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ORIGINAL ARTICLE

Sex estimation using computed tomography of the mandible

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Abstract Sex estimation of skeletal parts is of great value even in the DNA era. When computed tomography (CT) facilities were introduced to forensic institutes, new possibilities for sex estimation emerged. The aim of this study was to develop a CT-based method for sex estimation using the mandible. Twenty-five CT-based measurements of the mandible were developed and carried out on 3D reconstructions (volume rendering) and cross sections of the lower jaw of 438 adult individuals (214 males and 224 females). Intraobserver and interobserver variances of the measurements were examined using intraclass correlation coefficient (ICC) analysis. Five discriminant functions were developed using different states of completeness of the mandible. The success rates of these equations were cross validated twice. The measurements were found to be highly reliable (for intraobserver 0.838 < ICC < 0.995 and for interobserver 0.71 < ICC < 0.996). For a complete mandible, the correct classification rate was 90.8%. For incomplete mandibles, the correct classification rates varied from 72.9 to 85.6%. Cross-validation tests yielded similar success rates, for the complete mandible 89% and for the incomplete mandible 67.5 to 89%. We concluded that CT techniques are appropriate for estimating sex based on the mandible size and shape characteristics. Suggested discriminant functions for sex estimation are given with data on the correct classification rates.

Keywords Sex estimation · Mandible · CT · Discriminant function

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Introduction

Sex estimation of skeletal material is one of the most fundamental tasks of forensic and physical anthropologists. Despite the revolutionary advancements in DNA methods in forensic science in recent years, the morphological methods used for estimating sex have retained their relevancy because of a number of reasons such as degradation of DNA under different forensic circumstances (e.g., fires) [1].

Various methods for sex estimation, based on different parts of the skeleton, have been reported [2–12]. Some of these methods rely on morphological features (descriptive), whereas others are based on measurements. The metric methods have a major advantage over the descriptive ones, since they are less dependent on the judgment of the observer [13]. A relatively new method, i.e., geometric morphometrics, has been applied for sex estimation to overcome the disadvantages of the morphologic method [14–17]. Although this method yields good results [16, 18], it requires both special equipment and a specialized researcher. Therefore, it is not applicable for most forensic and physical anthropologists.

Mandibles are both sexually dimorphic and durable (i.e., recovered intact or in an adequate condition) and are thus good candidates for sex estimation of unknown individuals [7, 15, 19–21]. Some studies have used metric characteristics of mandibles to create discriminant functions for sex identification [15, 19, 22]. These studies focused on standard measurements of the mandible such as mandibular angle, bicondylar and bigonial breadths, ramus height, and symphysis height. Other studies used descriptive methods, e.g., flexure of the ramus, shape of the chin, and gonial flaring [6, 23–26]. These methods, based either on continuous or discrete variables, suffer from various deficiencies; to wit, the variables for sex estimation were either arbitrarily selected or statistically picked from a small pool of measurements; the selected metric variables were limited by the available measuring tools (e.g., caliper); most methods were not cross-validated and did not respond to forensic needs (e.g., often only a fragment of the mandible is available); and they were constructed on samples derived from homogeneous populations. With regard to the latter, nowadays, most societies have become more heterogeneous owing to the increase in human mobility between countries and continents [27].

In recent years, recognizing the contribution of various imaging techniques, especially computed tomography (CT) scans, to postmortem investigation has increased [28–32], accompanied by studies that ensure the validity and reliability of these techniques [33–37]. Accordingly, CT is becoming a common diagnostic tool in many forensic institutes. Thus, the need for a CT-based method to estimate sex from skeletal remains has emerged. The aim of this study was to develop a CT-based method for sex estimation using the mandible, which overcomes much of past studies' deficiencies.

Materials and methods

The study sample was derived from the current Israeli population. This population is particularly suitable for studying biological variation in heterogeneous populations due to its extensive mixture of people migrating to Israel from different parts of the world. The study design is retrospective. Head and neck CT scans of 438 individuals (214 males and 224 females), over the age of 20 years, were randomly selected from a pool of CT scans carried out between the years 2000 and 2012 at the Carmel Medical Center, Haifa, Israel (Brilliance 64, Philips Medical System, Cleveland, Ohio; slice thickness 0.9–3.0 mm, pixel spacing 0.3–0.5 mm, 120 kV, 250–500 mA, number of slices 150–950, and matrix 512 × 512). All CT scans were carried out for diagnostic purposes and for whom a CT exam was medically necessary. Inclusion criteria were as follows: age ≥20 years, intact lower incisors, and at least two teeth of the posterior unit (premolars and/or molars) on each side. Exclusion criteria included the absence of the lower incisors; dental implants and metal restorations that interfere with the measurement; prominent facial and mandibular asymmetry; cranio-facial, temporomandibular joint, or muscular disorders; trauma; previous surgery in the head and neck region (medical files or signs on the skull); and technically aberrant CT scans. This study was approved by the ethical board of the Carmel Medical Center (number 0066–11-CMC).

Two sets of measurements (Table 1) were taken using the Philips portal (thin client). The first set (n = 13) includes surface (external) linear measurements from a 3D reconstruction of the mandible, using the volume rendering application of the software (Fig. 1). The second set (n = 12) includes internal linear and area measurements from 2D images or cross sections of the mandible (Fig. 2). Measurements of the mandibular body and symphysis region were taken in relation to the mandibular plane.

In many forensic/archeological cases, the mandible is incomplete; therefore, we calculated discriminant functions for sex estimation for five different states of completeness of the mandible (hereafter referred to as scenario I to V). Scenario I relates to a complete mandible; therefore, all CT-based measurements could be included in the regression analysis. Scenario II relates to half a mandible (from ramus to chin); thus, measurements of the ramus (length, width, and cross-sectional area (CSA)), body (length, heights, and CSAs), coronoid (height, width, and CSA), condyle (width), mandibular angle region (angle, width, and CSA), and antegonial notch area could be included in the regression analysis. Scenario III relates to a fracture of the mandible where only the mandibular arch (without rami) exists. Here, three external measurements, body height at the premolar and molar regions and chin width, and six internal measurements of the symphysis and chin (heights, thicknesses, and areas) could be included in the regression analysis. Scenario IV included the ramus alone (from coronoid and condyle to the mandibular angle). Here, five external measurements could be included in the regression analysis, which are ramus length and width, coronoid length and width, condyle width, and two internal measurements ramus width CSA and coronoid width CSA. In scenario V, a small fragment of the mandibular body was included. Thus, two external measurements and two internal measurements were included in the forward analysis, which are the mandibular body heights at the premolar and molar regions and their CSAs, respectively.

Statistical analysis

Data were analyzed using SPSS 21.0 software. Significance was set at $p < 0.05$. Intraobserver and interobserver variations

Table 1 Definitions of CT-based external and internal mandibular measurements

Measurement		Definition
External (volume rendering)	Ramus length	The distance from the highest point on the condyle to the gonion
	Ramus width	The distance between the anterior and posterior indentations of the mandible ramus
	Body length	The distance from the most anterior point of the chin to a line placed along the posterior border of the ramus
	Body height P1-P2[a]	The vertical distance from the alveolar crest between the first and second premolars to the inferior border of the mandibular body
	Body height M2-M3[a]	The vertical distance from the alveolar crest distal to the second molar to the inferior border of the mandibular body
	Mandibular angle[a]	The angle formed by the inferior border of the mandibular body and the posterior border of the ramus
	Mandibular angle width	The distance between the gonion and deepest point on the concavity connecting the anterior border of the ramus with the mandibular body
	Coronoid width	The distance between the deepest point on the mandibular notch and the anterior border of the coronoid process
	Coronoid height	The vertical distance between the most superior point of the coronoid process and the coronoid process width line, perpendicular to it
	Condyle width	The distance between most lateral and medial points of the condyle head
	Chin width	The distance between the right and left mental tubercles
	Bicondylar breadth	The distance between the most lateral points of the right and left condyle heads
	Bigonial breadth	The distance between the right and left gonions
Internal (cross sections)	Chin height[a]	In the midsagittal plane, the distance between the menton and the supramentale
	Chin thickness[a]	In the midsagittal plane, the thickness of the chin, measured from pogonion to chin height line (perpendicular to the latter)
	Chin area[a]	In the midsagittal plane, the symphyseal area located anterior to the chin height line
	Symphysis area[a]	In the midsagittal plane, total area of the symphysis
	Symphysis thickness[a]	In the midsagittal plane, the distance between the pogonion and the most posterior point of the symphysis
	Symphysis height[a]	In the midsagittal plane, the distance between the most superior point on the alveolar bone and menton point
	Ramus width CSA[a]	The cross-sectional area of the mandibular ramus along the ramus width line
	Body height CSA P1-P2[a]	The cross-sectional area of the mandibular body along the body height line
	Body height CSA M2-M3[a]	The cross-sectional area of the mandibular body along the body height line
	Mandibular angle width CSA	The cross-sectional area of the mandibular body along the mandibular angle width line
	Coronoid width CSA	The cross-sectional area along the coronoid process width line
	Antegonial notch area[a]	The area between the lower border of the mandible and the mandibular plane line

CSA cross-sectional area

[a] Measurements taken in relation to the mandibular plane (the inferior margins of the mandibular body is positioned parallel to the horizontal plane)

were examined on 15 individuals using the intraclass correlation coefficient (ICC) analysis. For intraobserver variation, measurements were taken twice with a 2-week interval between each by the same researcher (TS). For interobserver variation, measurements were taken by an additional independent researcher (either HM or VS). ICC was interpreted

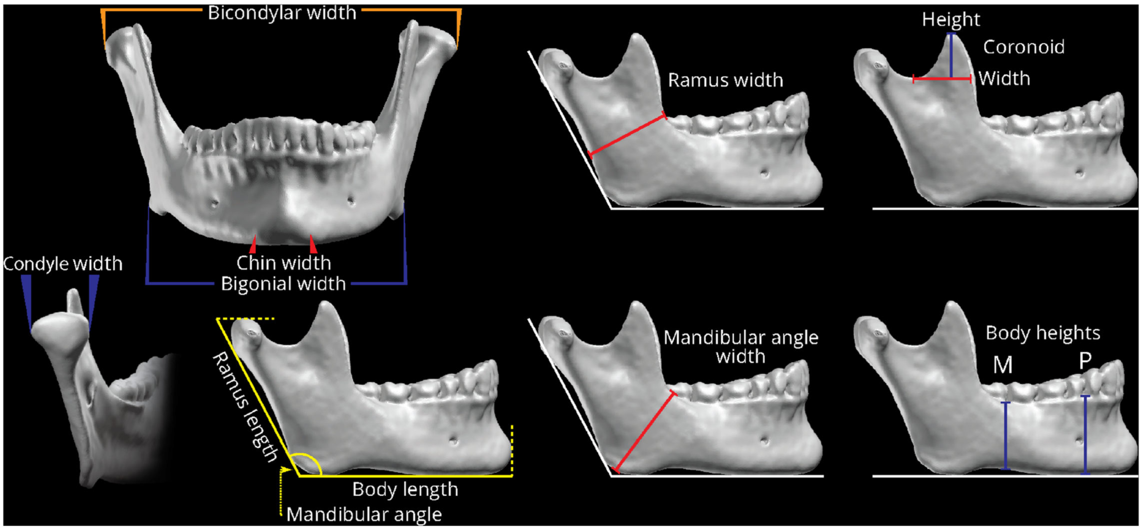

Fig. 1 Measurements of the mandible taken from a 3D model using the volume rendering technique. Anatomical definitions for each measurement appear in Table 1. Note that measurements of mandibular body height were taken when the mandible was positioned in the mandibular plane (the inferior margins of the mandibular body are positioned parallel to the horizontal plane) in a lateral view (i.e., ascending rami overlap)

according to the Cicchetti [38] categorization system, <0.40 poor agreement, 0.40–0.59 fair agreement, 0.60–0.74 good agreement, and 0.75–1 excellent agreement.

General summary information, i.e., mean and standard deviation (SD) for each measurement, were obtained via descriptive statistics. An independent sample *t* test was used to examine the significance of differences between males and females for each measurement. The rate (%) of sexual dimorphism for each measurement was calculated as follows: % dimorphism = [(mean males − mean females)/mean females] × 100. Discriminant functions for sex estimation and their success rates were calculated using logistic regression (forward analysis). Odds ratios (OR) and 95% confident intervals (CIs) were given for variables included in the discriminant equations.

Validation To examine the validity of the success rates of the suggested discriminant functions for sex estimation, two cross-validation tests were conducted. Random sampling was carried out, using the function RAND (Excel 2013), to select 40 individuals for the test group, i.e., each of the 438 individuals received a random number; the 20 males and 20 females with the lowest numbers were included in the test group. The obtained discriminant functions, based on 398 individuals, were used to estimate the sex of the individuals in the test group. This procedure was carried out twice.

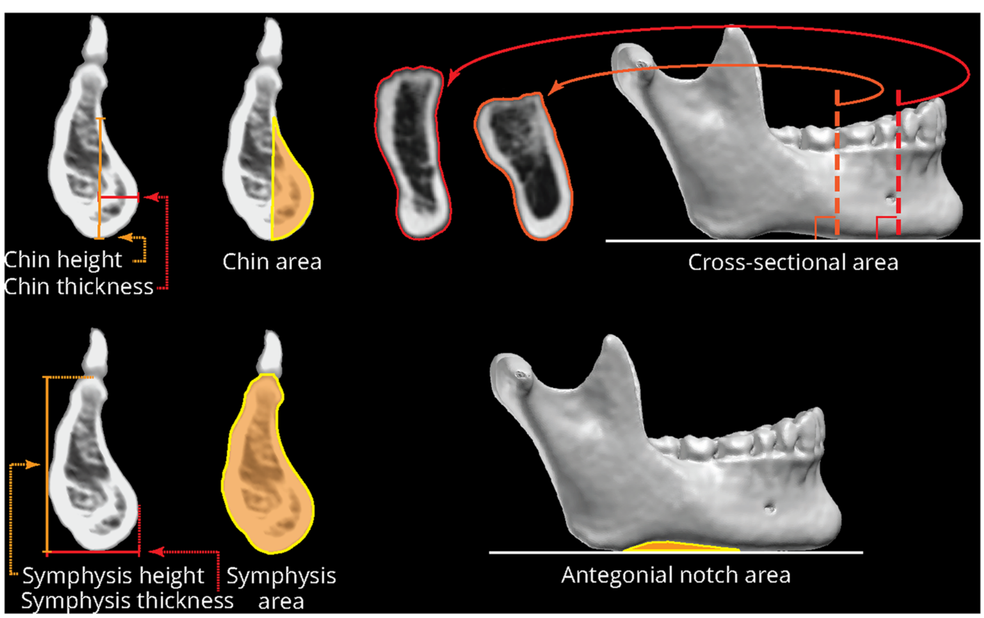

Fig. 2 Measurements of the mandible taken from lateral and cross-sectional images. Anatomical definitions for each measurement appear in Table 1. Note that cross sections of the mandibular body and symphysis were carried out perpendicular to the mandibular plane (the inferior margins of the mandibular body are positioned parallel to the horizontal plane). The antegonial notch is the space created between the inferior margin of the mandibular body and the mandibular plane

Results

The studied population ($n = 438$) consisted of 49% males and 51% females with no significant differences ($p > 0.05$) in age (53.3 ± 19.9 and 56.2 ± 20.6 years, respectively). ICC values for intraobserver and interobserver variations are presented in Table 2. The intraobserver variation of both external and internal measurements showed excellent results (0.905 < ICC < 0.991 and 0.838 < ICC < 0.986, respectively). The interobserver variation of external measurements showed excellent results for all measurements (0.85 < ICC < 0.996), except for two, coronoid width and chin width, which yielded good results (0.71 and 0.715, respectively). Most internal measurements (10 out of 12) showed excellent results (0.763 < ICC < 0.98), except for two (the chin area and the antegonial notch area), which yielded good results (0.741 < ICC < 0.785).

Significant differences between males and females were found for all mandibular external measurements and for most of the internal measurements (Table 3). For all measurements, except for mandibular angle, males have a greater means than females (Table 3). Sexual dimorphism rates varied from 1.6 to 103.1%. The most dimorphic traits were the antegonial notch area (103%), the chin width (22.3%), the body height CSAs (premolar 15.7% and molar regions 16.6%), the symphysis area (13.9%), the ramus length (13.5%), the body height at the molar region (11.1%), the coronoid height (10.8%), the body height at the premolar region (10.5%), the condyle width (10.4%), and the symphysis height (10%). A logistic regression analysis (forward method) was carried out separately for each scenario (I–V). In scenario I, a complete mandible, 6 out of the 25 measurements, were included in the discriminant function, which are ramus length, coronoid height, chin width, bigonial breadth, symphysis height, and antegonial notch area (Table 4), with a successful classification rate reaching 90.8% (similarly for males and females) (Table 5). In scenario II, half mandible, 4 out of 16 measurements, were included in the discriminant function, which are the ramus length, the coronoid height, the condyle width, and the antegonial notch area (Table 4). The classification rate using these

Table 2 Intraobserver and interobserver reliability tests: intraclass correlation coefficient (ICC) analysis

Measurement		Intraobserver variation [mean (SD)]			Interobserver variation [mean (SD)]		
		First round	Second round	ICC	First observer	Second observer	ICC
External (volume rendering)	Ramus length	67.2 (±5.23)	67.5 (±4.32)	0.921	67.5 (±4.32)	68.1 (±4.21)	0.902
	Ramus width	31.7 (±2.6)	31.4 (±2.5)	0.969	31.1 (±3.06)	32 (±2.9)	0.961
	Body length	77.3 (±6.67)	77.6 (±6.32)	0.991	77.6 (±6.32)	77.3 (±6.53)	0.989
	Body height P1-P2	31.4 (±3.15)	32.1 (±2.87)	0.956	32.1 (±2.87)	31.6 (±3.14)	0.966
	Body height M2-M3	25.5 (±3.78)	25.9 (±3.78)	0.97	25.9 (±3.78)	26.1 (±3.87)	0.94
	Mandibular angle	121.5 (±7.36)	121.2 (±7.36)	0.991	121.2 (±7.36)	121.8 (±7.143)	0.961
	Mandibular angle width	33.7 (±4.79)	34 (±4.6)	0.986	32.9 (±4.34)	32.8 (±4.19)	0.988
	Coronoid width	21 (±1.94)	21 (±1.76)	0.923	21.3 (±1.76)	19.2 (±2.02)	0.71
	Coronoid height	17.4 (±2.18)	17.4 (±2)	0.949	17.4 (±2)	16.3 (1.677)	0.82
	Condyle width	18.76 (±2.58)	18.6 (±2.68)	0.981	18.6 (±2.68)	18.9 (±2.24)	0.949
	Chin width	25.3 (±6.28)	25.7 (±5.58)	0.905	25.7 (±5.58)	27.5 (±7.49)	0.715
	Bicondylar breadth	121.2 (±6.25)	121.3 (±6.42)	0.995	121.3 (±6.42)	120.8 (±6.09)	0.996
	Bigonial breadth	90.3 (±7.39)	89.8 (±6.72)	0.93	89.8 (±6.72)	89.7 (±5.98)	0.9
Internal (cross sections)	Chin height	24.7 (±2.31)	24.6 (±2.76)	0.895	24.6 (±2.76)	23.4 (±2.98)	0.785
	Chin thickness	4.7 (±1.03)	4.7 (±1.06)	0.907	4.7 (±1.06)	4.6 (±0.92)	0.763
	Chin area	63.5 (±16.6)	64.5 (±16.25)	0.838	64.5 (±16.25)	63. 9 (±20.15)	0.747
	Symphysis area	297 (±44.07)	303.4 (±44.99)	0.971	303.4 (±44.99)	286.8 (±50.1)	0.931
	Symphysis thickness	15.4 (±2.47)	15.4 (±2.4)	0.986	15.4 (±2.4)	15.5 (±2.66)	0.98
	Symphysis height	32.7 (±2.4)	32.7 (±2.27)	0.963	32.9 (±2.19)	33.3 (±2.26)	0.946
	Ramus width CSA	226.2 (±54.92)	232.98 (±53.76)	0.933	215.8 (±34.86)	176.3 (±33.16)	0.907
	Body height CSA P1-P2	349.1 (±94.51)	364.9 (±44.02)	0.964	333.7 (±64.77)	324.3 (±68.2)	0.934
	Body height CSA M2-M3	310.3 (±41.78)	301.4 (±44.51)	0.901	303.8 (±56.71)	289.8 (±59.76)	0.886
	Mandibular angle width CSA	269.6 (±65.55)	279.4 (±67.92)	0.904	259.8 (±45.99)	236.9 (±43.15)	0.931
	Coronoid width CSA	67.3 (±17.93)	66.5 (±16.54)	0.84	59.1 (±15.74)	48.7 (±17.61)	0.897
	Antegonial notch area	36.9 (±38.14)	34 (±32.75)	0.966	34 (±32.75)	35.1 (±39.81)	0.741

CSA cross-sectional area

Table 3 Descriptive statistics (*N*, mean, and standard deviation (SD)) by sex; an independent sample *t* test for differences between males and females (*p* value) and percent of dimorphism are presented

Measurements		Male			Female			*p* value	Percent of dimorphism[a]
		N	Mean	SD	*N*	Mean	SD		
External (volume rendering)	Ramus length	213	66.9	5.50	224	58.9	4.17	<0.001	13.5
	Ramus width	214	31.8	3.15	224	30.2	2.76	<0.001	5.3
	Body length	214	79.9	5.19	224	75.0	4.65	<0.001	6.4
	Body height P1-P2	202	32.6	3.23	205	29.5	2.77	<0.001	10.5
	Body height M2-M3	152	26.4	2.88	137	23.8	3.01	<0.001	11.1
	Mandibular angle	214	123.5	7.62	224	125.6	6.44	0.002	1.6
	Mandibular angle width	214	34.5	3.98	224	31.5	2.89	<0.001	9.3
	Coronoid width	214	23.7	2.41	224	22.4	2.27	<0.001	5.6
	Coronoid height	210	19.4	3.43	220	17.5	2.87	<0.001	10.8
	Condyle width	212	20.3	2.22	224	18.4	2.21	<0.001	10.4
	Chin width	214	28.3	5.60	224	23.2	5.72	<0.001	22.3
	Bicondylar breadth	214	122.4	5.77	224	115.7	5.64	<0.001	5.8
	Bigonial breadth	214	94	5.99	224	87.1	5.58	<0.001	8.0
Internal (cross sections)	Chin height	209	21.6	3.07	223	21	2.58	0.033	2.8
	Chin thickness	209	4.0	0.99	223	3.9	1.05	0.212	3.1
	Chin area	209	52.9	18.54	223	50.3	17.16	0.130	5.2
	Symphysis area	213	322.9	56.31	224	283.5	44.94	<0.001	13.9
	Symphysis thickness	214	15.5	2.06	224	14.4	1.66	<0.001	7.5
	Symphysis height	214	33.1	3.41	224	30.1	2.57	<0.001	10.0
	Ramus width CSA	209	241.6	49.11	214	230.3	44.61	0.014	4.9
	Body height CSA P1-P2	197	354.9	66.71	196	306.8	57.18	<0.001	15.7
	Body height CSA M2-M3	148	307.8	53.52	130	264.0	50.24	<0.001	16.6
	Mandibular angle width CSA	209	285.2	58.84	214	261.1	48.97	<0.001	9.2
	Coronoid width CSA	209	64.2	16.8	214	60.9	16.31	0.041	5.4
	Antegonial notch area	214	40.3	38.92	224	19.9	23.05	<0.001	103.1

CSA cross-sectional area

[a] % Dimorp = [(|mean males − mean females|)/mean females] × 100

measurements was 85.6%, with similar rates for males and females (Table 5). In scenario III, when only the mandibular arch (mandible without rami) was considered for analysis, only three internal measurements out of nine were included in the discriminant function, which are the chin height, the chin width, and the symphysis height (Table 4). The successful classification rate was 79.1%, with a slightly higher correct classification rate for males (80.3%) than for females (77.8%) (Table 5). Scenario IV describes a situation where only the ramus was considered for sex estimation (from coronoid and condyle to the mandibular angle). Two out of seven measurements were included in the discriminant function, which are the ramus length and the coronoid height (Table 4). A correct classification rate of 82.2% (with similar rates for males and

Table 4 Mandibular measurements included in the discriminant functions (forward analysis) to estimate sex in various states of completeness of the mandible (scenario I to V)

Scenario	Variables in the equation				OR	95% CI (OR)	
	Measurement	B	SE	*p*		Lower	Upper
Scenario I complete mandible	Ramus length	−0.31	0.056	<0.001	0.74	0.66	0.82
	Coronoid height	−0.24	0.075	0.002	0.79	0.68	0.91
	Chin width	−0.15	0.043	0.001	0.86	0.79	0.94
	Bigonial breadth	−0.25	0.048	<0.001	0.78	0.71	0.85
	Sympysis height	−0.27	0.092	0.004	0.77	0.64	0.92
	Antegonial notch area	−0.04	0.01	<0.001	0.96	0.94	0.98
	Constant	59.59	7.905				
Scenario II half mandible	Ramus length	−0.32	0.051	<0.001	0.73	0.66	0.80
	Coronoid height	−0.29	0.063		0.75	0.66	0.85
	Condyle width	−0.36	0.099		0.7	0.58	0.85
	Antegonial notch area	−0.03	0.008		0.97	0.95	0.98
	Constant	33.2	4.171				
Scenario III mandibular arch	Chin width	−0.19	0.031	<0.001	0.83	0.78	0.88
	Chin height	0.15	0.062	0.018	1.16	1.03	1.31
	Symphysis height	−0.55	0.076	<0.001	0.58	0.50	0.67
	Constant	18.89	2.519				
Scenario IV mandibular ramus	Ramus length	−0.36	0.035	<0.001	0.7	0.65	0.75
	Coronoid height	−0.29	0.048		0.75	0.68	0.83
	Constant	28.05	2.66				
Scenario V mandibular body	Body height P1-P2	−0.363	0.052	<0.001	0.7	0.63	0.77
	Constant	11.22	1.617	<0.001			

Cut value 0.5 (>0.5 = female)

SE standard error, *OR* odds ratio, *CI* confidence interval

females) was achieved (Table 5). Scenario V included a fragment of the mandibular body. Only two measurements out of four were included in the discriminant function, which are the body height at the premolar region and its CSA (Table 4). A correct classification rate of 72.9% (76.9% for males and 68.3% for females) was achieved (Table 5). Table 5 presents the discriminant functions for sex estimation with correct classification rates for the five scenarios of the mandibular state of completeness.

Cross-validation analysis revealed that the fit of our models to a sample of observations, which was not used to estimate the model, was high (Table 6), yielding a mean success rate of 89% for scenarios I (complete mandible) and II (half mandible).

Discussion

The current study provides a series of discriminant functions for sex estimation based on measurements taken from CT scans of the mandibles. Each function was constructed based on a different state of completeness of the mandible. Our study shows a high rate of success discrimination for complete (90.8%) and partially preserved (half) mandibles (85.6%). Successful classification rates of previous methods using different features of the mandibles vary from 59 to 94% [14, 18, 20, 22, 24, 30]. The only study where a successful classification rate greater than ours (94.2%) was reported by Loth and Henneberg [23], who relied on mandibular ramus flexure. However, researchers who tested their method found much lower accuracy rates (66–85.8%) [24, 25, 39]. Additionally, geometric morphometric analysis of the ramus flexure [16] showed that the accuracy of sex estimation using this feature is low and that it has better classification characteristics for males than for females. Considering the rate of sexual dimorphism in mandible features (Table 3), it is clear that discrimination between the sexes based on a single trait is problematic.

The predictive rates of previous studies are lower than ours for two main reasons: (1) variables for sex estimation were either arbitrarily selected or were statistically taken from a small number of measurements and (2) various size and shape characteristics of the mandible could not be utilized by the traditional measuring tools (e.g., CSA and bone thickness).

Our method exhibits several major advantages over previous methods. First, the suggested method enables forensic

Table 5 Discriminant functions for sex estimation and successful classification rates (%) for various states of completeness of the mandible (scenarios I to V)

Scenario		Discriminant function[1] p>0.5 is a female[2]	Correct classification rate (%) Male	Female	Overall
I		=59.59 − (0.3**Ramus length*) − (0.24**Coronoid height*) − (0.15**Chin width*) − (0.25**Bi-gonial breadth*) − (0.27**Sympysis height*) −(0.04**Antegonial notch area*)	91	90.5	90.8
II		=33.2 − (0.32**Ramus length*) − (0.29**Coronoid height*) − (0.36**Condyle width*) − (0.03**Antegonial notch area*)	85.5	85.7	85.6
III		=18.89 − (0.19**Chin width*) + (0.15**Chin height*) − (0.55**Symphysis height*)	80.3	77.8	79.1
IV		=28.05 − (0.36**Ramus length*) − (0.29**Coronoid height*)	81.6	82.7	82.1
V		=11.22 − (0.36* *Body height P1-P2*)	76.9	68.3	72.9

[a] $\text{Logit}(p) = \beta_0 + \beta_{1*}X_{1+}\beta_{2*}X_{2+\ldots} + \beta_{n*}X_n$

[b] $p = 1\backslash 1 + \exp.^{-\text{logit}(p)}$

anthropologists to change from descriptive evaluations (e.g., the robusticity rate, the gonial eversion magnitude) to numeric ones. Second, measurements included in the discriminant equations for sex estimation were taken from a large pool of mandibular measurements, tested statistically for their discrimination power. Third, it enables access to morphological features (e.g., CSA of the mandibular body) not possible by traditional measuring tools (e.g., caliper). Fourth, it provides clear knowledge on the success rates for males and females from a heterogeneous population that has undergone cross-validation. Fifth, it is more adequate for forensic needs because it covers different states of completeness of the mandible.

Table 6 Success rates of sex estimation based on cross-validation tests in various states of completeness of the mandible (scenarios I–V)

Scenario		Success rates—calculated Cross-validation 1 Male	Female	Total	Cross-validation 2 Male	Female	Total	Average Male	Female	Total
I	Complete	85%	90%	87.5%	90%	90%	90%	88%	90%	89%
II	Half mandible	85%	95%	90%	90%	85%	87.5%	88%	90%	89%
III	Mandibular arch	80%	65%	72.5%	90%	60%	75.0%	85%	63%	74%
IV	Ramus only	75%	65%	70%	75%	90%	82.5%	75%	78%	76.5%
V	Fragment of the mandibular body	75%	55%	65%	75%	65%	70%	75%	60%	67.5%

Limitations of the study

The discriminant functions were developed based on a given population. Although the study population is heterogeneous, the equations should be tested on other populations as well. Although the presented functions can be applied to mandibles of all ages, their applications for elderly individuals should be carried out carefully to ensure that they meet the inclusion criteria (e.g., intact incisors, the presence of molars or premolars at the measured location).

Conclusions

A simple, reliable, and valid method is suggested for forensic scientists for estimating sex, using CT scans of mandibles retrieved from a modern western industrial society. Five discriminant functions, based on mandibular measurements, were constructed to cover various conditions of completeness of the mandible. The greater the completeness of the mandible is, the higher the rate of success discrimination (up to 90.8%) will be. This method is not age dependent and has specific inclusion and exclusion criteria.

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