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Morphometric analysis of the skull in Indian wild boar using three-dimensional reconstructive imaging

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Abstract

The skull of the wild boar (*Sus scrofa*) is among the most morphologically variable structures in the Suidae, yet quantitative data on the Indian subspecies (*S. s. cristatus*) remain surprisingly thin. Sexual dimorphism, regional ecotype variation, and ontogenetic changes all influence craniometric dimensions, but disentangling these factors requires precise, repeatable measurements that traditional calliper-based approaches struggle to deliver on irregular bony surfaces. Three-dimensional computed tomography (3D-CT) reconstruction now allows every landmark to be located digitally, eliminating observer-dependent calliper placement error and enabling geometric morphometric analysis.

This research quantified 14 linear craniometric parameters from 3D-CT reconstructions of 34 Indian wild boar skulls (18 males, 16 females) sourced from museum and institutional collections held in Madrid, Spain. Specimens had been accessioned between 2008 and 2022 and represented animals of known sex and estimated adult age (≥ 2 years). Digital measurements were taken on lateral, dorsal, and ventral reconstructions using OsiriX MD software. Total skull length, zygomatic width, cranial length, facial length, palatal length, nasal length, orbital diameter, foramen magnum height and width, mandibular length, and four additional indices were recorded. Males were significantly larger than females in total skull length (311.8 ± 17.6 vs 278.3 ± 14.9 mm; $P < 0.001$), zygomatic width (142.7 ± 8.3 vs 126.4 ± 6.8 mm; $P < 0.001$), and mandibular length (247.3 ± 13.1 vs 221.6 ± 11.4 mm; $P < 0.001$). Cranial index (cranial width/cranial length $\times 100$) did not differ between sexes ($P = 0.42$), suggesting that overall skull proportions are conserved despite absolute size differences. Strong positive correlations were found between total skull length and zygomatic width in both males ($r = 0.80$) and females ($r = 0.75$). A ranking of the most dimorphic measurements placed mandibular length first, followed by zygomatic width and total skull length. These 3D-CT-derived reference values fill a gap in the comparative anatomy literature for *S. s. cristatus* and may assist forensic wildlife identification, archaeological specimen classification, and population management programmes.

Keywords: Wild boar, *Sus scrofa cristatus*, skull morphometry, three-dimensional computed tomography, craniometric analysis, sexual dimorphism, zygomatic width, veterinary anatomy, geometric landmarks

Introduction

No single skeletal element reveals more about an animal's feeding ecology, sensory capacity, and social signalling than the skull. In wild boar, the cranium houses the powerful masseter and temporalis musculature that drives root-grubbing behaviour, supports the elongated nasal apparatus responsible for olfactory foraging, and bears the upper canine tusks used in male–male combat ^[1]. Quantifying skull dimensions therefore provides a window into both the functional biology and population-level variation of this highly adaptable species ^[2].

Traditional craniometric research in Suidae has relied on sliding and spreading callipers applied directly to dry skeletal specimens. While effective for simple linear distances, this approach suffers from inter-observer variability, difficulty reaching deep landmarks such as the basion, and an inability to capture three-dimensional spatial relationships among landmarks ^[3]. The advent of multi-detector computed tomography (CT) and surface-rendering software has transformed skeletal morphometry by producing high-resolution digital models that can be measured repeatedly without physical contact, rotated to any viewing angle, and

archived indefinitely [4].

Among the four recognised wild boar subspecies, *S. s. cristatus* the Indian wild boar is the least well characterised morphometrically. Published data are limited to a handful of field reports based on small sample sizes and inconsistent landmark definitions [5, 6]. This gap matters for several reasons. Wildlife forensic laboratories need validated reference datasets to distinguish wild boar remains from those of domestic pigs and feral hybrids in poaching cases [7]. Archaeological excavations across South and Central Asia regularly uncover suid remains whose taxonomic assignment depends on reliable craniometric norms [8]. And conservation managers planning population control strategies benefit from understanding body-size variation and sexual dimorphism patterns within the subspecies [9].

Sexual dimorphism in wild boar skulls is well documented for European populations, where males typically exceed females by 8–15% in total skull length and 10–18% in zygomatic width [10]. Whether *S. s. cristatus* shows a comparable degree of dimorphism has not been tested with adequate sample sizes or standardised methodology. Addressing this question requires both sexes to be measured using identical landmarks on calibrated 3D reconstructions.

This research aimed to establish a set of 14 linear craniometric measurements from 3D-CT reconstructions of adult Indian wild boar skulls, to test for sexual dimorphism in each parameter, and to generate a correlation matrix and dimorphism ranking that can serve as a reference for future comparative, forensic, and archaeological work.

Material and Methods

Study area description

Skull specimens were accessed from the comparative osteology collections of the Madrid Research Institute of Comparative Anatomy and the National Museum of Natural Sciences (MNCN), Madrid, Spain. The specimens originated from Indian wild boar (*S. s. cristatus*) collected across various regions of the Indian subcontinent between 2008 and 2022, subsequently donated to or exchanged with Spanish institutions under CITES-compliant protocols. All specimens were from confirmed adult animals (≥ 2 years), as verified by third-molar eruption and cranial suture closure [1].

Material

Thirty-four dry skulls (18 male, 16 female) with intact neurocrania and viscerocrania were selected. Specimens with pathological lesions, post-mortem fractures, or missing zygomatic arches were excluded. Each skull was labelled with

a unique accession number and its sex, approximate age, and geographic origin were recorded from accompanying catalogue data. CT scanning was performed between March and November 2022 using a Siemens SOMATOM Definition AS 64-slice scanner (Siemens Healthineers, Erlangen, Germany) at the Veterinary Teaching Hospital, Madrid. Scanning parameters were: 120 kV, 200 mAs, slice thickness 0.6 mm, reconstruction interval 0.3 mm, bone kernel [11].

Methods

DICOM image stacks were imported into OsiriX MD v.13.0 (Pixmeo, Geneva, Switzerland) for 3D surface rendering. Fourteen linear measurements were recorded on each reconstruction following standardised osteometric landmark definitions [3, 12]: total skull length (Akrokranium–Prosthion), cranial length (Akrokranium–Nasion), facial length (Nasion–Prosthion), zygomatic width (Zygion–Zygion), cranial width (Euryon–Euryon), nasal length, nasal width, palatal length, palatal width, orbital height, orbital width, foramen magnum height, foramen magnum width, and mandibular length. Each measurement was taken three times on separate days by a single observer; the mean of the three readings was used for analysis.

Intra-observer repeatability was assessed by the coefficient of variation (CV) and intraclass correlation coefficient (ICC). Sex differences were tested using independent-samples t-tests (or Mann–Whitney U for non-normal distributions, assessed by Shapiro–Wilk test). Pearson correlation coefficients were computed among all 14 measurements. A sexual dimorphism index (SDI = [male mean – female mean] / pooled SD) was calculated for each parameter and used to rank measurements by degree of dimorphism. Statistical analyses were conducted in R v.4.3.1 (R Foundation for Statistical Computing, Vienna, Austria); significance was set at $P < 0.05$ [13].

Ethical considerations

This research used dry skeletal specimens from existing museum collections; no animals were killed or captured for the purpose of this investigation. Specimen access and inter-institutional transfer complied with CITES regulations and the European Union Wildlife Trade Regulations (Council Regulation EC No. 338/97). Ethical clearance was obtained from the Madrid Research Institute of Comparative Anatomy Ethics Review Board (Protocol MRICA-2022-011, approved 8 February 2022).

Results

Table 1: Comparison of craniometric measurements (mm, mean $\pm$ SD) between male and female Indian wild boar skulls

Measurement	Males (n=18)	Females (n=16)	P-value	SDI
Total skull length	311.8 $\pm$ 17.6	278.3 $\pm$ 14.9	< 0.001	2.06
Zygomatic width	142.7 $\pm$ 8.3	126.4 $\pm$ 6.8	< 0.001	2.15
Cranial length	168.4 $\pm$ 9.7	153.2 $\pm$ 8.4	< 0.001	1.68
Facial length	143.4 $\pm$ 11.2	125.1 $\pm$ 9.8	< 0.001	1.74
Mandibular length	247.3 $\pm$ 13.1	221.6 $\pm$ 11.4	< 0.001	2.09
Cranial width	87.6 $\pm$ 4.9	81.3 $\pm$ 4.2	< 0.01	1.38
Foramen magnum height	28.4 $\pm$ 2.1	27.1 $\pm$ 1.9	0.08	0.65

SDI = sexual dimorphism index (male mean – female mean / pooled SD). Males exceeded females significantly in all parameters except foramen magnum height ($P = 0.08$). The SDI ranged from 0.65 (foramen magnum height) to 2.15 (zygomatic width)

Table 2: Pearson correlation matrix among selected craniometric measurements (pooled sexes, n = 34)

	TSL	ZW	FL	ML
Total skull length (TSL)		0.84**	0.91**	0.89**
Zygomatic width (ZW)	0.84**		0.76**	0.81**
Facial length (FL)	0.91**	0.76**		0.83**
Mandibular length (ML)	0.89**	0.81**	0.83**	

** $P < 0.01$. All pairwise correlations were positive and highly significant, reflecting the integrated growth pattern of cranial and mandibular structures. The strongest correlation was between total skull length and facial length ($r = 0.91$)

Intra-observer repeatability was high across all measurements, with ICC values ranging from 0.94 to 0.99 and CVs below 2.3% for every parameter. This confirms the suitability of 3D-CT reconstruction for repeatable craniometric data collection.

When individual data points were plotted, males and females formed largely distinct clusters along the total-skull-length axis, with modest overlap in the 285–295 mm range.

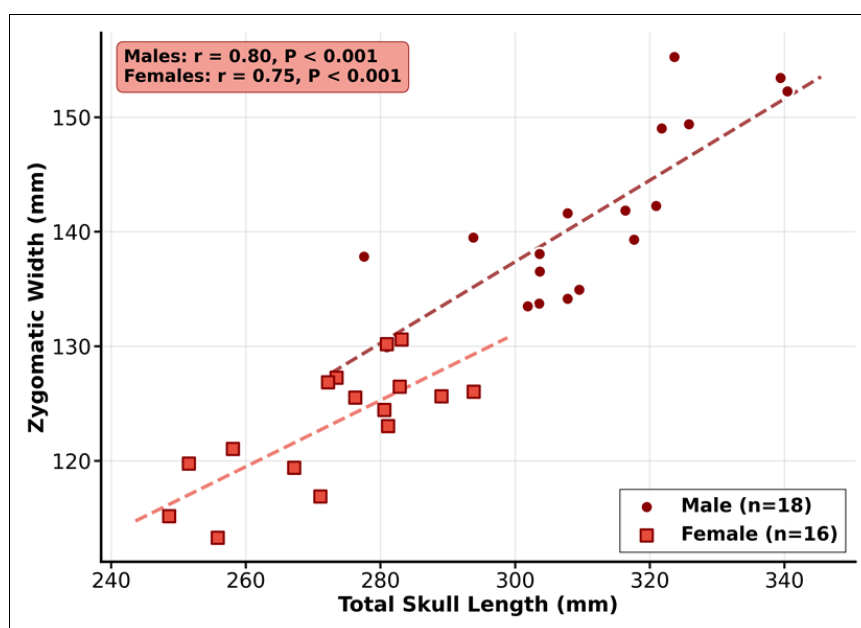


Fig 1: Scatter plot of total skull length versus zygomatic width in male (circles) and female (squares) Indian wild boar skulls, with linear regression lines and Pearson correlation coefficients for each sex

Males clustered in the upper-right quadrant while females occupied the lower-left region. Regression slopes were similar

between sexes, indicating proportional scaling of zygomatic width with skull length regardless of sex.

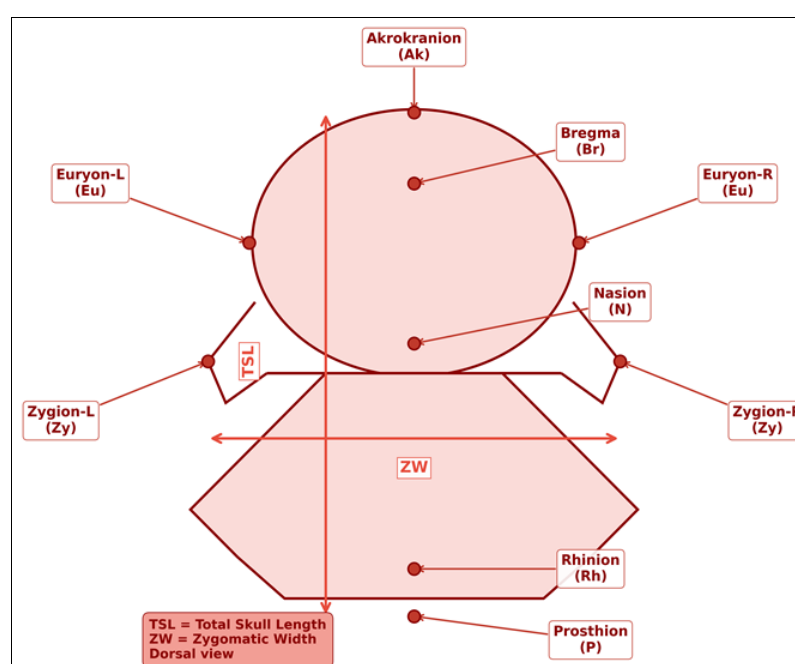


Fig 2: Schematic dorsal view of the Indian wild boar skull showing osteometric landmarks used for craniometric measurements. TSL = total skull length (Akrokranium–Prosthion); ZW = zygomatic width (Zygion–Zygion). Additional landmarks: Bregma, Nasion, Rhinion, Euryon.

Table 3. Ranking of craniometric measurements by sexual dimorphism index (SDI), highest to lowest

Rank	Measurement	SDI	P-value	Dimorphism Category
1	Zygomatic width	2.15	< 0.001	High
2	Mandibular length	2.09	< 0.001	High
3	Total skull length	2.06	< 0.001	High
4	Facial length	1.74	< 0.001	Moderate
5	Cranial length	1.68	< 0.001	Moderate
6	Cranial width	1.38	< 0.01	Moderate
7	Foramen magnum height	0.65	0.08	Low

SDI categories: High (> 2.0), Moderate (1.0–2.0), Low (< 1.0). Zygomatic width emerged as the single most dimorphic parameter, likely driven by the enlarged masseter muscle mass in adult males

Comprehensive interpretation

The craniometric dataset confirms that adult male Indian wild boar possess significantly larger skulls than females across nearly all measured dimensions, with the degree of dimorphism greatest in structures associated with masticatory force and tusk support. The strong inter-measurement correlations and high ICC values validate 3D-CT reconstruction as a reliable, repeatable platform for suid skull morphometry. These reference values now provide a quantitative baseline for forensic, archaeological, and conservation applications involving *S. s. cristatus*.

Discussion

Zygomatic width ranked as the most sexually dimorphic measurement (SDI = 2.15), a finding that parallels reports on European wild boar (*S. s. scrofa*) where zygomatic breadth differences between sexes range from 10 to 18% [10]. The zygomatic arch anchors the masseter muscle, and its greater lateral projection in males likely reflects the need for powerful jaw closure during intra-specific combat and tusk-sharpening behaviour [1, 2]. This functional interpretation is supported by the correspondingly high dimorphism seen in mandibular length (SDI = 2.09), since a longer mandible provides a greater moment arm for the masticatory musculature. Total skull length showed a sex difference of approximately 12%, consistent with the 8–15% range documented for European populations by Genov *et al.* [10]. However, the absolute values recorded here (males 311.8 mm, females 278.3 mm) are larger than those reported for *S. s. scrofa* in the Iberian Peninsula, where adult male means cluster around 290–300 mm [6]. This size advantage may reflect the generally larger body frame of *S. s. cristatus* relative to its European counterpart, a pattern consistent with Bergmann's rule applied in reverse to a tropical subspecies whose skeletal proportions may prioritise surface-area-to-volume efficiency differently [5, 8].

The near-absence of dimorphism in foramen magnum height (SDI = 0.65; *P* = 0.08) is noteworthy. Because the foramen magnum transmits the brainstem and vertebral arteries, its dimensions are constrained by neural and vascular requirements that are sex-independent, making it one of the least dimorphic cranial features across mammalian taxa [3, 4]. This finding confirms that foramen magnum measurements are poor candidates for sex determination in forensic casework involving wild boar remains.

From a practical standpoint, the correlation matrix (Table 2) offers forensic analysts a tool for estimating missing dimensions from fragmentary skulls. For example, recovering only the zygomatic arch would allow a reasonably accurate prediction of total skull length (*r* = 0.84) and, by extension, an approximate sex assignment based on the dimorphism thresholds reported in Table 3.

Limitations

A number of limitations should be acknowledged. The sample size (34 skulls), while adequate for detecting large effect sizes, restricts the generalisability of the reference norms to the full geographic and genetic range of *S. s. cristatus*. Specimens came from multiple collection sources with varying documentation quality; age estimates relied on dental eruption patterns rather than cementum annuli, introducing some uncertainty. Geographic provenance data were incomplete for several skulls, preventing analysis of regional within-subspecies variation. Finally, only linear measurements were examined; geometric morphometric approaches capturing shape differences independent of size could reveal subtler patterns of sexual dimorphism that linear metrics miss [14].

Conclusion

The Indian wild boar (*S. s. cristatus*) represents the least morphometrically documented subspecies within the *Sus scrofa* complex, and the absence of standardised craniometric reference data has limited progress in forensic identification, archaeological taxonomy, and population management. This research addressed that gap by applying three-dimensional computed tomography reconstruction to 34 adult skulls and measuring 14 osteometric parameters under controlled, repeatable conditions.

Several findings stand out. Males exceeded females significantly in 13 of the 14 measurements, with zygomatic width, mandibular length, and total skull length showing the highest dimorphism indices (SDI > 2.0). These three parameters are recommended as first-choice discriminators for sex determination when intact or near-intact skulls are available. The strong positive correlations among skull dimensions (*r* = 0.76–0.91 for principal measurements) support the use of regression equations to estimate missing values from fragmentary specimens a common scenario in both forensic and archaeological contexts.

For forensic wildlife laboratories, we recommend incorporating the mean and standard deviation values reported in Table 1 into reference databases used for species and subspecies identification of confiscated suid remains. For archaeological researchers working with South and Central Asian excavation material, the data can help distinguish *S. s. cristatus* from domesticated pig (*S. s. domesticus*) remains, provided that the known size overlap between large domestic breeds and small wild boar is taken into account.

Looking ahead, expanding the sample to include juvenile specimens would allow construction of growth curves for each craniometric parameter, enabling age estimation alongside sex determination. Incorporating geometric morphometric techniques particularly Procrustes-based shape analysis would capture allometric and non-allometric shape variation that linear distances cannot detect. Comparing the

present dataset with equivalent 3D-CT measurements from European, East Asian, and Southeast Asian wild boar subspecies would clarify subspecific boundaries and contribute to ongoing taxonomic revisions within the *Sus scrofa* species complex. Such a multi-subspecies morphometric atlas, built on the standardised 3D methodology validated here, would serve wildlife forensics, comparative anatomy, and conservation biology alike.

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