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ORIGINAL ARTICLE

Sex determination with morphological characteristics of the skull by using 3D modeling techniques in computerized tomography

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Abstract

Sex determination is a major area of investigation in forensic anthropology. As technology has advanced, imaging methods such as computed tomography and magnetic resonance imaging are being investigated as alternatives to conventional forensic anthropological research techniques. This study aimed to investigate the suitability of three-dimensional (3D) modeling of volumetric cranial computed tomography (CCT) images for sex estimation from skull morphology. In this study, CCT angiography images from the Department of Radiology 2017 archives were used retrospectively, and 3D images were obtained after the reconstruction of 85 cases of CCT images. The sex-dependent morphological characteristics of the skull were evaluated by three blinded observers and scored on a scale of 1–5 points according to the "Standards for Data Collection from Human Skeletal Remains". The accurate sex estimation rates of the first, second and third observers were 91.8, 92.9 and 92.9%, respectively. The rate of accurate sex estimation for males was 98–100%, while this rate varied between 83.3–86.1% for females. Consistency in sex estimation between the three observers was 83.5%, with a Kappa value of 0.763 ($z = 12.2$; $p = 0.0001$*). The glabella was the most effective morphological trait used to estimate sex. The results of this study show that sex can be estimated from morphological features in volume-rendered CCT 3D images. Thus, sex can be estimated by digital images without the need for maceration processes, and the transfer of digital data in place of physical material will make it possible to gain expert opinions in forensic anthropology.

Keywords Forensic medicine · Anthropology · Buikstra · 3D modeling

Introduction

The accurate estimation of sex from skeletal remains is an important topic in forensic anthropology because the accurate identification of other biological characteristics (such as age, height and weight) used in the determination of identity are closely associated with sex [1–4]. The skull is one of the most dimorphic parts of the human skeleton [3]. Morphological or morphometric methods are used for the estimation of sex from skull bones. Physical anthropologists and medical forensics specialists conventionally manually investigate the regions of sexual dimorphism, including the overall appearance of the skull, the nuchal crest, the orbita, the glabella, the mastoid process and the mandible [4–10]. Aiming to make evaluations easier, Acsádi and Nemeskéri [11] and Buikstra and Ubelaker [12] scored and diagramed these regions. However, the accuracy of estimating sex is hard to estimate, as various loading factors exist [4]. Krogman and Iscan reported that sex can be estimated with 92% accuracy only when the skull is present [5]. Stewart reported that sex estimation can be conducted using the skull with 90% accuracy [7]. It has been reported that sex estimation is accurate 85 to 95% of the time [9, 10, 13–15]. The use of morphometric methods provides a high level of confidence by reducing the subjectivity of morphological methods, but these methods do not make a significant difference in the accuracy of sex estimation [9, 16–20].

Currently, anthropologic methods are used in computerized tomography (CT) and magnetic resonance (MR) imaging of bones of which sex and age are known and these imaging

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modalities have been known to help in differentiating between different segments of modern societies [16]. It is possible to examine the bones without needing the maceration processes, especially in decomposed bodies; the advantages of these methods include shortened examination time and no damage to the bone tissue [16, 21–26]. In morphometric analysis studies using CT images for sex estimation, it is seen that the results are similar to those of classical anthropological methods [27, 28]. There have been a number of studies investigating the use of CT imaging techniques in the evaluation of the morphological characteristics of skulls for the estimation of sex [16, 25, 29, 30]. Ramsthaler et al. showed that volume-rendered cranial computerized tomography (CCT) images are appropriate sources of data for sex estimation, as these images allow three-dimensional reconstruction of bone structures [16].

This is a feasibility study that evaluates the potential of showing the cranium morphology from volume-rendered CCT three-dimensional (3D) images and estimating sex from these morphological appearances. In this study (which was blinded systematically), sex estimation was performed by three unbiased observers using Buikstra and Ubelaker's morphological scoring system. Inter-observer consistency and intra-observer consistency were evaluated.

Material and methods

Cranial CT angiography images of patients aged 18 years and older were obtained by the radiology department from 01/01/2017 to 31/12/2017 and analyzed retrospectively for different indications in this study. Sexual dimorphic properties on skeletons are due to hormones released during the development of the fetus. However, until the end of puberty (usually between the ages of 15 and 18), skull and pelvic sex distinguishing bone characteristics are minimal, and methods developed for sexual distinction in adult skulls are invalid for children [31, 32]. For this reason, only individuals over the age of 18 were included in the study. Scans with movement artifacts and cases of head trauma or bone pathologies were excluded. For the final analysis, CCT images of 85 patients, including 36 females and 49 males, were included in the study. The mean age of the entire sample was 45.60 ± 14.05 years (min: 18 years, max: 76 years), while mean age of females and males was 46.11 ± 13.01 and 45.22 ± 14.83 years respectively (Fig. 1).

The CCT angiography investigations were conducted with a 16-detector MSCT device (Brilliance CT 16 V2.00 Philips Medical Systems, Cleveland, OH), and scans were obtained in 1 mm slices. The archived images were reloaded onto a standard work station (MxViewexp; release 4.01; Philips Medical Systems), and images used for scoring were obtained after a

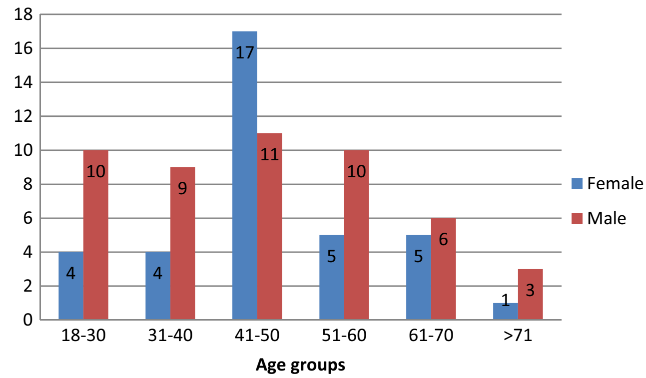

Fig. 1 Real sex and age distributions of all cases in the study

three-dimensional reconstruction was performed through bone window adjustments.

The obtained 3D images were investigated by three blinded observers, and sex estimations were made based on the diagram in "Standards for data collection from human skeletal remains" [12] using the 1–5 point scoring scale adapted by Walker from Buikstra and Ubelaker [9, 12]. Skull nuchal crests, mastoid processes, supraorbital margins, glabellas, and mental eminence were evaluated. In the images, the skulls were rotated to obtain the best match with the diagram, and each region was scored independently, ignoring the other characteristics (Fig. 2). The scores were given as follows: 1: female; 2: probable female; 3: ambiguous sex; 4: probable male; and 5: male (Fig. 3).

One month after the first evaluations, all three observers re-evaluated the same cases in a blinded manner using the same methods to estimate sex.

The data were analyzed using the R Studio - "irr" package and SPSS version 24.0 (Armonk, NY: IBM Corp) [33, 34]. Continuous variables were presented as the mean ± standard deviation, and categorical variables were reported as numbers and percentages. A discriminant analysis was used on the models established for the estimation of sex. The Kappa value was calculated to determine inter-observer consistency, and Kendall's Tau-B correlation analysis was carried out to investigate the intra-observer consistency of the investigations performed 1 month later.

Results

The detailed results of sex estimation of the observers based on the scoring of cranial dimorphic characteristics after the 3D-modeling of volume-rendered CCT images are shown in Table 1. The accurate sex estimation rates of the first, second and third observers were 91.8, 92.9 and 92.9%, respectively. There was no statistically significant difference between observer 1 and observer 3 in either sex accuracy ratio, but observer 2's accuracy in estimating males was statistically

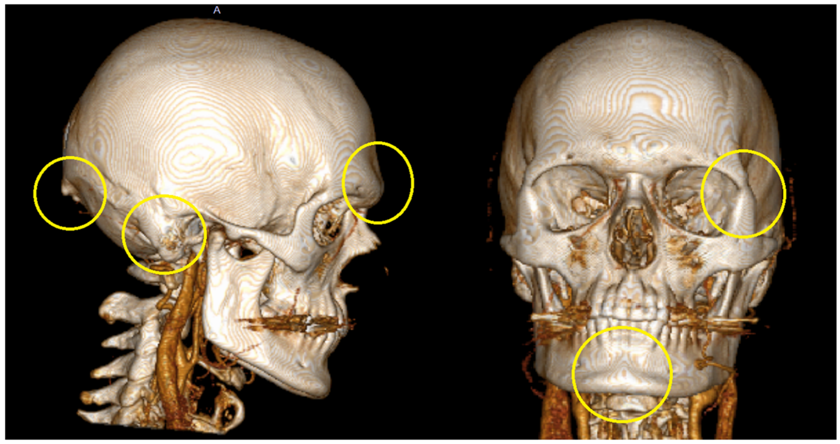

Fig. 2 Example of reconstructions in 3D volume-rendered CCT of case no. 2, a 44-year old, male. The dimorphic cranial traits (the nuchal crest, the mastoid process, the supraorbital margin, the glabella and the mental eminence) evaluated for sex estimation were shown in yellow circles

significantly higher than the accurate estimating of females ($p < 0,05$) (Table 2).

Based on the results of discriminant analysis and the analysis of the effects of the scores given by all observers for the specific nuchal crest, the mastoid process, the supraorbital margin, the glabella and the mental eminence in the estimation of sex, the glabella had the strongest effect in all models (Tables 3-4).

The consistency between the three observers in sex estimation was 83.5%, with a Kappa value of 0.763 ($z = 12.2$; $p = 0.0001$*). It was observed that all three observers correctly estimated the same 71 cases, which included 47 males and 24 females. There were not any joint cases in which all three observers did not make the correct estimation. Observer 1 and observer 2 mistakenly estimated that the same two females were males, while observer 1 and observer 3 had one female and observer 2 and observer 3 had two females. When the consistency of sex estimation between two independent observers was analyzed, the Kappa values were found to be high and statistically significant in all pair-wise comparisons (Table 5).

For each observer, the sex estimations performed during the first and second evaluations were significantly consistent with the actual sex ($p < 0.05$). When intra-observer consistency was evaluated, a statistically significant relationship was noted between the first and the second predictions of all observers ($p < 0.05$) (Table 6).

Discussion

In this study, it was shown that volume-rendered CCT 3D images were of a quality that would permit sex estimation from the morphological characteristics of the skull. Currently, identification studies based on CT and MR images are carried out in forensic anthropology. There are numerous studies investigating the advantages and disadvantages of these methods to determine whether or not they can serve as alternatives to conventional methods [21–26, 35]. Bone tissues should be prepared for examination by removing all soft tissues in unidentified decomposed bodies. These imaging methods may be advantageous in that they allow the possibility of examination without the need for maceration [16, 29]. Maceration is time-consuming, and there are previous studies that mention that there is a risk of harming the integrity of bone and DNA during sampling procedures [36, 37]. Imaging methods provide alternative and accurate measuring techniques that can be employed in cases of semi-fleshed, charred or otherwise highly decomposed or degraded samples where maceration cannot be tried prior to analysis [38]. There are also studies suggesting that the DNA extraction required by maceration damages skulls tested for sex estimation, and therefore, nondestructive methods are needed [39, 40]. Mantini and Conroy discussed the usefulness of 3D imaging methods in both fossil and modern skeletons as they permit non-destructive observation and examination [41, 42].

Shipping skeletons that require sex estimation to specialist laboratories presents many challenges, such as the financial burden of the transfer, the risk of physical damage or loss of samples during transfer, obtaining the required legal permission from judicial authorities for the dispatch of samples, and diplomatic procedures that need to be carried out if samples are sent from one country to another. CT data are stored in the PACS (Picture Archiving and Communication System) and transmitted using DICOM (Digital Imaging and Communication in Medicine), which is a global information technology standard that is used in virtually all hospitals worldwide that is designed to produce, manage, and distribute images. One advantage of the method tested in this feasibility study is that the DICOM data can be delivered to an expert through an online method or any storage unit (such as CD, DVD, or portable memory) after the samples are sent to the nearest hospital for CT scans.

The disadvantage of the method used in this study is that conventional morphological experts are not able to hold the skeletons in their hands to feel for margins and crests like they

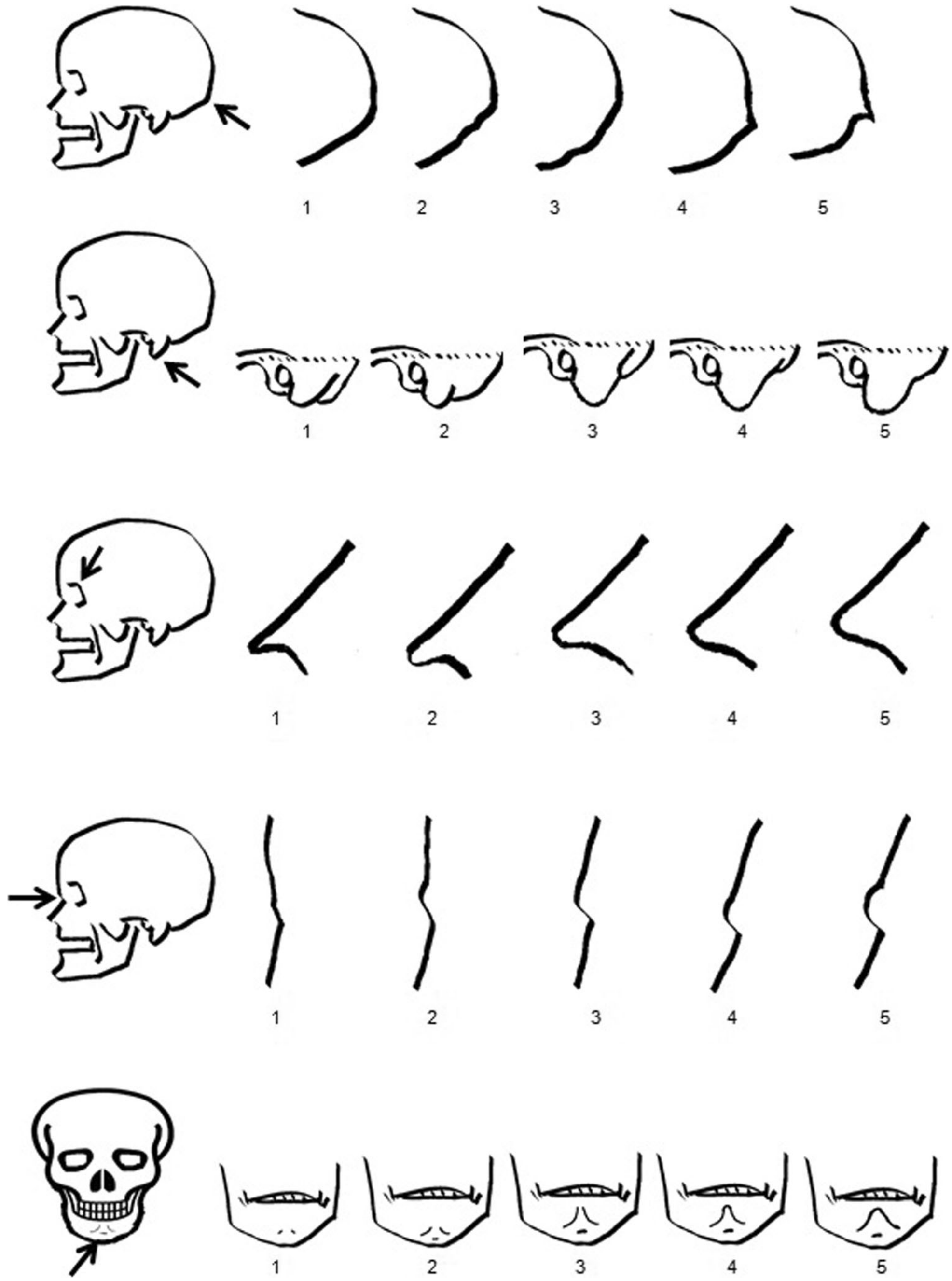

Fig. 3 Standard for scoring cranial traits (from Buikstra and Ubelaker [12]) (Illustration: Kemalettin Acar)

are usually able to. However, this disadvantage may be eliminated by additional morphometric examinations.

There are studies in the literature that state cranial CT images can be successfully used to estimate sex [16, 27–29, 43, 44]. Franklin et al. used volume-rendered CTs to assess bizygomatic width and cranium and head base length and found that sex was differentiated in a Western Australian population with an accuracy rate of 90% [27]. In a study by Fatah et al. on bass-donated collections that used a 3D approach, sex-related differences were noted in the glabellar region, the frontal slope and the head base curve as shape-related variables with greater than 95% accuracy, as determined in a cross-validated linear discriminant analysis [28]. Grabherr et al. carried out a feasibility study to show how CT can be used effectively for anthropologic purposes, and demonstrated that 3D multi-detector computed tomography (MDCT) images of skeletal parts such as the skull and pelvis were of sufficient quality to allow examinations performed on real skeletons [29]. Ramsthaler et al. also showed how volume-rendered CCT images were appropriate for the collection of data for the morphological estimation of sex on skulls, classifying sex correctly in 96% of cases by evaluating 17 morphological traits on the sample images [16].

Table 1 Detailed results of sex estimates of the first and second assessments of the three observers

Case information			First estimated sex			Second estimated sex		
Case ID	Age	Sex	Observer 1	Observer 2	Observer 3	Observer 1	Observer 2	Observer 3
1	41	female	female	female	female	female	female	female
2	44	male	male	male	male	male	male	male
3	41	female	female	male	male	male	male	male
4	44	male	male	male	male	male	male	male
5	62	male	male	male	male	male	male	male
6	43	female	female	female	female	female	female	female
7	30	male	male	male	male	male	male	male
8	72	female	female	female	female	female	female	female
9	30	male	male	male	male	male	male	male
10	52	male	male	male	male	male	male	male
11	49	male	female	male	male	female	male	male
12	49	female	female	female	female	female	female	female
13	51	male	male	male	male	male	male	male
14	66	female	female	female	female	female	female	female
15	65	female	female	female	female	female	female	female
16	55	female	female	female	female	female	female	female
17	44	female	female	male	female	male	male	female
18	43	female	female	female	female	female	female	female
19	22	female	male	male	female	male	male	female
20	39	male	male	male	male	male	male	male
21	42	female	female	female	male	female	male	female
22	26	male	male	male	male	male	male	male
23	38	male	male	male	male	male	male	male
24	54	female	male	female	female	male	female	female
25	43	male	male	male	male	male	male	male
26	42	female	male	female	female	female	female	female
27	46	male	male	male	male	male	male	male
28	30	male	male	male	male	male	male	male
29	60	female	female	male	female	female	female	female
30	36	male	male	male	male	male	male	male
31	58	male	male	male	male	male	male	male
32	39	female	female	female	female	female	female	female
33	31	male	male	male	male	male	male	male
34	47	female	female	male	male	female	female	male
35	63	male	male	male	male	male	male	male
36	46	male	male	male	male	male	male	male
37	43	female	female	female	female	female	female	female
38	45	female	male	male	female	female	male	female
39	30	male	male	male	male	male	male	male
40	37	male	male	male	male	female	male	male
41	42	male	male	male	male	male	male	male
42	51	female	male	female	female	male	female	female
43	72	male	male	male	male	male	male	male
44	43	male	male	male	male	male	male	male
45	63	female	female	female	female	female	female	female
46	35	male	male	male	male	male	male	male
47	27	male	male	male	male	male	male	male

Table 1 (continued)

Case information			First estimated sex			Second estimated sex		
Case ID	Age	Sex	Observer 1	Observer 2	Observer 3	Observer 1	Observer 2	Observer 3
48	54	female	female	female	female	female	female	female
49	21	female	male	female	male	male	female	female
50	18	male	male	male	male	male	female	male
51	45	female	female	female	female	female	female	female
52	69	female	female	female	female	female	female	male
53	42	female	female	female	female	female	female	female
54	42	male	male	male	female	male	male	female
55	44	male	male	male	male	male	male	male
56	21	male	male	male	male	female	male	male
57	44	female	female	female	female	female	female	female
58	21	male	male	male	male	male	male	male
59	20	female	female	female	female	female	female	female
60	33	male	male	male	male	male	female	male
61	42	female	female	female	female	female	female	female
62	49	male	male	male	male	male	male	male
63	48	female	female	female	female	female	female	female
64	57	male	male	male	male	male	male	male
65	52	male	male	male	male	male	male	male
66	37	female	female	female	male	male	female	female
67	53	male	male	male	male	male	male	male
68	36	female	female	female	female	female	male	female
69	52	male	male	male	male	male	male	male
70	35	male	male	male	male	male	male	male
71	57	male	male	male	male	male	male	male
72	33	female	female	female	female	female	female	female
73	24	male	male	male	male	male	male	male
74	67	male	male	male	male	male	male	male
75	71	male	male	male	male	male	male	male
76	70	female	female	female	female	female	female	female
77	69	male	male	male	male	male	male	male
78	76	male	male	male	male	male	male	male
79	56	male	male	male	male	male	male	male
80	65	male	male	male	male	male	male	male
81	51	male	male	male	male	male	male	male
82	65	male	male	male	male	male	male	male
83	29	female	female	female	female	female	female	female
84	34	male	male	male	male	male	male	male
85	43	female	female	female	female	female	female	female

The actual data of the cases are given in the first three columns. The other columns contain estimates of sex after the first and second evaluation of the three observers

In this study, sex estimations were made with a high accuracy rate of 91.8–92.9% by using the 5 morphological characteristics in the cranial trait scoring system of Buikstra and Ubelaker. This rate of accuracy is similar to that seen in conventional anthropologic cranial dimorphism analyses performed on bone collections. Walker identified sex using modern skulls with an accuracy rate of 88% based on logistic regression models that included five variables [9]. A study by Kruger et al. [10] of bone collections from a Southern African population used the same scoring system and correctly estimated sex with an accuracy rate of 84–93%. Garvin et al. reported that the rate of accurate sex estimation varied

Table 2 The counts and rates of sex estimation of the three observers

			Correct classification		Incorrect classification		Total	
			n	%	n	%	n	%
Estimated sex	[a] Observer 1	Female	30	83.3	6	16.7	36	100
		Male	48	98	1	2	49	100
		Total	78	91.8	7	8.2	85	100
	[b] Observer 2	Female	30	83.3	6	16.7	36	100
		Male	49	100	0	0	49	100
		Total	79	92.9	6	7.1	85	100
	[c] Observer 3	Female	31	86.1	5	13.9	36	100
		Male	48	98	1	2	49	100
		Total	79	92.9	6	7.1	85	100

Values were expressed as number (n) and percentages (%). Row percentages are taken. The correctly classification of males was higher than females for observer 2. McNemar test was used. (a: $p = 0.125$; b: $p = 0.031$*; c: $p = 0.219$) (*$p < 0.05$ statistically significant)

Table 3 Estimation results obtained by discrimination analysis using the cranial traits scores

	Canonical Correlation Coefficient	Wilks' Lambda	Nuchal crest	Mastoid process	Supraorbital margin	Glabella	Mental eminence
Observer 1	0.802	0.357	0.831	0.765	0.611	0.876	0.619
Observer 2	0.833	0.306	0.51	0.621	0.447	0.913	0.541
Observer 3	0.864	0.253	0.798	0.78	0.826	0.842	0.761

Standardized values are used for all coefficients

Table 4 Correct sex estimation rates obtained by discriminant analysis using the cranial traits scores

	Female % Correctly classified	Male % Correctly classified	Total % Correctly classified
Observer 1	29 (%34.1)	48 (%56.5)	77 (%90.6)
Observer 2	31 (%36.5)	45 (%52.9)	76 (%89.4)
Observer 3	31 (%36.5)	48 (%56.5)	79 (%93)

Table 5 Pairwise consistency between observers in sex estimation

			Observer 2			
			Female	Male	Total	Kappa (p)
Observer 1	Sex estimated	Female	26 (%30.6)	5 (%5.9)	31 (%36.5)	0.770 (p = 0.0001*)
		Male	4 (%4.7)	50 (%58.8)	54 (%63.5)	
		Total	30 (%35.3)	55 (%64.7)	85 (%100)	
			Observer 3			
Observer 1	Sex estimated	Female	26 (%30.6)	5 (%5.9)	31 (%36.5)	0.723 (p = 0.0001*)
		Male	6 (%7.1)	48 (%56.5)	54 (%63.5)	
		Total	32 (%37.6)	53 (%62.4)	85 (%100)	
			Observer 3			
			Female	Male	Total	Kappa (p)
Observer 2	Sex estimated	Female	27 (%31.8)	3 (%3.5)	30 (%35.3)	0.797 (p = 0.0001*)
		Male	5 (%5.9)	50 (%58.8)	55 (%64.7)	
		Total	32 (%37.6)	53 (%62.4)	85 (%100)	

*$p < 0.05$ statistically significant

Table 6 Results of intraobserver consistency for each observer of the first and after 1 month evaluations

	−1		0		1		kappa	p
	n	%	n	%	n	%		
Observer 1	3	3.5	78	91.8	4	4.7	0.823	0.000
Observer 2	2	2.4	79	92.9	4	4.7	0.848	0.000
Observer 3	1	1.2	81	95.3	3	3.5	0.901	0.000

Values were expressed as number (n) and percentage (%). *$p < 0.05$ statistically significant

between 74 and 94% while studying craniums of American White, American Black, medieval Nubian and Arikara Native American populations, with an overall accuracy rate of 85% [45].

In the present 3D-modeling study, the trait with the highest performance in the classification of sex was found to be the glabella. It was previously reported that the glabella and the mastoid process were the best sex discriminants in classical anthropological examinations of the cranial bone [9, 45]. In an earlier study addressing 3D modeling of the cranium, a cut-off value of 78.2° detected on the glabellar slope angles differentiated male and female craniums with a high rate of accuracy. In that same study, the glabella was evaluated on a scale of 1–5 points, and the scores were found to be higher for males than females (mean of 3.1 in males and 1.7 in females). Sex was able to be predicted with 83% accuracy [30]. Ramsthaler et al. [16] conducted a volume-rendered CCT study and found that using the arcus superciliaris or the glabella as the only parameter for sex estimation yielded accuracy rates of 85 and 81%, respectively. It is known that males have a larger glabella projection than females, while morphometric studies have shown that male glabellas have a wider surface area and greater volume [46, 47].

Although studies using morphological features for sex estimation use a diagram standardized with sequential scoring, it is important to evaluate observer bias because subjective data are used in the scoring [48]. In our study, intra-observer and inter-observer analyses were carried out to evaluate observer bias, and both the inter-observer consistency ($k = 0.763$) and the consistency of the predictions performed at different times by the same observers were found to be acceptable. These results show that there is a low-level inter-observer risk of incorrect sex estimation when using morphological characteristics in virtual images obtained from 3D models of the skull.

The small number of the cases in this study presents limited statistical analysis. Additional studies with more cases are being planned by the authors to achieve more significant results.

In the future, the technical development of imaging methods could be helpful for practicing and widening the method in this study. New studies should be planned with different approaches to the issues, such as combining this method with morphometric methods.

Conclusion

The results in this study show that volume-rendered CCT images visualize the cranium well enough to allow high-quality classical anthropological examination. Sex was estimated accurately 91.8–92.9% of the time, with low inter-observer error in evaluations using five cranial dimorphic features. The availability of sex estimation from virtual images of the skull will enable identification without the need for maceration processes in decomposed bodies and for the delivery of images of skulls to experts without physically transporting human material. It also allows skeletal remains to be examined without touching or sampling, which may damage the structure. CT images are stored permanently in PACS, and they can be reviewed if additional data needs to be collected or a second opinion is necessary. The volume-rendered process allows the expert to view elements from different angles and take measurements that are comparable to measurements obtained on dry bones. Furthermore, consultations can be made from anywhere in the world through the use of DICOM. Storing of digital records of skeletons of which sex and age are known will serve as an important anthropological digital data bank for new research projects.

Key points

1. The 3D-modeling technique based on volume-rendered CCT produced images of the skull that were of sufficient quality to allow evaluation of morphology.
2. The 3D-modeling technique based on volume-rendered CCT images allowed morphological sex estimation without the need for maceration processes.
3. A 91.8–92.9% accuracy rate in sex estimation was achieved by using the cranial trait scoring system of Buikstra and Ubelaker.
4. The glabella was the most effective morphological trait used to estimate sex.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was initiated following the granting of approval by the Non-interventional Clinical Trials Ethics Committee. All procedures performed in studies were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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