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ORIGINAL ARTICLE

Sex estimation by CT image analysis of the rib cage in a Mediterranean population

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Abstract

Sexual dimorphism in the human species is key to the development of sex estimation techniques in the human skeleton. This dimorphism is manifested, as in other regions of the skeleton, in the bones that constitute the thoracic cage, according to the existing bibliography. In this aspect, the study of the human skeleton through 3D images has also proved to be useful for the development and validation of sex estimation methodologies for the reconstruction of the osteobiological profile.

For this purpose, a sample of 240 thoracic CT scans of adult individuals was selected from a collection of 3D images belonging to the University of Granada, provided by the Castilla-La Mancha Health Service (SESCAM). Different measurements of the thoracic bones (ribs R2 to R5 width, sternum length and width, and clavicles width) have been taken with OsiriX software, with the aim of developing discriminant functions for sex estimation.

The obtained results are positive, allowing sex estimation through 3D images of the thorax with up to 89.6% accuracy through discriminant functions, which shows the usefulness of image analysis for the reconstruction of the osteobiological profile.

Keywords Sex estimation · CT images · Forensic Anthropology · Thoracic cage

Introduction

Sex estimation is essential in Forensic Anthropology for the reconstruction of the osteobiological data, and consequently for the identification of skeletal remains [1, 2]. However, although it is possible to estimate sex from the skeleton in a relatively straightforward manner, there are occasions when the necessary bones are not available, due to the degree of preservation [3], which is conditioned by numerous intrinsic (e.g. bone mineral density, pathologies…) and extrinsic factors (e.g. post-mortem alterations, fauna…) [4]. Consequently, it is important to extract as much information as possible from the available fragments [5].

In general, morphological examination of the skull and/or pelvis is the basis of sex estimation methods [6–9]. However, techniques that focus on the postcranial skeleton for sex estimation are also available in these cases of poorly preserved or incomplete skeletons. Among these, studies performed on the humerus [10] or the femur and tibia [11], as well as the rest of long bones [12] can be highlighted.

It has been demonstrated that the bones of the thoracic cavity are also very useful for sex estimation, as they have been shown to be dimorphic elements of the skeleton [13, 14]. In this aspect, the sternum has been one of the most studied thoracic bones with respect to sexual dimorphism, being Hyrtl [15] who defined the so-called 'Hyrtl's Law', according to which "in females, the manubrium generally exceeds half the length of the sternal body, while in males, the sternal body is generally twice as long as the manubrium" [15]. Similarly, different rules such as 'the 149' [16] or 'the 136' [17], were defined to determine the sternal lengths for each sex using measurements at the sternum,

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Table 1 Distribution of the sample by sex and age

Sex	*N*	Age			
		Min.	Max.	Mean	S.D.
Males	140	18	93	54.39	19.78
Females	140	17	90	54.58	19.87

based on the establishment of cut-off points according to the different measurements [3].

Similarly, and despite ribs tend to be the worst preserved bones in most forensic scenarios, they have also been shown to be useful anatomical regions for sex estimation through metric studies. İşcan [5] investigated the dimorphism of the sternal extremity of the fourth rib for sex estimation, a methodology that has subsequently been evaluated and validated by different authors in diverse population groups [5, 18–21]. Additionally, it has been demonstrated that the rib neck is a useful dimorphic element for sex estimation [22], offering the additional benefit of being a more recognisable region and with a higher conservation rate than the sternal extremity [23, 24].

In this aspect, just as the study of dry bones is fundamental for sex estimation, the study of the human skeleton through the analysis of 3D images is also very useful, with numerous studies on sex estimation through the analysis of CT scans and radiographs of the thoracic cavity [3, 13, 25–29]. With this intention, the objective of this study is to analyse 3D thoracic images of patients from the Spanish population to develop discriminant functions that will allow the estimation of sex in the Mediterranean population using 3D thoracic images.

Materials and methods

The Laboratory of Physical Anthropology of the University of Granada has a PACS (Picture Archiving and Communication System) station that enables it to receive and store DICOM (Digital Imaging and Communication in Medicine) images. Thanks to this, the Laboratory has a database of hospital CT scans, with a slice size of 0.5 millimetres, from the Castilla-La Mancha Health Service (SESCAM), with most of them performed with Toshiba Aquilion, Toshiba Lightspeed VCT and GE Medical Systems HiSpeed NX/I devices. This database, which is continuously growing, currently includes more than 20,000 previously anonymised studies of clinical patients [30–32]. From these patients, their sex, age, and date of the test are known. CT images transfer to the Laboratory was approved by the SESCAM ethics committee.

From this database, a total of 280 individuals, aged between 17 and 93 years, were randomly selected, trying to homogenise the different age groups under study, considering the high availability of material (Table 1) (Fig. 1).

Among these 280 individuals, only those whose CT scan was thoraco-abdominal, including the medial epiphysis of the clavicle, the sternum, and ribs R1 to R7 were selected, discarding those whose analysis did not include any of the aforementioned bones, those whose images were too distorted, or those with pathologies that directly affected the above-mentioned bones or altered the natural processes of bone degeneration.

For this research, the methodology of Uysal Ramadan et al. [3], which consists of taking different measurements of

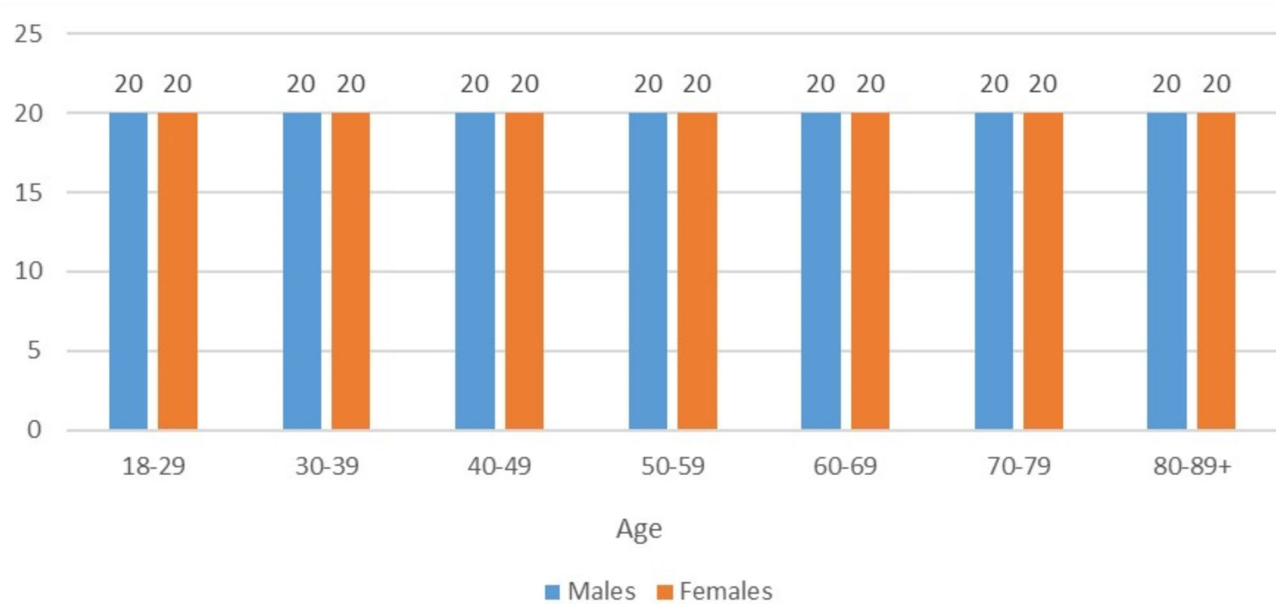

Fig. 1 Distribution of the sample by age groups

the thoracic bones using 3D images for the study of sexual dimorphism, was followed and adapted. The measurements studied were mostly taken from Uysal Ramadan et al. [3], although some others from García-Parra [32] were also taken (Fig. 2):

- Sternal manubrium length. Two different measurements were taken:
  - A. Maximum distance between the highest point of the manubrium (between the jugular and clavicular notches) and the manubrium-sternal joint [3] **[MAL1]**.
  - B. Maximum distance between the midpoint of the jugular notch and the manubrium-sternal joint [32]. **[MAL2]**

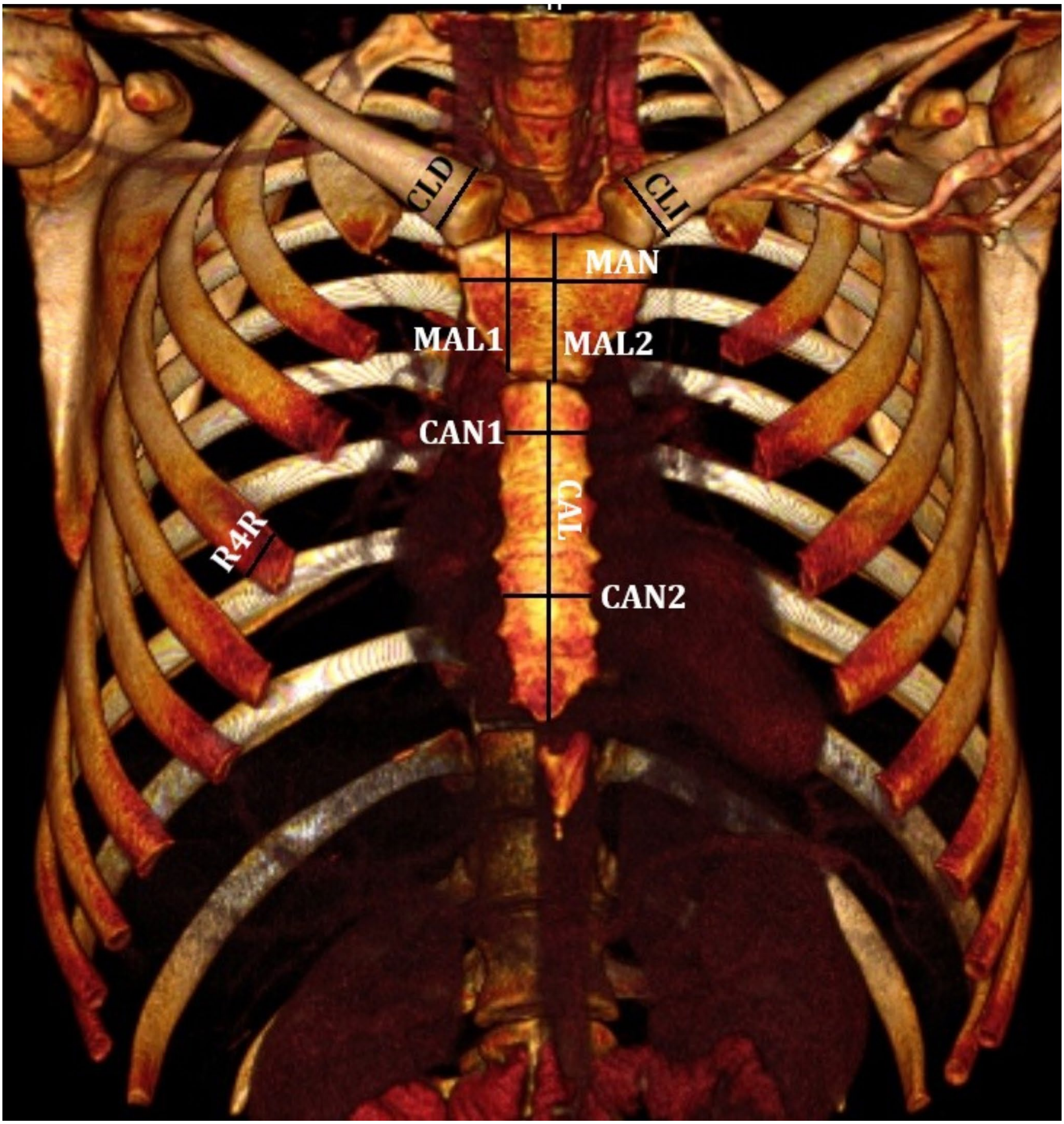

Fig. 2 Measurements taken at the different bones of the thoracic cage

- Sternal body length. Maximum distance between the manubrium-sternal and xipho-sternal joints. **[CAL]**
- Thickness of the sternal manubrium. **[MG]**
- Manubrium width. Distance between the notches of the first rib on both sides. **[MAN]**
- Width of sternal body. Taken in two regions:
  - Between R2 and R3 notches **[CAN1]**.
  - Between R4 and R5 notches **[CAN2]**.
- Sternal body thickness. **[CG]**
- Sternal index. Division between the length of the manubrium and the length of the sternal body, multiplied by 100 [(MAL1/CAL)x100] **[IE]**.
- Sternal area. Calculated by multiplying the sum of the length of the manubrium and body with the sum of the three widths taken, then dividing by three [(MAL1 + CAL)x(MAN + CAN1 + CAN2)/3] **[AE]**.
- Width of ribs R2 to R5. Although Uysal-Ramadan et al. (2010) only consider the width of the fourth rib, it has been extended to the second to fifth ribs. Distance between the upper and lower edge of the rib just proximal to the costal fossa, on both sides. **[R2-5R; R2-5 L]**
- Width of the medial epiphyses of the clavicles. Distance between the upper and lower border of the medial epiphysis of both clavicles. **[CLD-CLI]**

OsiriX software was employed for the image analysis. Once the measurements were taken, a descriptive statistical analysis of the measurements collected was carried out, disaggregated by sex, calculating the maximum and minimum values, as well as the mean value and standard deviation. Subsequently, and prior to the rest of the statistical tests, the intra-observer and inter-observer error was calculated, using Lin's Correlation Coefficient of Concordance [33–35]. The latter was calculated through the re-measurement of a subsample of 30 individuals, with initial assessments conducted by the primary observer, followed by a second measurement conducted by an experienced and independent observer, with an interval of approximately one month between measurements to minimise potential biases.

Next, the normality and homoscedasticity of the variables studied were checked using the Kolmogórov-Smirnov and Levene tests. Once the normality and homoscedasticity of the variables analysed were verified, the existence of significant differences was tested using Student's t-test for independent samples, to confirm the existence of significant differences between sexes.

Subsequently, the discriminant analysis procedure was carried out. Such analysis has the advantage of eliminating subjective criteria in sex estimation, as they are based on objective measures, and are simple to use without prior experience. Furthermore, it can also be used in cases of poor preservation of skeletal material, as many of them rely on bone fragments [36].

This analysis was performed in two different ways, through univariate discriminant functions, where each of the variables was tested individually, and multivariate discriminant functions, where discriminant functions with more than one variable were developed.

For the development of the discriminant functions, the stepwise method was applied, in which the software selects the variables with the highest discriminatory potential and excludes those with low utility for sex discrimination. For the insertion of variables, the values set by default by the program were used: input value $F \geq 3.84$ and output value $F \leq 2.71$.

Once the variables with the highest discriminatory potential were identified, the non-typified coefficients and the constant were selected for the creation of the discriminant function. To calculate the cut-off point, the mean of the centroids of both groups was obtained. In this context, the discriminant function operates as follows: the value of each variable is multiplied by its coefficient, all values are summed, and then the value of the constant is added. Individuals whose scores exceed the cut-off point are classified as male, while those below the cut-off point are classified as female. Individuals whose scores align precisely with the cut-off point are classified as indeterminate.

Finally, to assess the reliability of the functions obtained, cross-validation was applied with the same collection. In this case, cross-validation tests the predictive capacity of the functions. This is achieved by generating as many discriminant functions as there are valid cases in the analysis, with one case being eliminated in each function. Each case is then classified according to the discriminant function in the creation of which it has not intervened. The program generates a matrix with the results of the initial classification and the results of the cross-validation. This matrix indicates the predictive capacity of each function. IBM SPSS, v. 25.0.0.0 was employed for statistical analysis.

Results

First, a descriptive analysis of the studied variables was conducted, whose results, disaggregated by sex, are shown in Table 2.

As can be seen, mean values tend to be higher in males. Results of the Student's *t* test for independent samples revealed significant differences between sexes in all variables ($p \leq 0.05$).

Next, the degree of concordance and reproducibility was analysed by calculating Lin's Concordance Correlation

Table 2 Descriptive statistics of the studied variables

Variable	Male				Female				Sign. (Student's t)
	Mean	Min	Max	SD	Mean	Min	Max	SD	
MAL1	45,83	33,50	59,80	5,5851	41,39	29,70	56,50	5,0033	**0.000**
MAL2	41,42	27,10	55,60	5,9380	37,18	10,70	52,60	5,9040	**0.000**
MAN	64,95	38,30	100,90	9,5161	53,74	31,60	83,50	6,7263	**0.000**
MG	10,02	6,30	13,90	1,3547	8,34	4,70	10,70	1,2095	**0.000**
CAL	106,42	77,20	131,60	11,5380	88,29	70,50	118,40	9,0987	**0.000**
CAN1	27,60	14,90	44,90	4,7980	23,33	12,70	35,10	3,7935	**0.000**
CAN2	33,33	17,70	52,90	6,1640	28,51	15,40	45,80	5,5482	**0.000**
CG	9,24	5,80	12,20	1,2838	7,80	4,00	11,10	1,1966	**0.000**
IE	43,54	30,15	66,54	6,9649	47,36	30,32	68,89	7,4795	**0.000**
AE	6401,22	3086,51	9081,18	1064,7365	4570,77	2561,72	7489,49	728,6880	**0.000**
CLD	23,58	14,20	31,40	3,2797	21,17	12,20	29,00	2,8060	**0.000**
CLI	23,39	14,60	31,30	3,1414	20,67	11,60	29,00	2,9990	**0.000**
R2R	12,13	8,10	17,70	1,8747	10,32	1,10	14,30	1,8370	**0.000**
R3R	14,19	9,20	18,90	2,2264	11,82	7,50	18,80	1,7658	**0.000**
R4R	15,25	9,70	20,20	2,1087	12,47	8,30	17,40	1,6980	**0.000**
R5R	14,64	10,20	19,20	1,9937	13,10	8,70	18,10	8,7417	**0.043**
R2L	11,89	7,70	18,70	1,7957	10,29	7,00	14,30	1,4291	**0.000**
R3L	13,88	8,70	17,90	2,0381	11,95	8,30	18,00	1,6634	**0.000**
R4L	15,10	10,10	20,10	2,0839	12,68	9,10	17,40	1,8013	**0.000**
R5L	14,86	10,50	19,70	2,1238	12,57	8,50	18,10	1,6183	**0.000**

Table 3 Results from intraobserver and interobserver errors

Variable	Intraobserver error		Interobserver error	
	CCC	Interpretation	CCC	Interpretation
MAL1	0.9404	Moderate	0.9340	Moderate
MAL2	0.9242	Moderate	0.9115	Moderate
MAN	0.9399	Moderate	0.9325	Moderate
MG	0.9060	Moderate	0.9100	Moderate
CAL	0.9491	Moderate	0.9582	Substantial
CAN1	0.9249	Moderate	0.9220	Moderate
CAN2	0.9343	Moderate	0.9128	Moderate
CG	0.9031	Moderate	0.9018	Moderate
CLD	0.9356	Moderate	0.9152	Moderate
CLI	0.9228	Moderate	0.9021	Moderate
R2R	0.9072	Moderate	0.9008	Moderate
R3R	0.9152	Moderate	0.9012	Moderate
R4R	0.9066	Moderate	0.9045	Moderate
R5R	0.9068	Moderate	0.9099	Moderate
R2L	0.9083	Moderate	0.9163	Moderate
R3L	0.9106	Moderate	0.9069	Moderate
R4L	0.9024	Moderate	0.9053	Moderate
R5L	0.9059	Moderate	0.9085	Moderate

Coefficient. The results of the intraobserver and interobserver errors are shown in Table 3, indicating moderate results in practically all the variables studied, however, with results above 0.9 in all cases, thus showing the reliability and reproducibility of the method.

Once the intra- and inter-observer errors were assessed, as well as the existence of significant differences between sexes, the discriminant functions were designed. First, univariate discriminant functions were developed. Of all the variables studied, only two of them obtained a correct classification rate above 80%, which were the variables CAL (Sternal Body Height) and AE (Sternal Area). The rest of the variables showed percentages ranging from 59.3 to 78.2%. The two discriminant functions with the highest hit rates, as well as their classification and cross-validation values, are summarised in Table 4.

Subsequently, multivariate discriminant analysis was performed. All variables were analysed together, applying the stepwise inclusion method to the discriminant analysis. After its application, three discriminant functions were selected, whose success rates exceed 80%, ranging from

Table 4 Univariant discriminant functions of the chest cage

Variable	Coef.	Constant.	Centroids	Cut-off point	% Correct classif.	% Cross valid.
Function 1						
CAL	0.096	-9.370	H = 0.872 M = -0.872	0.000	81.1%	81.1%
Function 2						
AE	0.001	-6.013	H = 1.003 M = -1.003	0.000	85.4%	85.1%

Table 5 Multivariant discriminant functions of the chest cage

Variables	Coefs.	Constant.	Centroids	Cut-off point	% Correct classif.	% Cross valid.
Function 1						
MG	0.224	-11.082	H = 1.270	-0.063	88.9%	87.9%
CAL	0.032		M = -1.396			
CG	0.220					
AE	0.001					
CLD	-0.066					
R4R	0.173					
Function 2						
MAL1	0.050	-13.872	H = 1.211	0.000	90.0%	87.9%
MAN	0.050		M = -1.211			
CAL	0.051					
R4R	0.162					
R4L	0.111					
Function 3						
MAL1	0.040	-14.952	H = 1.309	0.000	90.4%	89.6%
MAN	0.035		M = -1.309			
MG	0.211					
CAL	0.048					
CG	0.145					
R4R	0.142					
R5L	0.095					

87.9 to 89.6%. These functions, as well as their classification and cross-validation values, are summarised in Table 5.

Discussion

While the estimation of sex by studying the human skeleton through dry bone has consistently yielded highly satisfactory results throughout the history of the discipline, there is a growing body of evidence indicating that 3D images may also be a valuable tool for this purpose. Following this, forensic identification methods must fulfil the so-called Daubert criteria [37, 38], i.e. they must show a high degree of repeatability and reproducibility in other osteological samples, a low level of error, and they must undergo peer review by external experts [37, 38], given the high variability among populations in the human species.

One advantage of 3D approach is that it facilitates easy and repeated access to the image file. Furthermore, as outlined by Djorojevic et al. [39], the utilisation of CT scans represents a highly efficacious and viable option in contexts such as major disasters or mass graves, where the conditions of the human remains preclude the application of conventional forensic methodology, such as the manual collection of information. This methodology is of significant value to the forensic anthropologist in their daily practice, as it introduces a new and efficacious method of sex estimation through thoracic images, which is particularly useful in mummified remains or those that have suffered such extensive damage or loss of tissue that a standard skeletonisation process is no longer possible. This contributes to the process of identifying victims of crimes against humanity or violent acts, as well as major disasters or missing people, facilitating the recognition of these individuals and the act itself. This process aims to repair the dignity of the victims and enable their identification, with the ultimate goal of returning the identified remains to their families and thereby concluding the mourning process. Consequently, the methodologies developed through 3D images represent a valuable tool in these situations.

Examples include the research of Uysal Ramadan et al. [3] who, by using CT scan measurements of the sternum and fourth rib, developed a series of regression formulae for sex estimation, which achieved a success rate of up to 88.2% (86.7% in females and 89.3% in males; R2: 0.715) in a Turkish population ($n = 340$; 143 females, 197 males).

Yet, prior to the use of 3D images of the thoracic cage for sex estimation, studies using radiographs for the same purpose had already been reported. One of these publications is authored by McCormick et al. [26], who report the possibility of accurately estimating the sex of adult individuals with up to 97–99% accuracy through the combination of ossification patterns of the thoracic cage with four metric variables. McCormick et al.'s [26] findings were evaluated by Torwalt and Hoppa [27], who endorsed the previous results of McCormick et al. [26], by applying multivariate logistic regression formulas, which allowed a correct classification of about 90.3% in females and 95.8% in males, with an overall classification rate of 93.1%.

Similarly, Macaluso Jr. and Lucena [40] by applying a radiographic method, proposed a series of discriminant functions for the estimation of sex using sternal measurements taken from posteroanterior radiographs of a sample of 116 individuals from a Spanish population (65 males and

51 females). The obtained results indicated that all the measurements taken by the authors showed significant differences between both sexes, while the proposed discriminant functions exceeded 80% of correct classification, reaching up to 89.7%, with sex biases of less than 5% [40].

Hence, in the present report, the obtained findings prove the existence of dimorphic differences in the thoracic bones in the Spanish population under study. First, the results of Student's t-tests for independent samples showed significant results ($p < 0.05$) when evaluating the difference between sexes, which highlighted this sexual dimorphism, with higher average sizes in males than in females.

Likewise, the discriminant analysis conducted subsequently proved to be useful for the development of discriminant functions to estimate the sex of an individual through a set of measurements taken by thoracic CT scans. While in the univariate discriminant analysis, only two variables provided a result higher than the minimum 80% to be considered adequate, in the multivariate analysis, three equations were obtained which, combining different measures, allow us to estimate sex with correct classification rates ranging between 87 and 90%. However, these multivariate functions have the limitation of requiring the use of a large number of variables, so that, in poorer states of conservation, they may not be used because not all the required variables might be measurable.

Nonetheless, not only is it a simple method to apply, given the ease of taking the measurements and applying the discriminant functions, but it is also a reproducible method. The results of the intra-observer and inter-observer error show values above 0.9 for all the variables analysed, and are therefore adequate for the evaluation of intra- and inter-observer error [33–35].

The obtained results are consistent with those obtained, also in a Spanish population, by García-Parra et al. [13]. Through the study of a sample of 105 sternums from the Skeletal Collection of San José (Granada), with known age, sex and cause of death, they studied their dimorphic potential for sex estimation through the application of discriminant functions, with results ranging from 87 to 91.8% accuracy. Their results were, at the same time, validated in two Portuguese populations, also with good correct classification rates [13].

Meanwhile, through the use of 3D images, Franklin et al. [41] conducted a study about the utility of the sternum by analysing 187 CT scans of sternums from a Western Australian population with no previous pathologies. Taking a series of measurements through the use of landmarks and semilandmarks, they applied discriminant analysis, the results of which allowed the estimation of sex with accuracy percentages ranging from 72.2 to 84.5%, with a sex bias of less than 5%. Similarly, Singh and Pathak [42], in a sample from northern India, evaluated the sexual dimorphism of the sternum to obtain discriminant functions and logistic regression formulae that would allow highly accurate sex estimation. The functions proposed by the authors enabled the correct classification of 84.8% with discriminant analysis, and 89.8% with the regression formulae, with better results in multivariate analyses than in univariate analyses [42].

Also, Ekizoglu et al. [28] studied a sample of 443 chest CT scans (241 males, 202 females) from Istanbul, Turkey, using morphometric analysis of different elements of the rib cage to test their dimorphic potential in sex discrimination. Their results allowed sex estimation with three discriminant models that exceeded 80% correct classification in both sexes, the best of them reaching 83.8% in males and 86.1% in females [28]. These results are consistent with those obtained later by Darwish et al. [43], who, in an Egyptian population, proposed a series of equations for sex estimation using the thorax study, with results ranging from 72.68 to 96.67%.

Ahmed et al. [44] studied the dimorphic potential of thoracic bones using 3D images of a Saudi hospital population, with a sample of 200 CT scans of the thoracic cavity. The results of descriptive statistics highlighted differences in size between sexes ($p = 0.001$), with larger dimensions in males than in females, except for the sternal index. They then proposed a series of discriminant functions, both univariate and multivariate, which yielded accuracy data ranging from 62.5 to 90.5%, with the best results provided by the multivariate discriminant functions. Similarly, in a Croatian population, Bedalov et al. [45] studied a series of thoracic CT images of 73 males and 55 females ($n = 128$), from which they took different sternal and rib measurements for the development of functions and indices that would allow sex estimation. In this regard, results indicated that, while the univariate discriminant function with the highest hit rate reached 82.8%, the index with the best correct classification rate achieved 89.1%, and the multivariate discriminant function with the best hit rate yielded 90.6%.

Recently, in an Iranian population, Ghorbanlou et al. [46] analysed a sample of 98 CT scans for sex estimation by studying the thoracic cavity using discriminant functions. The results showed a high rate of correct classification using multivariate discriminant functions, with a 94.2% accuracy rate and a sex bias of 5.8%. Likewise, the authors reported that the best variable for sex discrimination is the sternal area, which yielded a 92.3% correct classification rate, with a 2.4% sex bias.

In summary, we can confirm that the results obtained in the present research validate the usefulness of the thoracic cage as an element for sex discrimination in the Mediterranean population, with very positive results, close to 90%, quite similar to those obtained by different authors over several decades of study of the thoracic bones, confirming their dimorphic potential in different populations, both with the use of the sternum individually, and with the use of ribs or sternum together, and also fulfilling the reliability and quality criteria.

Conclusions

Concerning the estimation of sex through 3D thoracic images, the metric study of these images is a very useful tool for the estimation of this osteobiological parameter, given the sexual dimorphism of the thoracic bones. In this respect, Student's t-tests for independent samples showed significant differences in the means of the different measurements taken in the thoracic CT scans, indicating larger sizes in males than in females.

Consequently, the univariate discriminant functions proposed for the estimation of sex yielded correct classification percentages below the minimum 80% required to be considered, except in two cases, for the variables CAL and AE, which provided a hit rate of 85% and 87.9% respectively.

When multivariate discriminant analysis was applied, better results were achieved than with univariate analysis, obtaining three discriminant functions with a potential correctness rate close to 90%. It is worth highlighting the function obtained for the variables [MAL1, MAN, MG, CAL, CG, R4R and R5L], which allows a correct classification rate of 89.7% to be achieved. The two remaining multivariate discriminant functions, given by the variables [MG, CAL, CG, AE, CLD and R4R] and [MAL1, MAN, CAL, R4R and R4L] respectively, also yielded very favourable results, 87.9% in both cases.

The obtained results therefore allow the estimation of sex through the thoracic cage through its metric study using 3D images, obtaining very positive results.

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Declarations

Conflict of interest The authors declare no competing interests.

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