rodríguez-Calvo MS, Febrero-Bande M, Muñoz-Barús JI. Estimating adult stature from radiographically determined metatarsal length in a Spanish population. *Forensic Sci Int.* 2013;226(1-3):297.e1-297.e4. doi:<http://dx.doi.org/10.1016/j.forsciint.2012.12.006>.
31. Petrovecki V, Mayer D, Slaus M, Strinović D SJ. Prediction of stature based on radiographic measurements of cadaver long bones: a study of the Croatian population. *J Forensic Sci.* 2007;52:547-552.
32. Kranjoti EF, Vorniotakis N, Galiatsou C, İşcan MY, Michalodimitrakis M. Sex identification and software development using digital femoral head radiographs. *Forensic Sci Int.* 2009;189(1-3):113.e1-113.e7. doi:10.1016/j.forsciint.2009.04.014.
33. Mostafa EM, El-Ellemi AH, El-Beblawy MA, Dawood AE-WA. Adult sex identification using digital radiographs of the proximal epiphysis of the femur at Suez Canal University Hospital in Ismailia, Egypt. *Egypt J Forensic Sci.* 2012;2(3):81-88. doi:<http://dx.doi.org/10.1016/j.ejfs.2012.03.001>.
34. Kranjoti EF, Bastir M, Sánchez-Meseguer A, Rosas A. Forensic anthropology population data A geometric-morphometric study of the cretan humerus for sex identification. *Forensic Sci Int.* 2009;189(1-3):111.e1-8. doi:10.1016/j.forsciint.2009.04.013.