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Research Article

Assessment of Sexual Dimorphism in Morphological Indices of the Second Cervical Vertebra: Implications for Forensic Medicine and Medical Diagnostics

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Abstract

Accurate determination of sexual dimorphism in skeletal structures is crucial in forensic anthropology and medical diagnostics. This study aimed to assess sexual dimorphism in various indices of the second cervical vertebra (axis) and other associated structures. A comprehensive analysis was conducted on axis dimensions, vertebral foraminal measurements, body diameters, odontoid process parameters, and auricular facet indices in male and female subjects. A total of 122 specimens were examined, comprising 62 male and 62 female specimens. The analysis revealed significant differences between male and female subjects in various morphological indices. In terms of axial dimensions, males exhibited larger average height, length, and width of the axis compared to females, indicating sexual dimorphism. Similarly, significant differences were observed in the maximum length and width of the vertebral foramen, with males demonstrating larger measurements. Additionally, males showed larger transverse and sagittal diameters of the body compared to females. Regarding the odontoid process, males displayed greater sagittal and transverse diameters, as well as maximum height, suggesting sexual dimorphism in this aspect. Furthermore, significant differences were noted in the mean sagittal angle of the dens axis between males and females. Analysis of the superior and inferior auricular facets also indicated notable morphological variations between the sexes. The findings highlight pronounced sexual dimorphism in the morphology of the second cervical vertebra and associated structures. These results underscore the importance of considering sex-related variations in skeletal assessments for forensic and diagnostic purposes. Further research in this area can enhance the accuracy of sex determination in skeletal remains and contribute to the development of new identification methodologies.

Keywords: sexual dimorphism, second cervical vertebra, forensic anthropology, morphological indices

1. Introduction

Recent research highlights the ongoing challenges and advancements in forensic identification techniques. While some argue against the conceptual validity of forensic identification [1]. Others emphasize its importance in medico-legal matters [2]. Proteomics has emerged as a valuable tool for analyzing various human samples, especially when DNA is degraded or absent [3]. This approach can provide a comprehensive view of sample characteristics and has applications in body fluid identification, ethnicity determination, and postmortem interval estimation. In forensic odontology, new methods have been developed for age, sex, and ethnicity determination using dental tissues [2]. Additionally, ancient DNA research has contributed significantly to forensic bone DNA analysis, offering improved protocols for sample selection, DNA extraction, and sequencing approaches [4]. These advancements demonstrate the evolving nature of forensic identification techniques and their potential for future development.

The research highlights the importance of forensic anthropology in human identification, particularly in challenging scenarios like mass disasters or decomposed remains. Sex determination from skeletal remains can achieve up to 98% accuracy when using the pelvis and skull [5]. However, females are misidentified about 10 times more often than males [5]. Pelvic morphology plays a crucial role in sex identification, with significant differences observed between sexes in Thai populations [6]. Age, ancestry, and stature estimation also contribute to creating a biological profile, with accuracy rates ranging from 83% to 98% [5]. Advanced imaging techniques like cone-beam computed tomography can enhance identification by examining unique features [7]. To improve accuracy and address uncertainties in forensic anthropology, Bayesian approaches are being explored for interpreting skeletal identifiers and combining multiple lines of evidence [8].

The studies have further explored sexual dimorphism in cervical vertebrae, particularly C2 and C7, for sex estimation in forensic anthropology. The second cervical vertebra (C2) has been identified as highly sexually dimorphic, along with the 12th thoracic and first lumbar vertebrae [9]. Computed tomography (CT) scans have been utilized to quantify morphological development and sexual dimorphism in C2–C7, revealing significant sex differences in growth trends and form-space ontogenetic trajectories during puberty [10]. In Iranian populations, studies using CT scans found that certain dimensions of C2 and C7 were associated with sex, achieving classification accuracies of 81.4% and 78.6%, respectively [11, 12]. These findings demonstrate the potential of cervical vertebrae, especially C2 and C7, as reliable indicators for sex estimation in forensic contexts, particularly when used in combination with other skeletal structures.

Existing literature emphasizes the importance of biological profiles in forensic anthropology for identifying human remains. These profiles typically include estimates of sex, age, stature, and ancestry, along with skeletal trauma analysis [13]. Age-at-death estimation remains challenging, with various reporting strategies showing different levels of accuracy depending on sample characteristics [14]. The proximal femur has been identified as a valuable skeletal element for assessing all four components of a biological profile when other remains are unavailable [15]. A multidisciplinary approach combining physical anthropological methods and genetic analysis can enhance the accuracy of sex and ancestry estimations. While sex determination shows high concordance between physical and molecular methods, ancestry estimation may sometimes yield discrepancies [16]. Every piece of information that is available to create a biological profile focuses on the identity of the deceased.

Accurate sex estimation can significantly reduce the pool of potential decedents, thereby increasing the chances of identification. However, it is important to recognize that sex traits can vary among individuals, leading to biological males exhibiting feminine traits and vice versa. This variability poses a challenge to studies that rely on binary categorization. While sex estimation methods may categorize an individual as male or female, anthropologists must consider all contextual clues before deciding. Additionally, it is essential to acknowledge that gender and sexual identity are diverse and multifaceted. Therefore, the term “sex estimation” should be used with caution, especially since it involves estimating the sex of a deceased individual unless they have communicated their identity, while alive. Inadequate attention has been paid to the sexual dimorphism of the second cervical vertebra in the Indian population. Therefore, this study aims to investigate sexual dimorphism in the second cervical vertebra (C2) by analyzing and comparing various morphological indices between male and female subjects. This comprehensive assessment aims to enhance understanding of sex-based variations in cervical vertebrae, with implications for forensic analysis, medical diagnostics, and anatomical research.

2. Materials and Methods

Samples procured for this study were the second cervical vertebra (C2) of known sex from different Medical Colleges in the south Indian region. This was further confirmed by some nonmetric sexual differences in axis vertebrae, such as males who often exhibit more robust and vertically oriented dens compared to females, texture and surface morphology including rough texture or more pronounced muscle attachment sites, reflecting differences in biomechanical stresses between sexes. A total of 122 specimens were examined, comprising 62 male and 62 female specimens. We have taken significant steps to ensure the diversity of our sample population by sourcing cadavers from various regions across India, including different medical colleges in states of Karnataka, Andhra Pradesh, Tamil Nadu, Dadra, and Nagar Haveli. By incorporating samples from these geographically and culturally distinct areas, we have enhanced the representativeness of our study, thereby strengthening the generalizability of our findings. This diverse sample population allows us to capture a broader range of anatomical variations, making our results more applicable to the general population. Key anatomical landmarks of the C2 vertebra were identified, including the odontoid process (dens), the body, the pedicles, the transverse processes, and the spinous process. These landmarks served as reference points for taking precise measurements. Digital sliding calipers with a precision of 0.1 mm were used for all measurements. The calipers were calibrated before each use to ensure accuracy. The calipers were equipped with a digital readout to minimize reading errors and enhance precision. Each measurement was taken three times to ensure consistency and reliability. The mean value of the three measurements was recorded as the final dimension. All measurements were documented in a structured data sheet. To ensure the accuracy and reliability of the measurements, the following quality control measures were implemented: The digital sliding calipers were calibrated before each measurement session. Two independent researchers then performed measurements to minimize inter-observer variability. Any discrepancies in measurements were resolved by re-evaluating the dimensions together and reaching a consensus. The measured parameters of the axis are described in Figure **1** and Table 1.

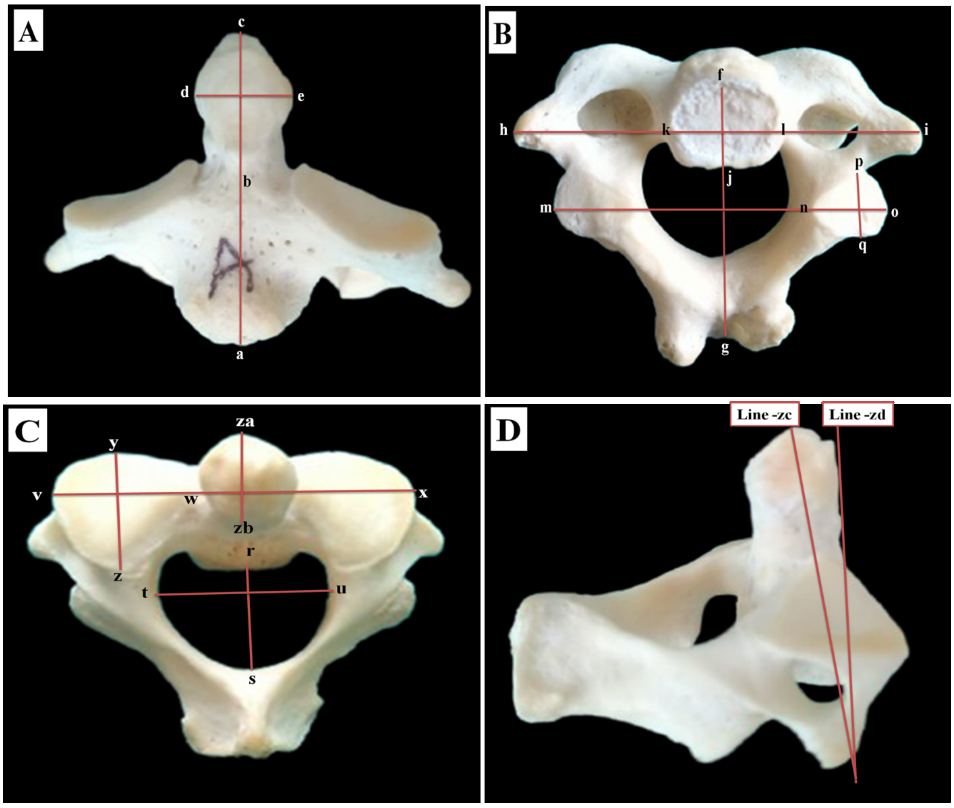

Figure 1: Representative photographs describing different measurements of axis A] Anterior view showing, a-c = Maximum height of axis, d-e = Transverse diameter of Odontoid process, b-c = Maximum height of Odontoid process. B] Inferior view showing, f-g = Maximum length of axis, h-i = Maximum width of axis, f-j = Maximum length of body, k-i = Maximum width of body, m-o = Maximum distance between inferior articular facets, p-q = Maximum length of inferior articular facets, n-o = Maximum width of inferior articular facets. C] Superior view showing, r-s = Maximum length of vertebral foramen, t-u = Maximum width of vertebral foramen, v-x = Maximum distance between the superior articular facets, y-z = Maximum length of superior articular facet, v-w = Maximum width of superior articular facet, za-zb = Antero-posterior diameter. D] Angle between line zc –zd = Sagittal angle of the dens axis.

2.1. Statistical analysis

The IBM SPSS Statistics for Windows, Version 22.0, was used to feed data into the computer and then interpret it. After determining if parametric data were normal using the “Kolmogorov-Smirnov test,”

Table 1: The measured parameters of the axis.

Parts Axis	Indices	Measurements	
		From	**To**
Axis proper	Maximum height	Lowest point of the edge of the vertebral body.	Uppermost point of the dens
	Maximum length	Most anterior point of the body	Most posterior point of bifid spinous process
	Maximum width	More extreme right lateral side	More extreme left lateral side
Vertebral foramen	Maximum length	Anterior most point at the inferior edge of the foramen in the median plan;	Posterior most point at the inferior edge of the foramen in the median plan
	Maximum width	Right Lateral most point of foramen	Left Lateral most point of foramen
Body	Maximum sagittal diameter	Antero-posterior point of the body	Posterior-inferior point
	Maximum transverse diameter	Right edges of the body	Left edges of the body
Odontoid process	Sagittal diameter (Antero-posterior diameter)	Anterior most point	Posterior most point
	Transverse diameter	Right lateral most point	Left lateral most point
	Maximum height	Highest point of the odontoid process	Line passing superiorly to superior articular facets
	Sagittal angle of the dens axis	The angle between axis passing longitudinally through dens and vertical line on sagittal plane	ND
Superior articular facets	Maximum distance between the superior articular facets	Most right lateral points of the facet	Most left lateral points of the facet
	Maximum length	Most anterior-most point	Most posterior-most point
	Maximum width	Right lateral most point	Left lateral most point
Inferior articular facets	Maximum distance between the superior articular facets	Most right lateral points of the facet	Most left lateral points of the facet
	Maximum length	Most anterior-most point	Most posterior-most point
	Maximum width	Right lateral most point	Left lateral most point

quantitative data were presented using the mean and the standard deviation. The findings obtained were considered significant at the (0.05) level. Two distinct groups of parametric variables were compared using the “student t-test.”

3. Results

3.1. Indices of axis

The axial dimensions of the second cervical vertebra (axis) were assessed between male and female subjects, revealing notable variations. Among males, the average height of the axis measured 38.10 ±

2.42, while in females, it averaged 35.25 ± 1.40. Similarly, the mean length of the male axis was recorded at 49.99 ± 5.92, compared to 48.22 ± 5.15 in females. Additionally, the width of the male axis was observed to be 55.70 ± 4.53, contrasting with 52.22 ± 5.96 in females (Figure **2**).

Statistical analysis indicated significant differences in the dimensions of the axis between genders. Specifically, when comparing maximum height, length, and width, male subjects exhibited significantly higher values than their female counterparts [t(120) = 11.12, p = 0.00001, t(120) = 2.46, p = 0.007227, t(120) = 5.09, p = 0.00001, respectively]. These findings underscore the presence of sexual dimorphism in the morphology of the second cervical vertebra (Figure **2**).

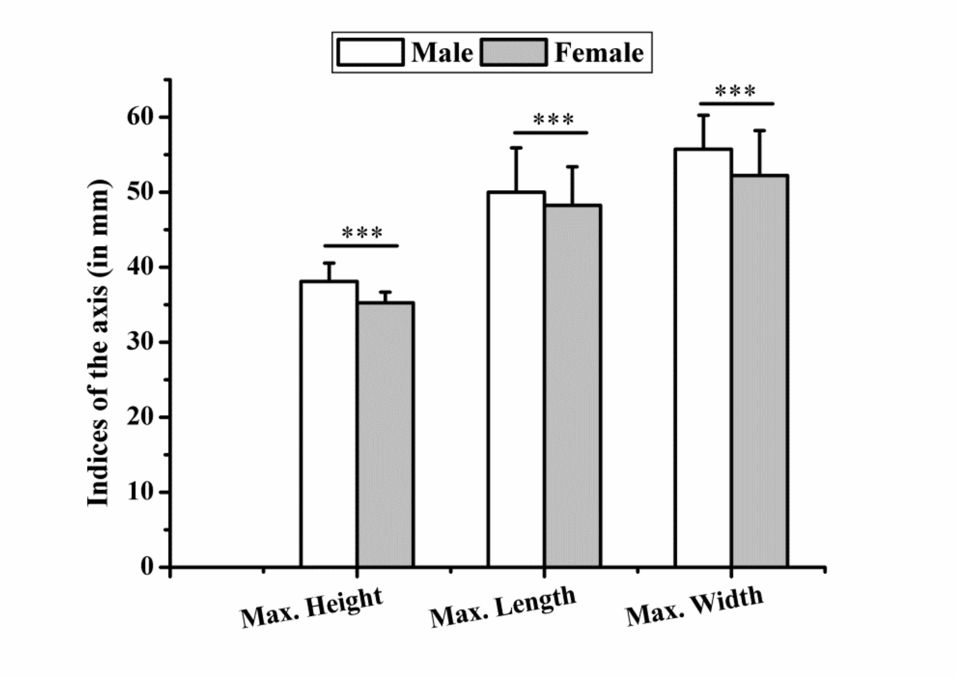

Figure 2: Gender-specific comparison of indices axis. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS= Not significant.

3.2. Indices of vertebral foramen

The mean maximum length of the vertebral foramen of the second cervical vertebra was assessed, revealing measurements of 16.46 ± 2.72 in male specimens and 16.241 ± 2.56 in female vertebrae. Additionally, the mean maximum width of the vertebral foramen of the second axis was determined to be 24.04 ± 2.454274 in males and 23.35 ± 2.72 in females (Figure **3**).

Comparative analysis of the vertebral foramen dimensions between males and females indicated noteworthy differences. Specifically, while the maximum length did not demonstrate a significant variance between male and female vertebrae [t(120) = 0.65, p = 0.25], a considerable distinction was observed in width [t(120) = 2.04, p = 0.021103]. These findings suggest a notable sexual dimorphism in the width of the vertebral foramen of the second cervical vertebra (Figure **3**).

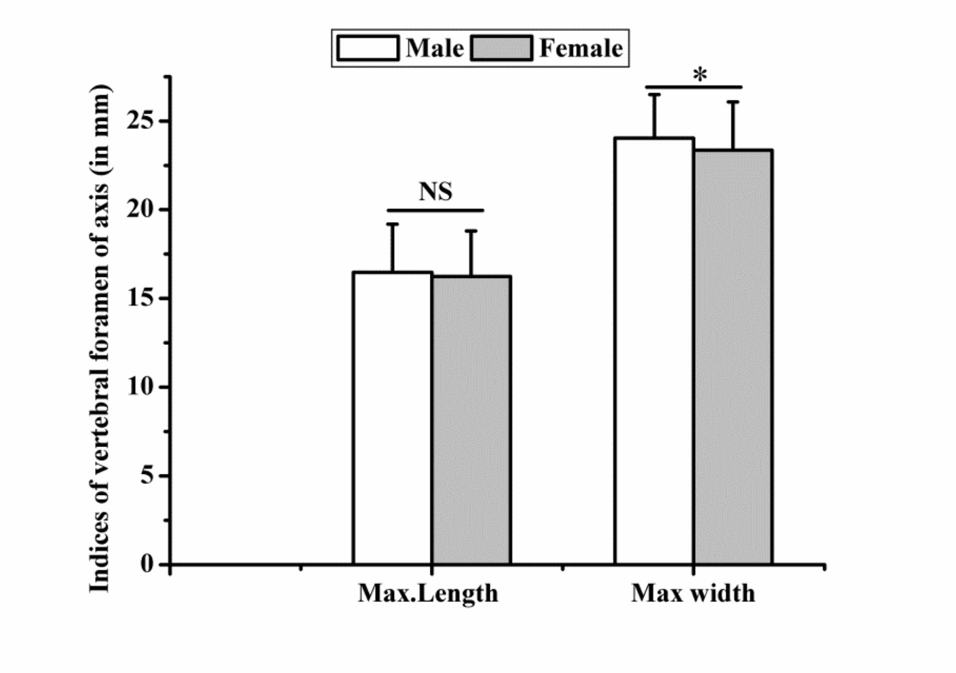

Figure 3: Gender-specific comparison of indices of vertebral foramen axis. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS = Not significant.

3.3. Indices of the body of axis

The comparison of the maximum transverse diameter of the body revealed a measurement of 19.76 ± 3.20 in males and 18.4 ± 3.26 in females. Similarly, the maximum sagittal diameter of the body was recorded as 15.05 ± 2.57 in males and 14.45 ± 2.31 in females. Statistical analysis indicated a significant difference between males and females in both transverse and sagittal diameters of the body [t(120) = 3.27, p = 0.000614, t(120) = 1.8991, p = 0.029381, respectively]. These findings suggest that males tend to have larger transverse and sagittal diameters of the body compared to females, highlighting potential sexual dimorphism in this aspect of vertebral morphology (Figure **4**).

3.4. Indices of the odontoid process

The comparative analysis of odontoid process dimensions between male and female axis vertebrae revealed significant distinctions. Specifically, the average sagittal diameter of the odontoid process was measured at 11.42 ± 1.69 in males and 10.8 ± 1.71 in females, with a transverse diameter of 9.84 ± 1.39 in males and 9.24 ± 1.17 in females. Additionally, the maximum height of the dens was recorded as 16.98 ± 2.16 in males and 16.09 ± 2.62 in females. These findings collectively indicate that the sagittal diameter, transverse diameter, and maximum height of the dens were notably greater in males compared to females [t(120) = 2.53, p = 0.005957, t(120) = 3.60, p = 0.000191, t(120) = 2.87253, p = 0.00222, respectively] (Figure ??A).

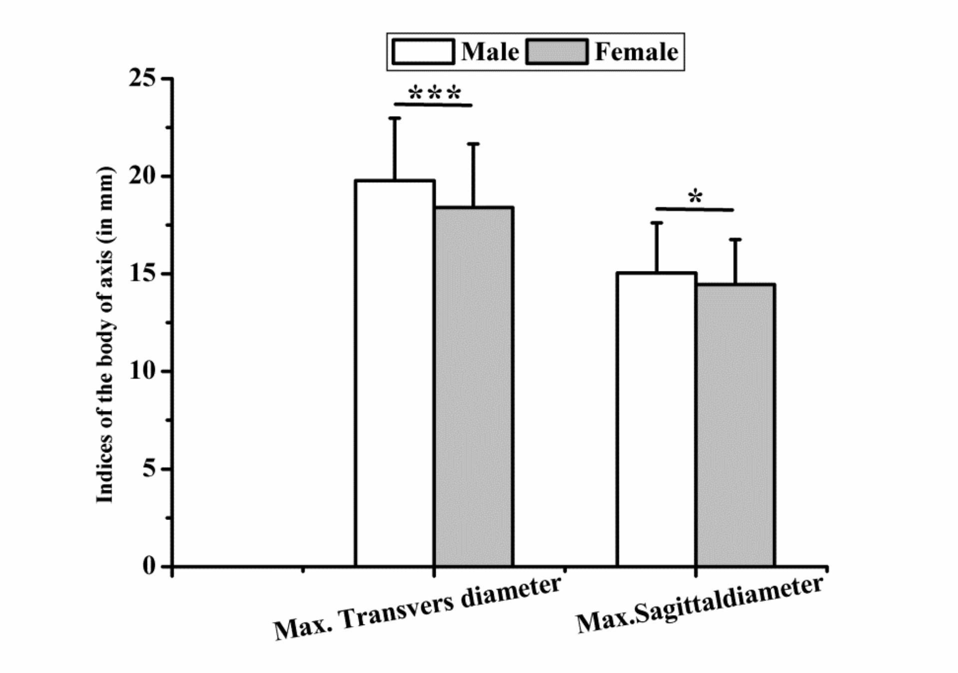

Figure 4: Gender-specific comparison of indices of vertebral foramen of axis. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS = Not significant.

Furthermore, the mean sagittal angle of the dens axis, representing the angle between an axis passing longitudinally through the dens axis and the vertical line on a sagittal plane, was calculated. It averaged 9.87 ± 1.09 degrees in male bones and 8.84 ± 0.95 degrees in females. This difference was found to be statistically significant [t(120) = 7.87, p = 0.00001], highlighting a distinct morphological variation between male and female axis vertebrae in terms of dens axis sagittal angle (Figure ??B).

3.5. Indices of superior auricular facet

In the assessment of the indices related to the superior auricular facet, notable differences were observed between male and female specimens. The mean maximum distance between two superior articular facets was measured at 45.60 ± 3.37 in male bones and 44.13 ± 4.06 in females. Furthermore, the maximum length of the facet was recorded as 13.86 ± 1.93 in males and 12.6 ± 1.68 in females, while the maximum width was found to be 14.15 ± 2.70 in males and 13.95 ± 2.65 in females (Figure **5**).

Upon conducting t-tests to compare the indices of the superior articular facet between male and female specimens, significant differences were noted in the mean maximum distance between two superior articular facets and the maximum length [t(120) = 3.05, p = 0.001238, t(120) = 5.41, p = 0.00001, respectively]. However, no significant distinction was observed in the width of the facet [t(120) = 0.57, p = 0.281863]. These findings underscore the morphological variations between male and female specimens in terms of the superior auricular facet of the vertebra (Figure **5**).

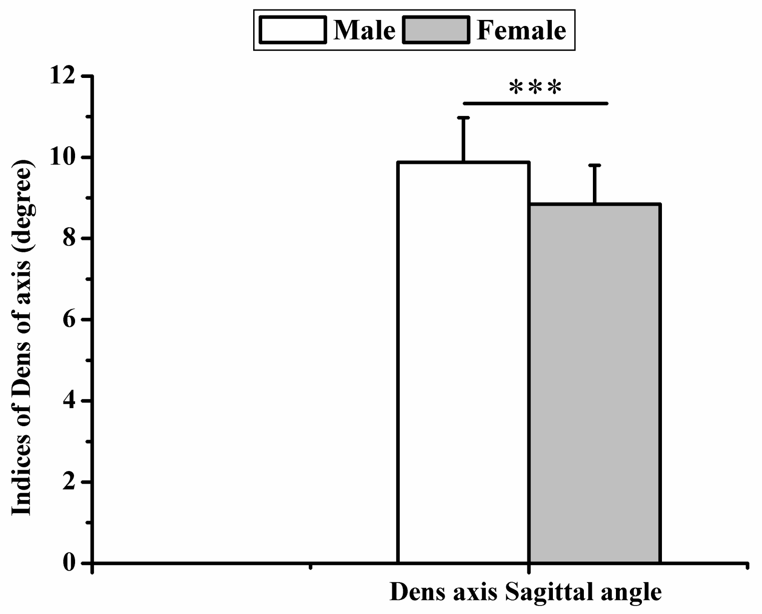

Figure 5: Gender-specific comparison of indices of [A] Odontoid process of Axis. [B] Dense axis sagittal angle. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS = Not significant.

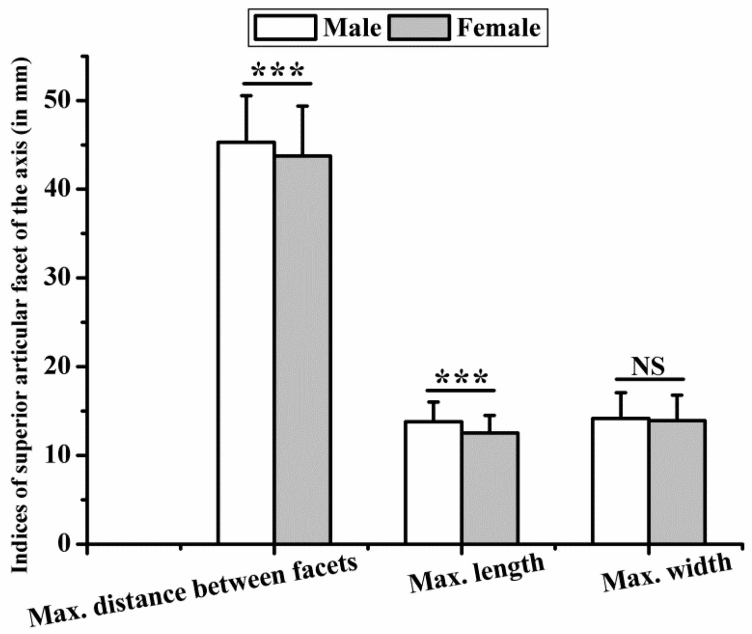

Figure 6: Gender-specific comparison of indices of superior auricular facet of axis. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS = Not significant.

3.6. Indices of inferior auricular facet

In the evaluation of the indices concerning the inferior auricular facet, notable distinctions were identified between male and female specimens. The mean maximum distance between two inferior articular facets was determined to be 46.4 ± 2.66 in male specimens and 44.8 ± 1.31 in females. Additionally, the maximum length of the facet was measured at 10.08 ± 1.31 in males and 9.29 ± 1.641867 in females, while the maximum width was recorded at 10.48 ± 1.69 in males and 9.51 ± 1.52 in females (Figure **6**).

Statistical analysis utilizing t-tests revealed significant differences between male and female parameters across all measured indices of the inferior articular facet. Specifically, significant distinctions were observed in the mean maximum distance between two inferior articular facets, maximum length, and width [t(120) = 4.59, p = 0.00001, t(120) = 4.12, p = 0.000026, t(120) = 4.64697, p = 0.00001, respectively]. These findings underscore the pronounced morphological variations between male and female specimens concerning the inferior auricular facet of the vertebra (Figure **6**).

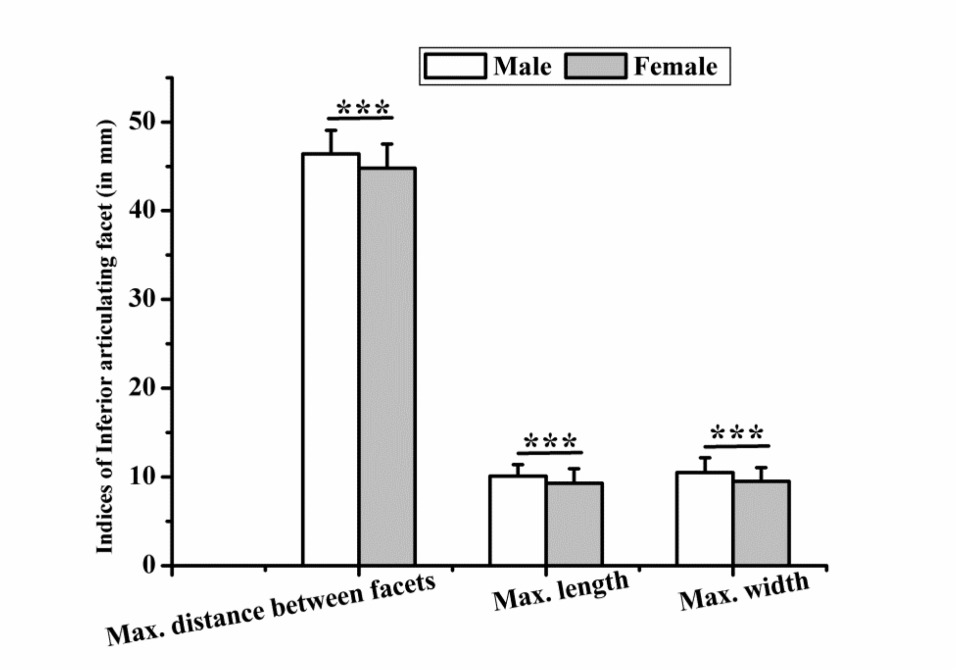

Figure 7: Gender-specific comparison of indices of superior auricular facet of axis. Values are represented as mean ± SD. The statistically significant differences are shown by superscripted stars (*). ** = P < 0.01, * = P < 0.05, and *** = P < 0.001, NS = Not significant.

4. Discussion

The findings of this study shed light on the morphological differences between male and female specimens in various aspects of the second cervical vertebra (axis). The observed variations in axial dimensions, odontoid process indices, and auricular facet characteristics underscore the presence of sexual dimorphism in the cervical vertebrae.

In the field of forensic medicine and toxicology research, estimating human sexual dimorphism is one of the biggest issues. The accuracy of estimating sex is 100% for the full skeleton, but when only some parts are accessible, the expectation drops dramatically. This means that many procedures must be used to provide a satisfactory diagnosis [17]. The research indicates that approaches to predict sex that have an accuracy of more than 80% need to be taken into consideration [18–21]. With an 85% rate of precision in determining sex, the femur is often selected first [22], including other long bones like the tibia (92.2%) [23], humerus (76.8%–95.5%) [24], and radius and ulna (76%–86%) [25]. In the present study, the accuracy using the C2 vertebra varied between 84.3% and 90.6%. Yet, using C2 alone has minimal effects on sex prediction [19]. With the expression of sexual dimorphism and precision comparable to the long bone, this anatomical feature has shown to be a good substitute for this purpose [18–20, 26–28].

Gama et al., [26] conducted research at the Forensic Sciences Center Portugal, utilizing a combination of measurements, from previous studies and their own, to analyze a sample of 190 individuals from Portugal. In their final analysis, Gama et al., [26] observed that the maximum width of the axis measurement exhibited an 11.18% difference between males and females. The sagittal maximum body diameter showed a 10.6% difference, and the length of the vertebral foramen had a 2.7% difference between males and females. These findings align with their results even in the Indian population, where each trait indicated males were larger than females in the sample. These consistent results suggest that human cervical vertebrae, particularly C2, demonstrate a noticeable degree of sexual dimorphism [26].

In this study, maximum height, length, width of vertebral foramen, transverse and sagittal diameters of the body, sagittal, transverse diameter and height, angle of odontoid process, maximum distance between superior articular facet, maximum length of superior articular facet, maximum distance between inferior articular process, maximum length, and maximum width of inferior articular process were significantly higher in males than in females.

The research carried out by Mostafavi et al., in the Iranian adult population, utilizing computed tomography scan images, determined that several anatomical measurements of the axis vertebra exhibited significant differences between males and females., Some parameters of this study were consistent with the findings reported by Mostafavi et al., [11] where, males had considerably greater maximum height, length, and breadth of the axis than females.

Although a statistically significant difference was observed in the maximum width of the vertebral foramen, the maximum length of the foramen was not as large as it was in the male. The results of Gama et al., were in contradiction with this [26]. Although the results of this study are similar to those of Gama et al., they also show that males transverse and sagittal body diameters were substantially bigger than those of females, in agreement with Mostafavi et al., [26].

The height, transverse diameter, and sagittal diameter are indices of the odontoid process. Compared to females, males had larger densities. According to the research by Gama et al., and Mostafavi et al., sagittal diameter and height showed significant variations, whereas transverse diameter did not.. They did not measure the angle of odontoid process or dense [11, 26]. Consistent with the previous study, the maximum distance between the superior articular facet and the maximum length of the superior articular facet was substantially higher in men [11, 26]. But not the maximum width, which conflicts with earlier research even though it was greater than females; however, not statistically significant. Earlier studies did not measure the maximum distance between the inferior articular process, they measured maximum length and maximum width. In this study indices of the inferior articular facet showed a significant elevation in male bone than that of female. Mostafavi et al., who measured maximum length was not significant but width exhibited significant distinction [11].

By employing eight-axis measurements and statistical testing, Wescott [19] led the way in the investigation of sexual dimorphism of C2, correctly identifying the sex of 400 participants with 83% of the sample. Wescott's first findings were supported by Marlow and Pastor [18] creating more distinguishing factors to use the axis to categorize the sexes. Marlow and Pastor's study included 153 participants, aged between 21 and 92. Since these people belonged to a known sex population, group membership was determined using a discriminant function analysis designed to magnify within-group differences. Individual discriminant functions in this experiment varied from 70.91% to 78.9%, with a total accuracy rate of 76.99% [18].

The greatest width of the vertebral foramen is one of the parameters that Gama et al., give as a logical addition to their investigation. Only the open vertebral foramen, through which the spinal cord passes, is covered by this measurement as it passes across the transverse plane of the vertebra. While the transverse measurement was exclusive to this work at the time of publication, earlier research had measured the sagittal width of the vertebral foramen [18, 19]. Unlike other investigations, Torimitsu et al., employed postmortem computed tomography (PCT) and fleshed cadavers from a Japanese community [20]. In all, 224 cadavers—112 men and 112 females—were investigated for this study. The accuracy percentage obtained by the researchers was 92.9%, and there were notable variations in size between males and females [20]. According to Torimitsu et al., the reason why men were much bigger than women in this study might be due to sex-related occupations and hormone surges [20].

The muscular attachments of these features might be the cause of most of their dimorphism. The transverse processes of C2 are linked to the levator scapulae, scalenus medius, and splenius cervicis, while the top and lower surfaces of these processes are home to the intertransverse muscles. The obliquus capitis inferior derives from the lateral surfaces of the spinous process, while the rectus posterior major attaches a little more posteriorly. Semispinalis and spinalis cervicis, multifidus deeper, and the interspinalis close to the apex are obtained by the inferior concavity of the process [29]. As the muscles experience increased strain, their attachment sites expand, potentially influencing the maximum width of the axis measurement in both sexes. Similarly, because of the muscle attachments of the obliquus capitis inferior and rectus capitis posterior major on the spinous process, a similar effect may occur regarding changes in the maximum length of the axis measurement [29]. The longus colli muscle, which joins directly to the vertebral body, can affect the measures of the body's transverse and sagittal diameters [29].

4.1. Implications for forensic and medical diagnostics

The analysis of the second cervical vertebra (C2) has revealed significant sexual dimorphism in various morphological indices, providing valuable insights for both forensic and medical diagnostics. These findings have several important implications for current practices:

4.2. Forensic implications

The research in forensic anthropology has focused on improving sex estimation methods for skeletal remains. Studies using the Athens Collection have developed and validated techniques based on cranial and postcranial elements for Greek/Eastern Mediterranean populations [30]. Practitioner surveys reveal variability in method preferences, highlighting the need for standardization in sex estimation protocols [31]. Anatomical knowledge of head and neck bones contributes significantly to sex estimation, with metric analyses of the glabella, frontal bone, mandible, and canine teeth showing high accuracy [32]. The axis vertebra is particularly useful due to its unique shape. Research on Portuguese-identified collections emphasizes the importance of population-specific standards and addresses emerging challenges in sex estimation, including the use of medical imaging, innovative statistical approaches, and the evolving understanding of sex and gender [33]. These advancements aim to enhance the accuracy and reliability of sex estimation in forensic anthropology.

4.3. Medical diagnostics implications

Sexual dimorphism plays a significant role in various medical conditions, influencing diagnosis, treatment, and outcomes. In osteoporosis, females are more susceptible, while males face higher risks of disability or death, with sex chromosomes and steroid hormones contributing to these differences [34]. The dens of the second cervical vertebra (C2) exhibit sexual dimorphism, with males having slightly larger dimensions, which has implications for screw fixation in fracture treatments [35]. These findings underscore the importance of considering sex as a biological factor in medical research and practice.

4.4. Integration into current practices

Sexual dimorphism in cervical vertebrae, particularly the second cervical vertebra (C2), has been demonstrated as a reliable method for sex determination in forensic and anthropological contexts.

Studies have shown that C2 measurements can accurately estimate sex with 83-92.9% accuracy across different populations [19, 36] and found significant sexual dimorphism in 13 indices of C2 and 9 indices of C7 vertebrae in an Egyptian sample, with density indices being particularly useful predictors. Similar dimorphism has been observed in Mediterranean populations, with approximately 80% accuracy for both C7 and T12 vertebrae [37]. These studies emphasize the importance of population-specific data and the potential for using vertebral measurements in forensic identification. The integration of computed tomography (CT) imaging has further enhanced the accuracy and applicability of these methods in forensic anthropology [20, 36].

By integrating these morphological indices into current practices, both forensic and medical fields can benefit from more accurate and personalized approaches to diagnosis, treatment, and identification.

In conclusion, our study highlights the utility of the C2 vertebra in discerning sexual dimorphism. Our findings still hold significance, while we acknowledge that its application in forensic contexts may be limited due to accessibility concerns compared to other bones, particularly in post-mortem scenarios. By complementing assessments of other anatomical structures, they enhance overall precision and offer valuable insights for forensic investigations. Therefore, while the use of C2 vertebra may be reserved for extreme cases, its inclusion in forensic analyses can ultimately improve accuracy and aid in the identification process.

5. Conclusion

The comprehensive evaluation conducted in this study illuminates significant morphological differences between male and female subjects in various indices of the second cervical vertebra (axis) and associated structures, confirming the presence of sexual dimorphism in vertebral morphology.

Males generally exhibited larger dimensions compared to females, indicating sexual dimorphism in vertebral morphology. These findings have implications for fields, such as forensic anthropology and medical diagnostics, emphasizing the importance of considering sex-related variations in skeletal assessments for accurate determinations. Further research may delve into underlying factors contributing to sexual dimorphism in vertebral morphology.

Strengths and Limitations of the Study

Strengths

The study thoroughly examines multiple morphological indices of the second cervical vertebra (C2), providing a detailed understanding of sexual dimorphism. Identified notable differences in axial dimensions, vertebral foramen measurements, and odontoid process characteristics between sexes, offering valuable insights for forensic and clinical applications. Results have practical relevance for forensic anthropology and clinical practices, enhancing sex determination and surgical planning.

Limitations

The variability in measurement techniques could impact the reliability of the results. The study provides only a snapshot of anatomical differences without considering longitudinal changes or developmental factors. The factors such as age or health conditions were not controlled for, which may influence the observed differences. The study does not address the functional consequences of the anatomical differences observed.

Hence, further studies are needed to include larger and more diverse samples to improve generalizability, employ longitudinal analysis to assess changes over time, utilize advanced measurement techniques for greater accuracy, control for confounding factors such as age and health conditions, and explore the functional implications of anatomical differences to provide a more comprehensive understanding of their impact.

Acknowledgments

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Ethical Considerations

We express gratitude to cadaver donors and their relatives, acknowledging their crucial contribution to scientific research. Ensuring confidentiality and privacy of the donor information is paramount to protect the dignity of the donors and maintain confidentiality. Adhering to informed consent protocols, even posthumously through donor consent agreements, respects the donors' autonomy and wishes.

Funding

None.

Conflicts of Interest

There are no conflicts of interest.

Authors' Contribution

Study conception and design: Yogesh D and Ashok Kumar Jyothi; data collection: Yogesh D, Praveen Kumar, Amarendar Sura, Swathi Priyadarshini, and Ashok Kumar Jyothi; interpretation of results: Yogesh D, Praveen Kumar, Amarendar Sura, Swathi Priyadarshini, and Ashok Kumar Jyothi; draft manuscript preparation: Yogesh D and Ashok Kumar Jyothi. All authors reviewed the results and approved the final version of the manuscript**.**

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