

The Role of Foramen Magnum Morphometric Measurements in Assessing Human Demographic Parameters: A Narrative Review

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ABSTRACT

Foramen magnum morphometry has been explored as a potential tool for demographic assessment in forensic, anatomical, and radiological fields. Nonetheless, differences in methodology and the characteristics of populations limit the ability to apply findings consistently.

Objective

The objective is to gather current evidence regarding the morphometric characteristics of the foramen magnum and to thoroughly evaluate their relevance for determining sex, estimating age, and understanding cranial base development.

Methods

We conducted a structured narrative review of studies that were published between 2000 and 2026 using PubMed, Scopus, and Google Scholar. We included peer-reviewed articles that reported quantitative morphometric measurements taken from osteological specimens or imaging methods such as computed tomography, cone-beam computed tomography, and magnetic resonance imaging. We obtained details regarding the study's design, the participants involved, the methods employed for measurement, and the demographic relationships. The results were arranged according to themes.

Results

The finding that received the most consistent support was sexual dimorphism. Males displayed significantly larger anteroposterior and transverse diameters, along with a greater calculated area and circumference. CT-based area and circumference measurements were better at distinguishing between variables than isolated linear parameters. Evidence supporting the estimation of adult age was limited, suggesting that the development of the cranial base was completed earlier than expected. Conversely, studies involving children demonstrated measurable differences related to growth. Ratio-based and proportional models remain in their nascent developmental phases and have yet to undergo comprehensive testing by external entities. Common limitations included the specificity of the population studied and the heterogeneity of the methodologies employed.

Conclusion

Foramen magnum morphometry serves as a useful supplementary method for determining an individual's sex; however, it is not particularly effective for estimating their age in adulthood. To enhance its utility across diverse populations, standardized measurement protocols and validation are required for each group.

Introduction

Forensic anthropology, bioarchaeology, and clinical anatomy all depend on being

able to identify people and make demographic profiles of them. Estimating sex and age is the most important aspect of

demographic evaluation, especially when examining broken or partial skeletal remains. The foramen magnum is a unique anatomical and forensic feature in the skull because it is protected at the base of the skull, matures quickly, and is relatively resistant to harm after death. The foramen magnum is the largest aperture at the base of the skull. It lets the medulla oblongata, vertebral arteries, spinal accessory nerves, and their ligaments to pass through. It is often characterized in terms of linear, areal, and shape-based metrics, such as anteroposterior diameter, transverse diameter, perimeter, area, and derived indices. These measurements can be obtained these measurements from dry skulls, cadaver specimens, and computed tomography datasets. Improvements in multidetector computed tomography have enhanced measurement accuracy and repeatability, facilitating in vivo population-based analysis (Goyal et al., 2016), (Muhammad et al., 2023; Uthman et al., 2012).

Researchers have extensively examined sexual dimorphism of the foramen magnum, as the cranial base hardens and alters shape more gradually than other regions of the skull. Many studies using osteology and CT scans show that there are statistically significant differences between males and females. Males consistently have larger anteroposterior and transverse dimensions, as well as a larger foramen magnum (Goyal et al., 2016; Juglan & I.K., 2016; Uthman et al., 2012). Most of the time, these differences are due to differences in the size of the skull and the strength of the bones (Saleh et al., 2019). There is clear proof of dimorphism, but the differences between the sexes are very different in different groups (Zdilla et al., 2017).

Research indicates that discriminant functions developed from one community often exhibit less accuracy when used in another, underscoring population uniqueness as a significant

constraint (Darwish et al., 2014). Consequently, foramen magnum morphometry is becoming increasingly viewed as a secondary tool for determining sex, especially when pelvic or long bone data are not available (Saleh et al., 2019).

Different methods make it much harder to understand sexual dimorphism. Variability in reported classification accuracy is due to differences in landmark definitions, imaging modality, slice orientation, and statistical modeling (Liu et al., 2021; Shearer et al., 2017). Linear measures could not accurately reflect intricate form variations (Christodoulou et al., 2020), whereas ratio-derived factors might enhance discrimination but create more methodological dependencies (Monti & Confalonieri, 2017).

The correlation between foramen magnum size and age is not as well defined as that of sex determination. In terms of development, the foramen magnum grows to almost adult size early in infancy, when the occipital synchondroses fuse (Wilk et al., 2022). As a result, most adult studies indicate weak or absent correlations between foramen magnum size and chronological age (Samara et al., 2017). CT scans of children and adolescents reveal quantifiable changes associated with growth, suggesting that age-related alterations are more pronounced during development than in adulthood (Dulkadir et al., 2025). The foramen magnum isn't very useful for figuring out someone's age, but it's still very important in developmental anatomy because it's close to cranial base sutures and ossification centers. The basioccipital, exoccipital, and supraoccipital parts make up the edges of the foramen magnum. They come together in a way that is easy to see. Alterations in these processes influence the final morphology and dimensions of the foramen magnum, being particularly significant in pediatric imaging and congenital craniovertebral junction anomalies (Wilk et al., 2022; Yadav et al.,

2024). Recent studies have investigated not only the absolute dimensions of the foramen magnum and the entire skull but also their proportional relationships. Research examining the ratios of cranial length to foramen magnum length and cranial breadth to foramen magnum width indicates the existence of consistent proportional patterns indicative of cranial base development (Dulkadir et al., 2025; Ulcay et al., 2021). These ratio-based methods offer novel perspectives; however, they are applicable solely to specific demographics and require additional validation.

Computed tomography has greatly expanded the field of foramen magnum research by enabling accurate imaging of internal bony structures and the analysis of large datasets sourced from historical records (Moodley et al., 2019; Saleh et al., 2019). CT-based morphometry reduces observer bias and facilitates comparisons across various age groups and populations; nonetheless, it is crucial to acknowledge the heterogeneity arising from reconstruction parameters and measurement planes (Avci et al., 2010; Luzzi et al., 2019).

Despite extensive research, the literature on foramen magnum morphometry remains incomplete. Differences in sample makeup, age distribution, sex ratio, and data analysis methods make it hard to compare research. In some instances, results on demographic usefulness are exaggerated, without adequate consideration of population reliance or methodological limitations. A focused narrative synthesis is essential to contextualise current information and elucidate the pragmatic utility of foramen magnum morphometry in demographic evaluation.

This narrative review examines the significance of foramen magnum morphometric measurements for assessing human demographic parameters, focusing on sex determination, age-related correlations, and developmental relationships with cranial base sutures in

anatomical, radiological, and forensic contexts.

METHODS

Design and Justification

This study was conducted as a systematic narrative review. A narrative approach was selected because of the considerable variability across published studies in population characteristics, age distribution, imaging techniques, landmark definitions, statistical modelling, and outcome reporting. The differences in methods and reported parameters made it difficult to perform a quantitative pooling or meta-analysis.

Analysis

We conducted a systematic literature search utilizing PubMed, Scopus, and Google Scholar. The search examined works published between January 2000 and a current or past date (e.g., January 2024). The keywords and their combinations included "foramen magnum morphometry," "foramen magnum CT," "foramen magnum MRI," "foramen magnum CBCT," "sexual dimorphism of the foramen magnum," "foramen magnum age estimation," and "cranial base development related to the foramen magnum."

We manually examined the reference lists of relevant articles to identify additional studies that fulfilled the criteria.

Eligibility Criteria

Studies were included if they:

Reported quantitative morphometric evaluations of the foramen magnum.

Utilised osteological specimens or imaging modalities such as computed tomography (CT), cone-beam computed tomography (CBCT), or magnetic resonance imaging (MRI).

Examined the relationships among sex, age, developmental status, and the morphology of the cranial base.

Were published in peer-reviewed journals in the English language.

Studies were excluded if they:

Focused exclusively on pathological compression or surgical techniques without considering morphometric assessment.

Case reports, conference abstracts, or sources that lacked peer review.

Did not possess any quantifiable morphometric data that could be extracted.

Study Selection and Data Extraction

We examined the titles and abstracts to determine their relevance. We examined the full texts of potentially eligible articles. The data gathered from each study included the following elements: population characteristics, sample size, age range, imaging modality or specimen type, morphometric parameters evaluated, statistical methods employed, and reported demographic correlations.

Data Compilation

Data were systematically categorized into established themes:

Key morphometric parameters

Sexual dimorphism

Variation by age

Models grounded in ratios and proportions

Formation of the cranial base

Due to the differing definitions of measurements and statistical reporting, no combined accuracy metrics were established. Critical appraisal focused on aspects such as population specificity, sample size, clarity of landmark definition, standardization of the imaging plane, and reproducibility of the results.

RESULTS

Morphometric characteristics of the foramen magnum

The literature evaluated used a uniform core set of morphometric characteristics to characterize the foramen magnum. The anteroposterior diameter, defined as the distance between the basion and the opisthion, and the transverse diameter, which is the distance between the broadest lateral edges, are common measures recorded (Rajkumar et al., 2017). Several studies that used CT and MRI also examined the area, circumference, and derived indices of the foramen magnum to facilitate their differentiation (Çelik & Akman, 2023), (Tellioğlu et al., 2017). Radiological investigations consistently found that bone borders were clearer to visualize with radiological investigations than with osteological approaches, which made measurements more reliable.

Sexual dimorphism of the foramen magnum

Sex-related variation constituted the most consistently validated demographic correlation (Samara et al., 2017). Most adult investigations indicated considerably greater anteroposterior and transverse diameters in men relative to women (Kenawy & Mousa, 2022). CT-based studies showed that the size and diameter of the foramen magnum were better at classifying sex than just linear measures. However, the degree of dimorphism differed across groups (Zdilla et al., 2017). Some regional studies found that the differences were smaller or not statistically significant, which shows that the results are specific to each community (Ogolo et al., 2024). The foramen magnum index exhibited variable sexual dimorphism and was often less accurate than absolute measurements (Kenawy & Mousa, 2022).

Variation due to age

There was little evidence that foramen magnum morphometry was related to age in adults (Çelik & Akman, 2023). Most studies on adults have shown that there is little or no association between foramen magnum diameters and chronological age, which

suggests that cranial base growth stops too soon (Çelik & Akman, 2023; Ogolo et al., 2024). Conversely, studies on children and teenagers showed measurable changes in the size of the foramen magnum throughout the early stages of growth, particularly related to the development of the cranial base (Dulkadir et al., 2025). Studies on craniosynostosis indicate alterations in developmental patterns, with the foramen magnum exhibiting reduced dimensions compared to age-matched controls (Skadorwa & Wierzbieniec, 2022).

Ratio and proportion-based analyses

Recent research looked at the relationship between the foramen magnum and the size of the skull as a whole. Studies supporting ratio-based theories, including golden ratio frameworks, have shown enduring proportional tendencies among certain populations and age groups. Nonetheless, these methodologies were ineffective across many groups, and their demographic significance for sex or age evaluation was considered supplementary rather than definitive (Saleh et al., 2019).

Cranial base sutures and developmental anatomy

Table A summary of research that investigated foramen magnum morphometry in connection to population, modality, and demographic results

Study (Author, Year)	Population / Region	Sample Type	Age Group	Modality Method	Morphometric Parameters	Demographic Focus	Key Outcomes	Notes / Limitations
Chethan et al., 2012	Indian	Dry skulls	Adults	Osteological	APD, TD, FMI, shape	Morphology	Wide variation in FM shape, baseline morphometric data	Sex and age not stratified
Juglan et al., 2016	Indian (Gwalior)	Living subjects	Adults	CT	APD, TD, area	Sex	Males showed significantly larger FM dimensions	Population-specific
Uthman et al., 2012	Iraqi	Living subjects	Adults	Helical CT	APD, TD, area, circumference	Sex	Circumference and area provided highest	Limited age range sex

Numerous studies of morphology and pediatric imaging have shown a link between the shape of the foramen magnum and the growth of cranial base sutures (Layton et al., 2022; Rijken et al., 2015). Alterations in the fusion of the occipital synchondrosis and the premature closure of the sutures influenced the morphology and dimensions of the foramen magnum, particularly in instances of craniosynostosis and other developmental abnormalities (Skadorwa & Wierzbieniec, 2022). These findings underscore the importance of developmental context in the analysis of morphometric data, especially among subadult populations.

The collective research indicates that foramen magnum morphometry provides the most compelling evidence for sexual differentiation (Zdilla et al., 2017), has limited utility for adult age estimation (Saleh et al., 2019), and has substantial developmental relevance in pediatric and cranial base disease contexts (Wilk et al., 2022). Methodological variance and demographic distinctiveness persist as substantial constraints on universal application.

							classification accuracy	
Goyal et al., 2016	Indian (Uttar Pradesh)	Living subjects	Adults	CT (16-slice)	APD, TD, FMI	Sex	Significant sex differences in APD and TD, FMI unreliable	FMI weak discriminator
Rajkumar et al., 2017	North Indian	Dry skulls	Adults	Osteological	APD, shape	TD, Sex	Male FM dimensions larger, shape variability noted	Age unknown
Ulcay et al., 2021	Turkish	Mixed	Adults	Anatomical ratios	FM–cranial ratios	Proportionality	Proposed golden ratio–based proportional model	Exploratory
Dulkadir et al., 2025	Pediatric (Turkey)	Living subjects	Children / adolescents	CT	Area, SD, TD	Age development	FM growth patterns differ pre- and post-adolescence	Pediatric only
Skadorwa and Wierzbieniec, 2022	European	Living subjects	Infants	CT	Area, SD, TD, SDI	Development sutures	Reduced FM area and altered growth in craniosynostosis	Pathology-specific
Ogolo et al., 2024	West African	Living subjects	Mixed	MRI	APD, TD, area, FMI	Population variation	Lower FM area and minimal sex difference	Ethno-regional variation
CBCT Review, 2021	Mixed	Review	Adults	CBCT	APD, TD, area	Modality comparison	CBCT provides reliable FM morphometry	Narrative review

Discussion

This review synthesizes the most recent evidence about how foramen magnum morphometry can be used in different demographic groups in both osteological and radiological settings. The results show that the foramen magnum shows measurable sexual dimorphism, but its usefulness depends on the context and the population (Öksüzler et al., 2022).

Determining Sex

Sexual dimorphism remains the most consistently observed demographic correlation (Samara et al., 2017). In many studies that used CT and osteology, males had much larger anteroposterior and transverse diameters, as well as larger

calculated areas and circumferences (Çelik & Akman, 2023; Lyrtzis et al., 2017). Classification accuracy exhibits considerable variation across populations, reflecting differences in the distribution of cranial size and the robustness of skeletal structures (Inskip et al., 2016; Saleh et al., 2019).

Parameters based on area and circumference tend to work better than those based on single linear dimensions because they take into account growth patterns that go in many directions instead of just one (Ajanović et al., 2023). However, derived indices like the foramen magnum index do not always effectively distinguish between groups (Çelik & Akman, 2023;

Darwish et al., 2014). This variability probably reflects both biological diversity and methodological inconsistency in how landmarks are found and how the measurement plane is oriented.

Importantly, many studies show that discriminant functions created based on one ethnic group tend to perform poorly when tested on another group (Darwish et al., 2014). This substantiates that foramen magnum morphometry should not be employed as a universal independent sex predictor. Instead, it ought to be used as an additional parameter, particularly in cases where only partial remains are present and indicators from the pelvis or long bones are unavailable.

Estimating Age

The evidence supporting the use of foramen magnum morphometry for estimating adult age is inadequate (Lucena et al., 2019). The growth of the cranial base mostly stops in early childhood after synchondrosis fusion, which limits changes in size after maturation (Cendekiawan et al., 2010; Sardi et al., 2008). Most research involving adults indicates that there is little to no correlation between morphometric parameters and chronological age (Şengül, 2017).

Conversely, pediatric datasets show measurable changes related to growth, particularly in terms of area expansion and proportional adjustments during both pre-adolescent and post-adolescent stages (Moodley et al., 2019). These findings indicate that the measurement of the foramen magnum is more crucial for assessing developmental stages than for determining the age of adults. Nonetheless, even among pediatric groups, growth patterns require long-term validation before they can be applied in clinical or forensic settings.

Proportional and Ratio-Based Models

Ratio-based methodologies represent an emerging area of research (Landi et al., 2020). Proportional models aim to

minimize variations among individuals and identify structural relationships by adjusting for overall cranial size (Güler & Yılmaz, 2023; Ulcay et al., 2021). Early research suggests that some groups have stable proportional patterns, such as the proposed golden ratio frameworks (Ulcay et al., 2021).

These models are still in the exploratory stage, although they are theoretically sound. Most are based on small sample sizes and have not been tested on people from different groups (Samara et al., 2017). Until they are validated externally across a range of demographic groups, proportional indices should be approached with caution and regarded as additional anatomical descriptors rather than as predictive tools.

Context of Development and Sutures

The shape of the foramen magnum is closely linked to the ossification centers of the cranial base and the fusion of the occipital synchondrosis (Coqueugniot & Minor, 2002; Raguž et al., 2017). Pediatric imaging and craniosynostosis research indicate that modified sutural development directly affects the size and configuration of the foramen magnum (Rijken et al., 2015; Skadorwa & Wierzbieniec, 2022). These findings emphasize the importance of developmental stratification when analyzing morphometric data.

Neglecting sutural status may complicate the interpretation of demographic data, particularly in samples comprising individuals of varying ages or health conditions (Barszcz et al., 2025). Subsequent morphometric studies should include standardized age stratification and, when possible, record sutural fusion status.

Imaging Modality Considerations

Due to its high spatial resolution and ability to reproduce bony landmarks, computed tomography remains the best method for morphometric assessments (Sandeep et al., 2022). Multidetector CT enables you to measure both area and circumference very

accurately using reconstructed planes (Joo et al., 2021; Schlett et al., 2010). CBCT is accurate for maxillofacial applications and exposes the patient to less radiation, but it has a narrower field of view (Alabdulwahid, 2021; Ghamri et al., 2023). MRI is well suited for evaluating soft tissues (Larrivee, 2023), but it is not the best modality for visualising the exact points where bones meet (Fischer et al., 2021). Intermodality discrepancies underscore the need for uniform measuring techniques in dataset comparisons.

Problems:

The main problems with the research are small sample sizes, lack of age breakdowns, inconsistent definitions of key events, and no external validation. Many osteological studies lack validated demographic data, which may lead to classification bias (Tiesler et al., 2017; Wolfhagen, 2023). Additionally, statistical models often focus on a specific population and are seldom subjected to preliminary testing (Calster et al., 2023; Sperrin et al., 2022). The methodological limitations make it clear that the claimed accuracy rates differ significantly and limit their general use.

Consequences

Foramen magnum morphometry provides dependable structural data and indicates a consistent size difference between sexes (Baisakh et al., 2025; Samara et al., 2017). When employed as a secondary part of a whole evaluation framework, its demographic value is most apparent. It doesn't help much with figuring out how old people are, but it does help a lot with developmental problems in kids in craniovertebral settings (Rijken et al., 2015).

Conclusion

This narrative review consolidates the latest research on foramen magnum morphometric parameters and their potential use in assessing human demographic characteristics. Foramen

magnum morphometry is most useful for determining sex (Baisakh et al., 2025), but less useful for estimating age (Samara et al., 2017) and for interpreting cranial base sutures (Coqueugniot & Minor, 2002). In both osteological and radiographic assessments, males consistently exhibit larger foramen magnum measures compared to females. This is notably true for the area, circumference, anteroposterior diameter, and transverse diameter. According to Kenawy and Mousa (2022), metrics based on area and circumference from computed tomography are better at identifying the difference between things than linear measures alone. variable groups have variable levels of sexual dimorphism (Darwish et al., 2014; Zdilla et al., 2017). This shows how important it is to have reference standards that are specific to each group and how dangerous it is to use prediction models across all groups.

On the other hand, there isn't much proof that foramen magnum morphometry can be used to figure out how old an adult is (Samara et al., 2017). The expansion of the cranial base stops early (Samara et al., 2017). Research on children and teenagers demonstrates that the dimensions of the foramen magnum vary significantly throughout growth, which has more relevance for developmental anatomy and growth evaluation than for ascertaining adult age (Moodley et al., 2019; Wilk et al., 2022) (Skadorwa & Wierzbieniec, 2022; Wilk et al., 2022). Changes in the way cranial base sutures grow also affect the shape of the foramen magnum, especially in subadult and pathological groups (Coqueugniot & Minor, 2002). This shows how important it is to think about the setting in which a person grows up when looking at morphometric data.

Cross-sectional imaging, especially computed tomography, has made foramen magnum measurements more accurate and easier to repeat. This means they may now be used on living people as well (Uthman et al., 2012). New proportional and ratio-

based models provide new ways of looking at the shape of the skull base. However, they haven't been tested enough to be used regularly in demographic research yet (Dulkadir et al., 2025; Ulcay et al., 2021).

Foramen magnum morphometry need to be considered an ancillary tool to enhance a thorough demographic evaluation. Its main purpose is to help figure out a person's sex and provide information about their development when regular skeletal indicators aren't accessible or aren't working well. Future research must concentrate on methodological uniformity, population-specific validation, and the amalgamation of developmental and three-dimensional approaches.

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