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# Morphometric and Morphological Parameters of the Adult Dry Human Mandible: An Observational Study with Sex-Based Comparison

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**Abstract**

Background: The mandible is widely regarded as one of the more sexually dimorphic bones of the facial skeleton, and its measurement continues to inform forensic and anatomical sex estimation, particularly when more established skeletal indicators such as the pelvis or skull are unavailable or fragmented.

Objective: To document the morphometric and morphological parameters of the adult dry human mandible and to compare these parameters between males and females.

Methods: This observational, cross-sectional study examined 100 adult dry mandibles of documented sex (50 male, 50 female). Thirteen linear and angular parameters were measured bilaterally with a digital vernier calliper and a goniometer, and eleven categorical morphological parameters were classified. Independent-samples t-test was used for continuous variables and the chi-square test (Fisher's exact where applicable) for categorical variables, with $p<0.05$ taken as significant.

Results: Most linear parameters were significantly greater in males, most notably the coronoid process and lingula, where every sub-measurement differed between sexes ($p<0.0001$). The gonial angle was significantly greater, that is more obtuse, in females (about 124 degrees versus about 119 degrees, $p<0.0001$). Ramus shape was the strongest categorical discriminator (chi-square 32.733, $p<0.0001$), while condylar process shape, mental foramen shape, symphysis menti shape, and mandibular canal type showed no significant sex difference.

Conclusion: The adult mandible shows sexual dimorphism that is substantial but anatomically selective, concentrated in specific regions rather than distributed evenly across the bone, and these findings offer population-specific reference data with practical relevance to forensic sex estimation..

**Keywords**: mandible; sexual dimorphism; morphometry; forensic anthropology; sex determination; osteology..

## INTRODUCTION

Identifying unknown human remains is one of the oldest practical problems in forensic medicine, and it has not gone away. A 2023 systematic review found that unidentified bodies continue to be recorded across forensic facilities worldwide, with wide variation between countries in how the problem is measured and reported, and with sex estimation repeatedly named as one of the first and most consequential steps once remains are recovered [1]. Sex estimation narrows the search for identity before age, stature, and ancestry can be meaningfully assessed, and it remains central to casework arising from mass disasters, migration deaths, archaeological excavation, and routine medico-legal investigation alike.

When the pelvis or an intact skull is available, sex can usually be estimated with high accuracy, but real casework rarely offers ideal material. Remains are frequently fragmented, burned, or incomplete, and the mandible, being the densest and most robust bone of the facial skeleton, is disproportionately likely to survive when softer or more exposed structures do not. This durability has kept the mandible under continuous study as a stand-alone tool for sex estimation, and recent work applying machine learning classifiers to cranial and mandibular measurements has reported encouraging accuracy using exactly this kind of material [2].

The biological basis for mandibular dimorphism is reasonably well understood. Sex steroids, and androgens in particular, act on bone directly and by influencing the size and pull of the muscles attached to it, so regions that anchor the temporalis, masseter, and medial pterygoid, such as the coronoid process, the ramus, and the gonial angle, tend to be the most strongly affected by the hormonal environment of puberty and adulthood [3]. This mechanism also helps explain why dimorphism is not static: geometric morphometric work using computed tomography has shown that the mandible continues to change shape with age in both sexes, with the gonial, coronoid, and symphyseal regions remaining the most active sites of change well into later adulthood, and with the pattern and timing of that change itself differing between men and women [4].

Because the degree and pattern of mandibular dimorphism vary across populations, reference data collected in one country cannot be assumed to transfer accurately to another. Studies from India have repeatedly shown this: a population-specific analysis of the mandibular ramus from panoramic radiographs in the Lucknow region derived local discriminant functions for sex estimation rather than relying on foreign norms [5], and comparable cone-beam and panoramic studies from Iraq and Iran have each generated their own accuracy figures using locally collected samples [6,7]. Radiographic gonial and antegonial angle studies extend this further, with recent panoramic-imaging work testing angle-based sex and age prediction in fresh cohorts [8,9]. Combined condylar, sigmoid, and coronoid angle assessments on orthopantomogram have also been used for age and sex estimation in Indian populations, underscoring how much of this literature still relies on two-dimensional radiographic proxies rather than direct measurement of the bone itself [10].

What is comparatively rare, at least in recent literature, is a single study that measures the dry mandible directly, across a wide panel of both linear and categorical parameters, in a South Asian population, and reports the results in a way that a forensic practitioner or anatomist could use as a reference table. Most contemporary papers focus on one or two structures, such as the ramus or the gonial angle alone, or work from radiographs rather than skeletal material, which introduces its own projection and magnification error. This study was undertaken to close that gap. The aim was to measure and classify a broad panel of morphometric and morphological parameters on a sample of adult dry mandibles of known sex, to compare these parameters between males and females, and in doing so to provide population-specific reference data that future forensic and anatomical work in this setting can draw on directly.

## Materials and Methods

### Study Design and Setting

This was an observational, cross-sectional, osteometric study, reported in line with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) recommendations for cross-sectional research [11]. The study was carried out in the Department of Anatomy, Faculty of Medicine and Health Sciences, SGT University, Budhera, Gurugram, in collaboration with the Postgraduate Institute of Medical Sciences (PGIMS), Rohtak.

### Study Population and Eligibility Criteria

The study sample comprised 100 adult human dry mandibles of documented sex, 50 male and 50 female, drawn from the osteology collection of the Department of Anatomy. Only mandibles that were intact, fully ossified, and free of fracture, gross pathology, or post-mortem damage that would interfere with landmark identification were included. Specimens with missing condyles, damaged rami, or extensive antemortem tooth loss affecting the alveolar measurements were excluded, as were specimens of uncertain or undocumented sex.

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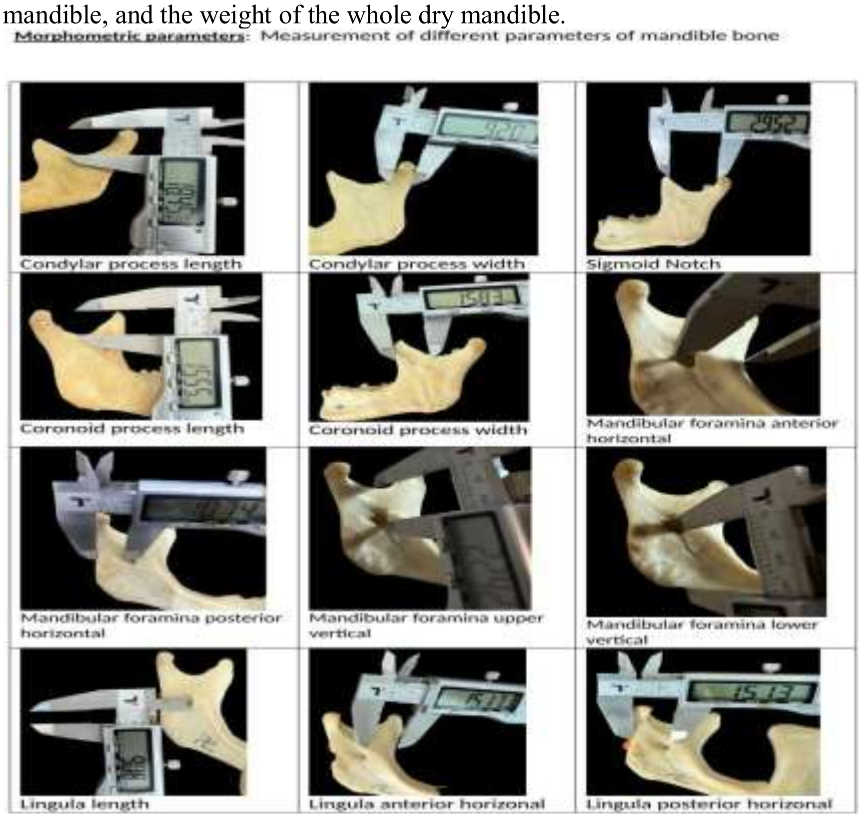
**Figure 1. Study material. The full sample of 100 adult dry human mandibles laid out for examination, alongside the digital vernier calliper and goniometer used for morphometric measurement.**

**Sample Size**

A sample of 50 mandibles per sex was set in line with the parent study protocol, which judged this to give adequate power to detect the moderate to large effect sizes typically reported for mandibular sexual dimorphism in comparable morphometric literature, while remaining feasible within the available archived collection.

**Morphometric Technique**

Thirteen linear and angular parameters were recorded bilaterally using a digital vernier calliper (accurate to 0.01 mm) and a goniometer, by examiners who repeated a subset of measurements to check consistency before proceeding to the full sample. The parameters measured were condylar process length and width, sigmoid notch width, coronoid process length and width, lingula height and its anterior and posterior horizontal distances, four distance measurements around the mandibular foramen, mental foramen transverse and vertical diameter with distances from the symphysis menti and the posterior ramus border, three ramus dimensions, mandibular canal length, mylohyoid line length, symphysis menti outer length, the distances between the two superior and between the two inferior genial tubercles, mesio-distal width of the central incisor, lateral incisor, and canine tooth sockets, the angle of the mandible, and the weight of the whole dry mandible.



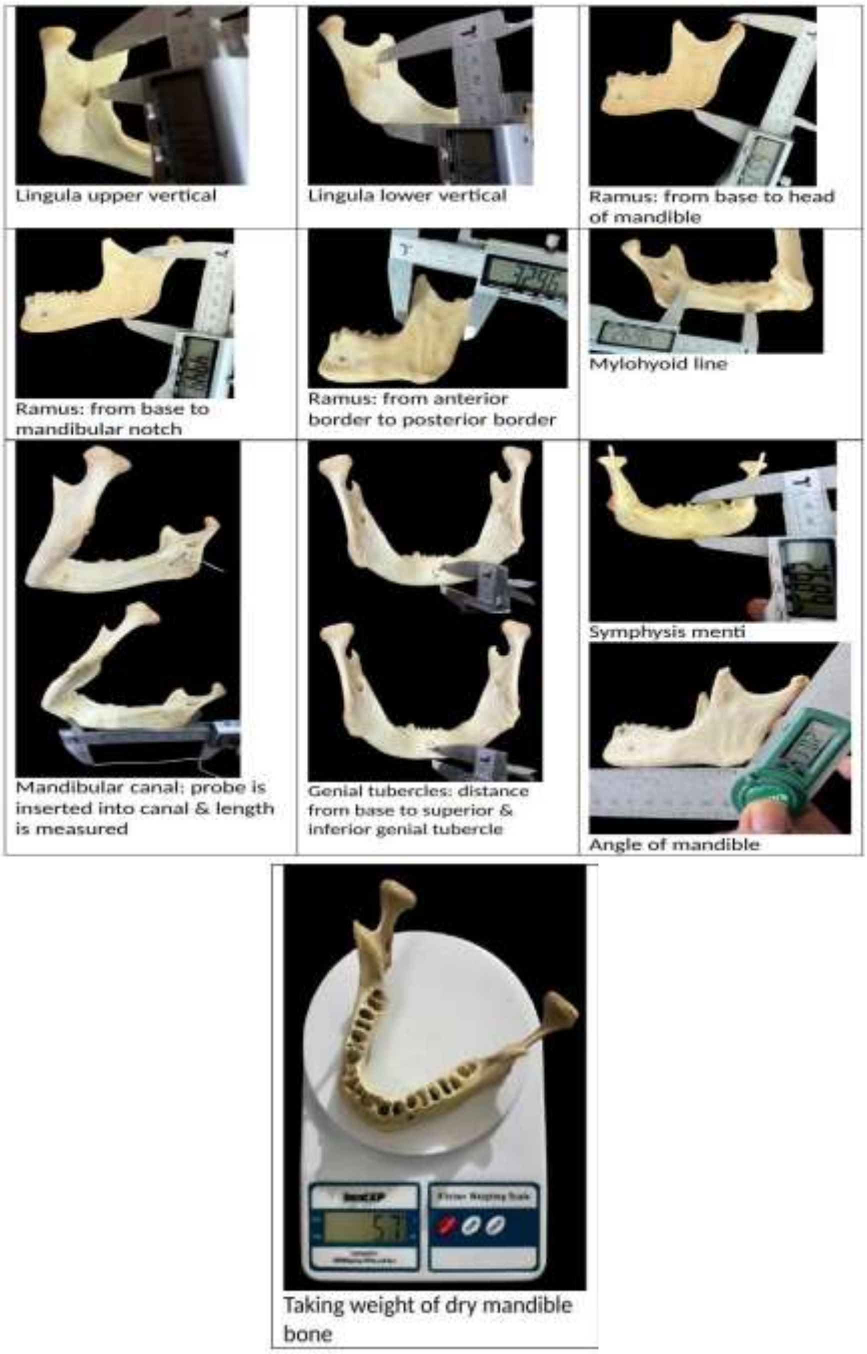



**Figure 2. Measurement technique for the morphometric parameters. Representative photographs showing calliper and goniometer placement for condylar process, sigmoid notch, coronoid process, lingula, mandibular foramen, ramus, mylohyoid line, mandibular canal, genial tubercles, symphysis menti, and angle of mandible, and weighing of the dry mandible specimen.**

**Morphological Classification**

Eleven categorical parameters were assessed and classified according to established descriptive criteria, combining right and left observations for each mandible. These were the shape of the condylar process, sigmoid notch, coronoid process, lingula, and ramus, the shape of the symphysis menti, the shape, exit direction, and position relative to the lower teeth of the mental foramen, the type of genial tubercle arrangement, and the type of mandibular canal seen on direct examination, recorded as normal, bifid, or trifid. Each parameter was scored independently by examiners following a shared reference key, and any discrepant classifications were resolved by joint re-examination of the specimen.

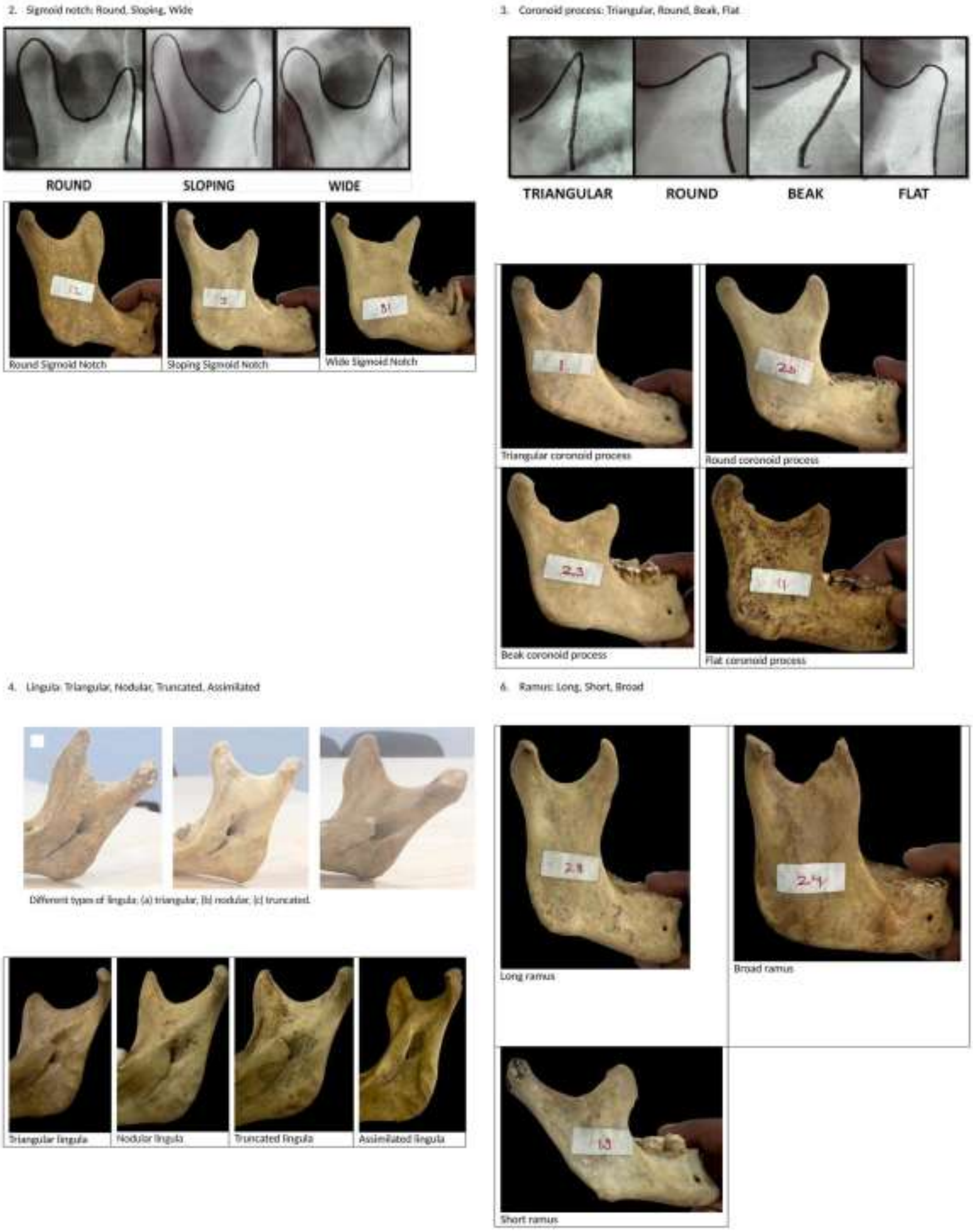



**Figure 3. Classification criteria for the four categorical parameters that reached statistical significance between sexes (Table 3): sigmoid notch shape (round, sloping, wide), coronoid process shape (triangular, round, beak, flat), lingula shape (triangular, nodular, truncated, assimilated), and ramus shape (long, short, broad), illustrated with representative dry mandible specimens.**

**Statistical Analysis**

Data were analysed using the Statistical Package for the Social Sciences (SPSS). Continuous variables are presented as mean and standard deviation and were compared between sexes using the independent-samples t-test. Categorical variables are presented as counts and percentages and were compared using the chi-square test, with Fisher's exact test applied where expected cell counts fell below five. A two-tailed p-value below 0.05 was taken as statistically significant throughout.

**Ethical Considerations**

The study used archived dry skeletal material already held by the Department of Anatomy for teaching and research purposes, and no living participants or additional radiation exposure were involved. Handling and reporting of the specimens followed the Indian Council of Medical Research National Ethical Guidelines for Biomedical and Health Research Involving Human Participants (2017), and the Institutional Ethics Committee reviewed and approved the study protocol.

## Results

### Morphometry of the Condyle, Ramus, and Related Posterior Structures (Primary Objective)

Condylar process length was significantly greater in males on both sides (right 20.23±1.75 mm versus 18.26±1.34 mm, $p<0.0001$; left 20.20±1.82 mm versus 18.24±1.47 mm, $p<0.0001$), while condylar width showed no significant sex difference on either side (Table 1). The coronoid process and lingula showed the most consistent dimorphism of any region measured, with every sub-parameter on both sides significantly greater in males (all $p<0.0001$). Ramus height and width were likewise significantly greater in males on both sides (all $p<0.0001$), and mandibular foramen posterior horizontal distance and both vertical distances were significantly greater in males ($p\leq0.0004$), although the anterior horizontal distance to the mandibular foramen did not differ significantly on either side.

**Table 1. Morphometric parameters of the condyle, sigmoid notch, coronoid process, lingula, mandibular foramen, and ramus in the adult dry mandible, by sex.**

| Parameter | Male, mean±SD | Female, mean±SD | t | p-value |
|---|---|---|---|---|
| **Condylar process (mm)** | | | | |
| Length, bilateral mean | 20.21±1.72 | 18.25±1.35 | 6.342 | <0.0001* |
| Length, right | 20.23±1.75 | 18.26±1.34 | 6.318 | <0.0001* |
| Length, left | 20.20±1.82 | 18.24±1.47 | 5.912 | <0.0001* |
| Width, bilateral mean | 8.68±1.14 | 8.52±0.98 | 0.772 | 0.4421 |
| Width, right | 8.66±1.29 | 8.64±0.95 | 0.079 | 0.9370 |
| Width, left | 8.70±1.15 | 8.39±1.39 | 1.214 | 0.2278 |
| **Sigmoid notch width (mm)** | | | | |
| Right | 26.12±2.99 | 25.23±2.08 | 1.724 | 0.0878 |
| Left | 26.25±2.83 | 24.97±2.22 | 2.507 | 0.0138* |
| **Coronoid process (mm)** | | | | |
| Length, right | 15.75±2.72 | 13.02±2.27 | 5.449 | <0.0001* |
| Width, right | 17.84±1.97 | 15.28±1.56 | 7.210 | <0.0001* |
| Length, left | 15.69±2.88 | 12.69±2.31 | 5.754 | <0.0001* |
| Width, left | 17.79±1.59 | 15.24±1.49 | 8.281 | <0.0001* |
| **Lingula (mm)** | | | | |
| Height, right | 9.51±1.91 | 8.02±0.71 | 5.116 | <0.0001* |
| Anterior distance, right | 16.91±2.73 | 14.05±1.31 | 6.676 | <0.0001* |
| Posterior distance, right | 17.47±1.89 | 15.73±1.27 | 5.407 | <0.0001* |
| Height, left | 10.13±1.71 | 7.96±0.65 | 8.419 | <0.0001* |
| Anterior distance, left | 17.47±2.33 | 14.42±1.06 | 8.412 | <0.0001* |
| Posterior distance, left | 17.70±1.84 | 15.55±1.25 | 6.800 | <0.0001* |
| **Mandibular foramen (mm)** | | | | |
| Anterior horizontal, right | 16.41±2.46 | 16.02±1.75 | 0.918 | 0.3608 |
| Posterior horizontal, right | 14.85±2.20 | 13.26±1.83 | 3.924 | 0.0002* |

| Parameter | Male, mean±SD | Female, mean±SD | t | p-value |
|---|---|---|---|---|
| Upper vertical, right | 24.65±3.71 | 21.53±2.19 | 5.133 | <0.0001* |
| Lower vertical, right | 26.35±3.48 | 22.04±3.98 | 5.757 | <0.0001* |
| Anterior horizontal, left | 16.85±2.74 | 16.34±1.80 | 1.101 | 0.2734 |
| Posterior horizontal, left | 14.95±2.30 | 13.49±1.62 | 3.672 | 0.0004* |
| Upper vertical, left | 23.93±3.71 | 21.28±2.40 | 4.248 | <0.0001* |
| Lower vertical, left | 25.48±4.01 | 22.51±3.73 | 3.841 | 0.0002* |
| **Ramus (mm)** | | | | |
| Height, base to condyle, right | 66.32±5.60 | 57.19±3.94 | 9.438 | <0.0001* |
| Height, base to notch, right | 49.90±5.05 | 44.05±2.95 | 7.068 | <0.0001* |
| Width, right | 31.89±3.11 | 29.78±1.97 | 4.057 | <0.0001* |
| Height, base to condyle, left | 65.53±5.46 | 56.90±4.08 | 8.958 | <0.0001* |
| Height, base to notch, left | 49.75±5.14 | 44.21±2.71 | 6.741 | <0.0001* |
| Width, left | 32.35±2.99 | 29.98±2.19 | 4.514 | <0.0001* |

*SD, standard deviation; t, independent-samples t statistic. *p<0.05. Values are mean±SD in millimetres unless stated otherwise. Bilateral mean is reported only where separately calculated in the source data (condylar process); for all other parameters, right and left sides are reported as measured.*

**Morphometry of the Mandibular Body, Symphysis, and Related Anterior Structures (Primary Objective)**
All eight mental foramen measurements were significantly greater in males (all p<0.0001) (Table 2). Mandibular canal length showed no significant sex difference on either side, while mylohyoid line length was significantly greater in males on the right side only. Symphysis menti outer length, all three alveolar socket widths bilaterally, and mandible weight were each significantly greater in males (p≤0.0081). The angle of the mandible was the one parameter in this region, and in the dataset as a whole, that ran in the opposite direction, being significantly greater in females on both sides (right 124.19±1.47° versus 118.82±2.03° in males, p<0.0001; left 124.36±1.54° versus 118.81±2.14°, p<0.0001).

**Table 2. Morphometric parameters of the mental foramen, mandibular canal, symphysis menti, genial tubercles, alveolar process, gonial angle, and mandible weight in the adult dry mandible, by sex.**

| Parameter | Male, mean±SD | Female, mean±SD | t | p-value |
|---|---|---|---|---|
| **Mental foramen (mm)** | | | | |
| Transverse diameter, right | 13.96±2.02 | 12.46±1.04 | 4.685 | <0.0001* |
| Vertical diameter, right | 13.95±1.49 | 12.38±1.10 | 5.946 | <0.0001* |
| Distance from symphysis, right | 26.22±1.85 | 23.84±1.37 | 7.321 | <0.0001* |
| Distance from ramus border, right | 66.42±4.23 | 61.65±2.12 | 7.125 | <0.0001* |
| Transverse diameter, left | 14.03±2.15 | 12.35±1.15 | 4.847 | <0.0001* |
| Vertical diameter, left | 13.65±1.42 | 12.12±1.06 | 6.135 | <0.0001* |
| Distance from symphysis, left | 26.78±1.79 | 24.14±1.24 | 8.603 | <0.0001* |
| Distance from ramus border, left | 65.87±4.39 | 61.47±2.00 | 6.438 | <0.0001* |
| **Mandibular canal and mylohyoid line (mm)** | | | | |

| Parameter | Male, mean±SD | Female, mean±SD | t | p-value |
|---|---|---|---|---|
| Canal length, right | 54.16±8.16 | 52.99±4.89 | 0.869 | 0.3872 |
| Canal length, left | 64.30±71.66 | 60.45±56.46 | 0.298 | 0.7660 |
| Mylohyoid line, right | 41.98±4.56 | 39.05±2.21 | 4.084 | <0.0001* |
| Mylohyoid line, left | 41.29±4.72 | 44.83±41.77 | −0.595 | 0.5530 |
| **Symphysis menti and genial tubercles (mm)** | | | | |
| Symphysis outer length | 30.81±2.35 | 26.54±1.88 | 10.043 | <0.0001* |
| Base to superior genial tubercle | 14.61±1.67 | 11.94±1.04 | 9.559 | <0.0001* |
| Base to inferior genial tubercle | 8.58±1.62 | 9.35±1.14 | −2.360 | 0.0208* |
| Superior to inferior tubercle | 6.00±1.42 | 3.05±1.56 | 8.820 | <0.0001* |
| **Alveolar process, mesio-distal socket width (mm)** | | | | |
| Central incisor, right | 2.95±0.37 | 2.70±0.28 | 3.891 | 0.0002* |
| Lateral incisor, right | 3.25±0.40 | 3.07±0.27 | 2.705 | 0.0081* |
| Canine, right | 4.76±0.63 | 3.77±0.40 | 9.418 | <0.0001* |
| Central incisor, left | 3.02±0.40 | 2.72±0.28 | 4.445 | <0.0001* |
| Lateral incisor, left | 3.32±0.48 | 3.09±0.27 | 2.860 | 0.0052* |
| Canine, left | 4.77±0.67 | 3.82±0.44 | 8.441 | <0.0001* |
| **Angle of mandible (degrees) and weight (g)** | | | | |
| Gonial angle, right | 118.82±2.03 | 124.19±1.47 | −15.153 | <0.0001* |
| Gonial angle, left | 118.81±2.14 | 124.36±1.54 | −14.877 | <0.0001* |
| Weight of dry mandible | 72.20±13.43 | 57.30±13.52 | 5.528 | <0.0001* |

*SD, standard deviation; t, independent-samples t statistic. *p<0.05. Values are mean±SD; distances and lengths in millimetres, angle in degrees, weight in grams. Negative t values indicate the female mean was higher than the male mean.*

**Categorical Morphology of the Dry Mandible (Secondary Objective)**

Of the eleven categorical parameters assessed, four reached statistical significance (Table 3). Ramus shape showed the strongest association with sex of any parameter in the study, metric or categorical (chi-square 32.733, p<0.0001), with a broad ramus predominating in males (59%) and a short ramus predominating in females (59%). Sigmoid notch shape (chi-square 13.190, p=0.0014), lingula shape (chi-square 14.293, p=0.0025), and coronoid process shape (chi-square 8.340, p=0.0395) also differed significantly between sexes. Condylar process shape, mental foramen shape, mental foramen exit direction, mental foramen location relative to the teeth, symphysis menti shape, genial tubercle type, and mandibular canal type showed no significant sex difference.

**Table 3. Categorical morphological parameters of the adult dry mandible, by sex (right and left combined, n=100 per sex unless stated otherwise).**

| Parameter | Predominant category, male / female | Male % | Female % | p-value |
|---|---|---|---|---|
| Condylar process shape | Angled / Angled | 31 | 31 | 0.9005 |
| Sigmoid notch shape | Wide / Round | 48 | 56 | 0.0014* |
| Coronoid process shape | Round / Round | 51 | 34 | 0.0395* |
| Lingula shape | Triangular / Assimilated | 37 | 37 | 0.0025* |

| Parameter | Predominant category, male / female | Male % | Female % | p-value |
|---|---|---|---|---|
| Mental foramen shape | Round / Round | 68 | 70 | 0.7651 |
| Mental foramen exit direction | Posterosuperior / Posterosuperior | 91 | 90 | 0.9751 |
| Mental foramen position relative to teeth | Below 2nd premolar / Below 2nd premolar | 73 | 65 | 0.0773 |
| Ramus shape | Broad / Short | 59 | 59 | <0.0001* |
| Symphysis menti shape (n=50/sex) | Triangular / Triangular | 74 | 72 | 1.0000 |
| Genial tubercle type (n=50/sex) | Type 2 / Type 2 | 60 | 48 | 0.0930 |
| Mandibular canal type | Normal / Normal | 97 | 92 | 0.2551 |

*Percentages given are for the single most frequent category in each sex and may refer to different categories in males and females; full category-wise breakdowns are available in the parent dataset. *p<0.05, chi-square test (Fisher's exact where applicable).*

**Parameters with the Strongest Sex-Discriminating Value (Applied Summary)**
Ranking all 24 assessed parameters by effect size identifies a consistent cluster of regions that separate the sexes most reliably (Table 4). Ranked by t-statistic among the metric parameters, symphysis menti outer length, ramus height, and lingula height and anterior distance produced the largest and most consistent separations, all with p<0.0001. Among categorical parameters, ramus shape stood well apart from the rest, its chi-square value roughly two and a half times that of the next strongest categorical trait. Mandible weight and the gonial angle, though on opposite sides of the male-female split, both ranked among the more discriminating parameters overall.

**Table 4. The ten parameters with the strongest sex-discriminating value, ranked by test statistic.**

| Rank | Parameter | Test statistic | Direction | p-value |
|---|---|---|---|---|
| 1 | Symphysis menti outer length | t = 10.043 | Male > Female | <0.0001* |
| 2 | Ramus height, base to condyle (right) | t = 9.438 | Male > Female | <0.0001* |
| 3 | Lingula height (left) | t = 8.419 | Male > Female | <0.0001* |
| 4 | Lingula anterior distance (left) | t = 8.412 | Male > Female | <0.0001* |
| 5 | Coronoid process width (left) | t = 8.281 | Male > Female | <0.0001* |
| 6 | Mental foramen distance from symphysis (left) | t = 8.603 | Male > Female | <0.0001* |
| 7 | Genial tubercle, superior to inferior distance | t = 8.820 | Male > Female | <0.0001* |
| 8 | Alveolar canine socket width (right) | t = 9.418 | Male > Female | <0.0001* |
| 9 | Gonial angle (right) | t = −15.153 | Female > Male | <0.0001* |
| 10 | Ramus shape (categorical) | $\chi^2 = 32.733$ | Broad-male / Short-female | <0.0001* |

*Ranking is derived from the test statistics reported in Tables 1 to 3 and does not represent a separate statistical analysis. t, independent-samples t statistic; $\chi^2$, chi-square statistic. *p<0.05.*

**Overall Pattern of Sexual Dimorphism Across All Parameters**
Taken together, 33 of the 41 individual metric measurements reported in Tables 1 and 2 reached statistical significance, and 4 of the 11 categorical parameters in Table 3 did the same (Table 5). Non-significant findings were concentrated in a recognisable subset, condylar process width, mandibular foramen anterior horizontal distance, mandibular canal length, and left mylohyoid line length among the metric parameters, and condylar process shape, mental foramen shape, exit direction and position, symphysis menti shape, genial tubercle type, and mandibular canal type among the categorical parameters, indicating that dimorphism in this sample was substantial but not universal.

**Table 5. Overall tally of statistically significant versus non-significant sex differences across all assessed parameters.**

| Parameter category | Total assessed | Significant (p<0.05) | Not significant | % significant |
|---|---|---|---|---|
| Metric (linear/angular) measurements | 41 | 33 | 8 | 80.5% |
| Categorical (morphological) parameters | 11 | 4 | 7 | 36.4% |
| **Overall** | **52** | **37** | **15** | **71.2%** |

*Counts are derived from the individual right- and left-side rows and categorical parameters reported in Tables 1 to 3 and represent a descriptive tally rather than a separate statistical test.*

**Discussion**
This study set out to describe the morphometric and morphological features of the adult dry mandible in a defined population and to see how far these features distinguish male from female specimens. The overall picture is one of dimorphism that is real and often large, but concentrated rather than uniform. Roughly four out of five linear measurements reached statistical significance, compared with just over a third of the categorical shape traits, and the parameters that separated the sexes most strongly were not scattered randomly across the bone but clustered in specific, biomechanically active regions: the coronoid process, the lingula, the ramus, the gonial angle, and mandible weight.
The primary finding, that linear dimensions of the coronoid process, lingula, ramus, and mental foramen were consistently and often markedly larger in males, sits comfortably alongside recent morphometric literature. Population-specific studies from Lucknow and other Indian centres have reported the ramus as one of the more useful single structures for sex prediction on panoramic imaging, developing local discriminant functions rather than importing figures from elsewhere, precisely because dimorphism in this region is known to vary by population [5]. Iranian and Iraqi cohorts studied with panoramic radiography and cone-beam computed tomography have reported broadly the same pattern, with coronoid height, condylar height, and ramus width all separating sexes with reasonable accuracy, though the exact cut-off values differ from series to series [6,7]. Machine-learning approaches applied to combined mandibular and dental measurements have reached similar conclusions from a different analytical angle, repeatedly identifying ramus height as one of the stronger predictors available once multiple parameters are combined [12]. The explanation usually offered, and the one best supported mechanistically, is that androgens act on bone both directly and through the muscles that pull on it, so structures anchoring the temporalis and masseter, which is to say the coronoid process and the ramus, grow under a stronger and more sustained mechanical load in males from puberty onward. A recent review of sex hormones and the musculoskeletal system makes exactly this point, noting that higher muscle mass and more robust attachment sites in males are a direct extension of androgen action on both bone and the muscle itself, rather than two independent effects [3].
The gonial angle deserves separate comment because its direction runs opposite to almost everything else measured. In this sample the angle was wider, that is more obtuse, in females on both sides, while every linear dimension of the ramus was larger in males. This is not a contradiction and is, in fact, the pattern most consistently reported elsewhere. A panoramic radiographic study using gonial and antegonial angles for gender prediction explained the mechanism in similar terms to those used here: a more prominent muscle attachment in males tends to pull the angle toward a more acute value, while the comparatively lighter attachment in females allows the angle to remain more obtuse even as the surrounding ramus grows to a smaller overall size [8]. Geometric

morphometric work using multislice computed tomography in an aging cohort adds a further layer to this picture, showing that the gonial, coronoid, and symphyseal regions continue to remodel throughout adult life, and that the rate and pattern of this remodeling itself differs between men and women, with women showing earlier and more marked age-related shape change in these same regions [4]. Read together, these findings suggest the gonial angle is not a fixed dimorphic marker so much as a dynamic one, shaped continuously by muscular loading and by age, which is worth bearing in mind whenever it is used for sex estimation in remains of uncertain age.

The secondary objective, describing which categorical shape traits do and do not distinguish the sexes, produced a more mixed picture, and this mix is itself informative. Ramus shape emerged as the single strongest discriminator in the entire study, metric or categorical, which fits naturally with the linear ramus findings already discussed: a structure under strong differential mechanical loading would be expected to differ in both its dimensions and its overall outline. Sigmoid notch and lingula shape were also significantly different between sexes, echoing morphological work from other Indian populations that has documented meaningful anatomical variation in the condylar, coronoid, and sigmoid notch region and linked it to both sex and population background [13]. By contrast, condylar process shape, mental foramen shape and position, symphysis menti shape, genial tubercle type, and mandibular canal type showed no significant sex difference at all. These are traits that are established relatively early in development and are less obviously tied to the mechanical demands of mastication, which is consistent with a developmental origin that owes more to general craniofacial patterning than to sex-specific muscular loading. Recent machine-learning work using the lingula specifically for sex prediction found it to be a useful but comparatively modest predictor on its own [14], which fits with the present finding that lingula shows strong linear dimorphism yet did not appear among the very strongest categorical markers, an example of how metric and categorical assessment of the same structure can lead to slightly different practical conclusions.

From an applied standpoint, the parameters identified here as the strongest individual discriminators, symphysis menti length, ramus dimensions, lingula measurements, mandible weight, the gonial angle, and ramus shape, form a reasonably compact panel that could be prioritised in future population-specific discriminant function work. This mirrors the direction much of the field is already moving in: three-dimensional reference-plane studies on cone-beam imaging continue to refine which foraminal and linear landmarks carry the most predictive weight [15], non-metric machine-learning classifiers built on South Indian samples have shown that combining several modest individual predictors can produce strong overall accuracy [16], regional Indian data on the coronoid process, condylar process, and ramus continue to accumulate as a comparison baseline [17], and machine-learning approaches are increasingly being extended from the mandible to the maxillary arch and dental arch as well [18]. That the present study was built from dry bone rather than only from panoramic or cone-beam imaging is itself a useful contribution, since direct measurement avoids the projection error, magnification distortion, and positioning artefact that all radiographic techniques carry to some degree, and provides a baseline against which radiographic methods applied to the same population can later be checked.

Several limitations should be kept in mind when interpreting these results. The sample was drawn from a single institutional collection, and the age, precise population background, and cause of death of the specimens were not always fully documented, which is a common constraint of archived osteological material rather than one specific to this study. The cross-sectional design captures a single snapshot of adult morphology and cannot speak to how these parameters change with age, even though the literature reviewed here shows clearly that at least some of them, particularly the gonial and coronoid regions, do change over the adult lifespan. No independent validation sample was used to test whether the parameters identified as the strongest discriminators could correctly classify sex in mandibles not included in the original measurement set, which would be a natural next step. Finally, this study measured the dry bone directly and did not include a radiographic comparison, so how faithfully these same parameters would be reproduced on panoramic or cone-beam imaging in this population remains an open question for further work.

## Conclusion

The adult human mandible in this sample showed clear but selective sexual dimorphism. Linear measurements of the coronoid process, lingula, ramus, and mental foramen, together with symphysis menti length and mandible weight, were consistently and often substantially greater in males, while the gonial angle was significantly more obtuse in females, a pattern that mirrors what has been reported in other populations and fits a plausible androgen and muscle-loading mechanism. Ramus shape was the strongest single categorical discriminator, while several other shape traits showed no sex difference at all. These findings offer population-specific reference data for the mandible that can support forensic sex estimation and future discriminant function work in similar settings, while pointing to the coronoid, lingula, ramus, gonial angle, and mandible weight as the parameters most worth prioritising when material is limited.

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