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# RESEARCH ARTICLE

## MORPHOLOGY AND MORPHOMETRY OF THE FORAMEN MAGNUM: A SYSTEMATIC REVIEW AND META-ANALYSIS OF ANATOMICAL STUDIES

**Marcelo Lucas de Lima Prado[1], Vitória Sobral Machado[1], Esther Andrade de Sá[1], Yasmin Souza Gifoni[1], Maria Clara Sobral de Gois Rosa Dias[1], Iapunira Catarina Sant'Anna Aragão[2], Felipe Matheus Sant'Anna Aragão[3], Francisco Prado Reis[4] and *José Aderval Aragão[1]**

[1]Department of Morphology, Federal University of Sergipe (UFS), Aracaju, SE, Brazil; [2]Postgraduate Program in Endocrinology, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), Rio de Janeiro, RJ, Brazil; [3]Heart Institute (InCor), Hospital das Clínicas, University of São Paulo, São Paulo, SP, Brazil; [4]Medical School, Tiradentes University (UNIT), Aracaju, SE, Brazil

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****Corresponding author:***
***José Aderval ARAGÃO***

### ABSTRACT

This meta-analysis aimed to synthesize available data on the morphology and morphometry of the foramen magnum (FM), identifying population and sexual patterns. Conducted in accordance with PRISMA and Cochrane guidelines, the study included observational research providing FM morphological and morphometric data from cadaveric dissection or imaging in human populations. A search of PubMed, Web of Science, and Scopus yielded 562 records; after screening, 19 articles comprising 3,432 individuals from five continents were selected. Pooled analysis using random-effects models revealed overall adult mean values of 29.458 mm (transverse diameter), 35.217 mm (anteroposterior diameter), and 853.975 mm² (area). Males exhibited larger dimensions than females, though with considerable overlap. Morphological analysis demonstrated predominance of hexagonal (16.8%), pear-shaped (16.4%), and oval (15.8%) configurations. Significant heterogeneity ($p<0.01$) was identified across studies, reflecting methodological and population differences. Findings indicate that while FM dimensions show relative consistency, significant population and sex-related variations exist, precluding universal anatomical standards. The morphological expression did not differ substantially between sexes. This study reinforces the FM's relevance in clinical, surgical, and forensic contexts, particularly for craniocervical approach planning and pathological understanding. Methodological heterogeneity and regional variability necessitate population-specific databases for accurate diagnostic and identification procedures, highlighting the need for standardized future research with diverse population samples. Mini-abstract This meta-analysis synthesizes foramen magnum morphometric data from 3,432 individuals across five continents, revealing population-specific dimensions and predominance of hexagonal, oval, and pear-shaped configurations



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# INTRODUCTION

The foramen magnum (FM), located in the occipital bone, establishes the communication between the cranial cavity and the vertebral canal (Samara *et al.* 2017; Akay *et al.* 2017). Important neurovascular structures pass through this opening, including the medulla oblongata and meningeal structures, rendering the craniocervical region a crucial point of anatomical and functional integration between the central nervous system and the vertebral column (Samara *et al.* 2017; Akay *et al.* 2017). Due to its strategic position, the FM holds relevance in several fields, including anatomy, neurosurgery, radiology, and forensic anthropology (Neely 1992). Beyond its functional importance, the FM exhibits considerable morphological and morphometric variability among individuals and human populations. From a morphological perspective, different shapes have been described in the literature, including oval, round, pear-shaped, and irregular forms, reflecting variations in cranial development and population-specific characteristics (Degno *et al.* 2019). Concurrently, morphometric studies have investigated parameters such as anteroposterior diameter, transverse diameter, and area of the foramen magnum, demonstrating that these measurements can vary significantly between population groups and age ranges (Kumar *et al.* 2022; Degno *et al.* 2019). Several studies demonstrate that these FM dimensions, such as anteroposterior and transverse diameters and total area, exhibit sex-related differences, enabling their use as auxiliary parameters for sex estimation (Gapert *et al*. 2013; Uthman *et al*. 2012), thereby aiding biological identification in osteological and forensic analyses, particularly when other cranial or skeletal regions are absent or damaged (Cui and Zhang 2013). This is due to the anatomical position of the FM at the skull base, which provides relative protection against mechanical damage, meaning it often remains preserved in situations of bone fragmentation compared to other bones in the region (Holland 1989). However, despite the growing number of studies dedicated to the morphological and morphometric analysis of the foramen magnum, much of the research focuses on specific populations (Natsis *et al*. 2013; Kumar *et al*. 2022), hindering a global comparison of results. Therefore, the aim of this systematic review was to synthesize the available data in the literature regarding the morphology and morphometry of the FM, contributing to the identification of population and sexual patterns described in existing studies and providing a more comprehensive understanding of the anatomical variability of the foramen magnum.

# MATERIALS AND METHODS

This systematic review and meta-analysis were conducted in accordance with the guidelines of the Cochrane Handbook for Systematic Reviews of Interventions and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Page *et al*. 2021). The entire planning process and all steps were registered with the International Prospective Register of Systematic Reviews (PROSPERO) under protocol CRD420261349646.

**Eligibility Criteria:** Observational studies (cross-sectional or case series) were included if they provided (1) morphological and morphometric data on the foramen magnum (FM) obtained through cadaveric dissection or imaging examinations, and (2) focused on human populations. Studies conducted on non-human populations, primary studies with insufficient data, single case reports, and review articles were excluded. No restrictions regarding publication date or language were applied.

**Search Strategy and Data Extraction:** The PubMed, Web of Science, and Scopus databases were searched to identify records using the following search strategy: ("foramen magnum" OR "occipital foramen") AND ("anatomical variation" OR variations) AND (cranium OR imaging OR cadaver).

Two independent authors participated in the screening of records and data extraction. The studies were imported from the databases into Zotero software, where deduplication and screening were performed. Subsequently, the selected studies were read in full by two authors to extract their data into an Excel spreadsheet, thereby minimizing bias in data selection. The reference lists of these studies were also examined to identify additional studies that fell within the scope of the review.

**Statistical Analysis:** Random-effects models were used to combine the variables and account for methodological heterogeneity. Data were analyzed using 95% confidence intervals (CIs) and the restricted maximum likelihood (REML) estimator. Statistical analyses were performed using Open Meta Analyst software.

# RESULTS

A total of 562 records were imported from the databases. After the exclusion of 201 records during the deduplication process, 261 records were screened by title and abstract review, resulting in 37 articles selected for full-text reading. Following full-text review, 19 articles were selected for inclusion in the review (Fig. 1). In accordance with PRISMA guidelines, the characteristics of all included studies are summarized in Table 1. Data were obtained from studies conducted across multiple continents, including Europe (Greece, Turkey, Switzerland, United Kingdom), Asia (India, China, Saudi Arabia), Africa (Ethiopia, Nigeria, South Africa), South America (Brazil, Peru), and North America (USA), comprising a total of 3,432 individuals (Table 1).

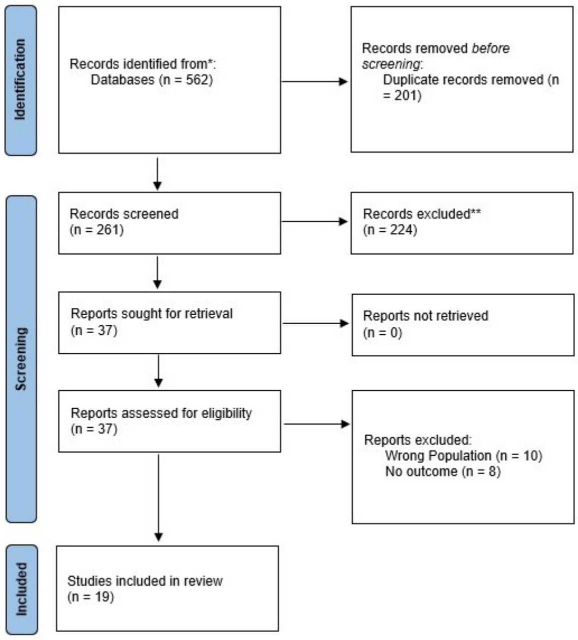


**Fig. 1. PRISMA flow diagram of study selection and screening**

The transverse diameter, anteroposterior diameter, and area of the foramen magnum (FM) were analyzed. The overall adult population means for these parameters were 29.458 mm (95% CI: 28.358–30.558) (Fig. 2A), 35.217 mm (95% CI: 34.231–36.203) (Fig. 2B), and 853.975 mm² (95% CI: 776.918–931.031) (Fig. 2C), respectively. Considering the sex-based division, the female population presented a transverse diameter of 28.868 mm (95% CI: 27.904–29.832) (Fig. 3A), an anteroposterior diameter of 34.284 mm (95% CI: 33.342–35.225) (Fig. 3B), and an area of 756.938 mm² (95% CI: 712.333–801.542) (Fig. 3C). The male population exhibited the following respective measurements: 30.590 mm (95% CI: 29.591–31.589) (Fig. 4A), 35.988 mm (95% CI: 34.887–37.090) (Fig. 4B), and 832.878 mm² (95% CI: 737.252–928.504) (Fig. 4C). The pooled analysis enabled estimation of the proportions of different foramen magnum morphologies. The pear-shaped configuration showed an estimated prevalence of 16.4% (95% CI: 0.7–45.3), corresponding to 75 cases out of 454 evaluated skulls. The oval shape presented a proportion of 15.8% (95% CI: 9.4–23.4), accounting for 348 out of 1,764 skulls. The round shape was observed in 12.1% of cases (95% CI: 6.7–18.7), representing 243 out of 1,764 skulls. The irregular shape yielded a pooled proportion of 10.3% (95% CI: 5.3–16.6), with 270 out of 1,764 cases.

**Table 1 Characteristics of included studies**

| Study (Year) | Country | Population (N) | Age Group | Sex (M/F) |
|---|---|---|---|---|
| Natsis (2013) | Greece | 143 | Adults | 77 / 66 |
| Dulkadir (2025) | Turkey | 201 | Children | 117 / 84 |
| Degno (2019) | Ethiopia | 54 | Adults | NR |
| Avci (2011) | Turkey | 30 | Adults | NR |
| Mehta (2014) | India | 100 | Adults | 53 / 47 |
| Aljarrah (2022) | Saudi Arabia | 472 | Adults | 236 / 236 |
| Kanodia (2012) | India | 100 | Adults | 36 / 64 (CT group) |
| Yataco-Wilcas (2024) | Peru | 17 | Adults | NR |
| Tubbs (2010) | USA | 72 | Adults | 40 / 32 |
| Murshed (2003) | Turkey | 110 | Adults | 57 / 53 |
| Ogolo (2024) | Nigeria | 315 | All ages | 165 / 150 |
| Srivastava (2020) | India | 60 | Adults | 30 / 30 |
| Edwards (2013) | Switzerland | 250 | Adults | 144 / 106 |
| Cui (2013) | China | 276 | Adults | 276 / 0 |
| Whitney (2013) | USA | 523 | Adults | 255 / 268 |
| Gapert (2013) | United Kingdom | 135 | Adults | 69 / 66 |
| Moodley (2019) | South Africa | 50 | Adults | NR |
| Kumar (2022) | India | 314 | NR | NR |
| Aragão (2014) | Brazil | 110 | All ages | 66 / 44 |

M = Male, F = female, NR = Not reported, N = Total number of subjects

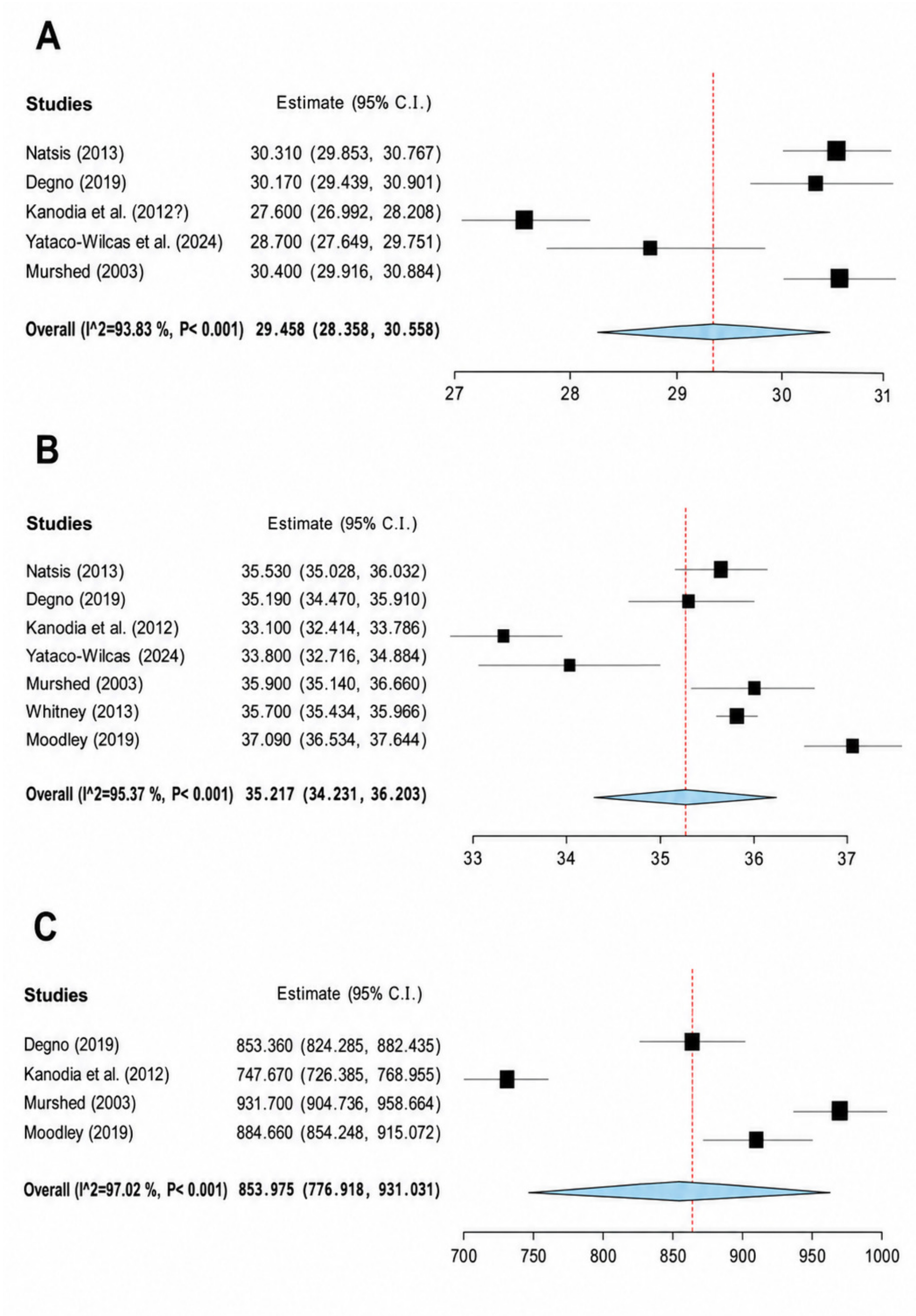


**Fig. 2 Pooled estimates for the overall population: (a) width; (b) length; (c) area**

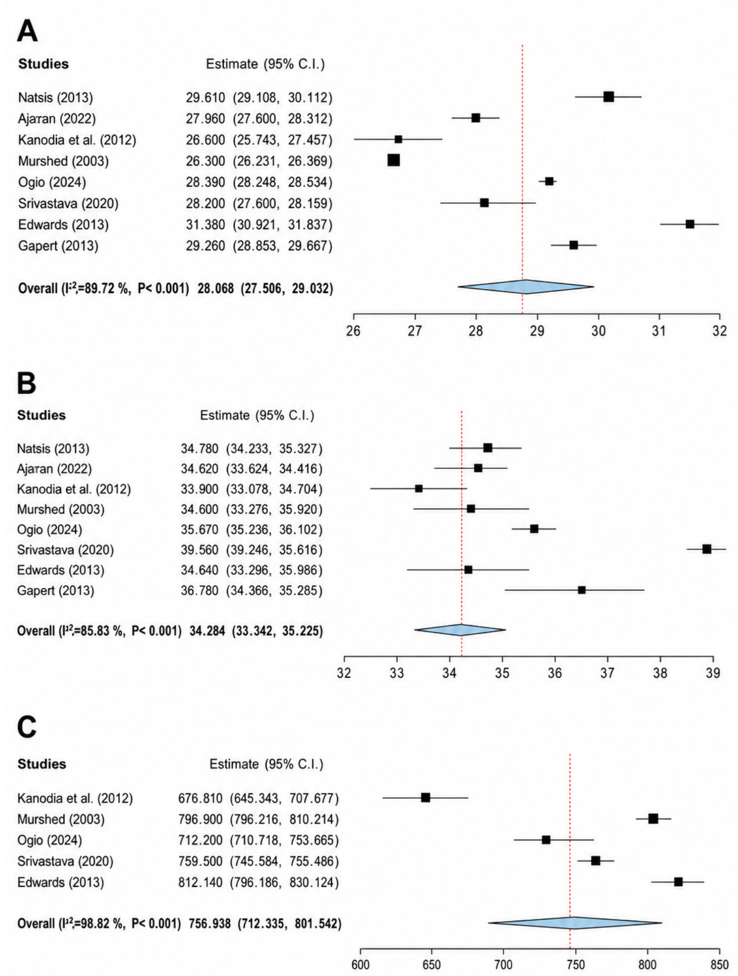


**Fig. 3 Pooled estimates for the female population: (a) width; (b) length; (c) area**

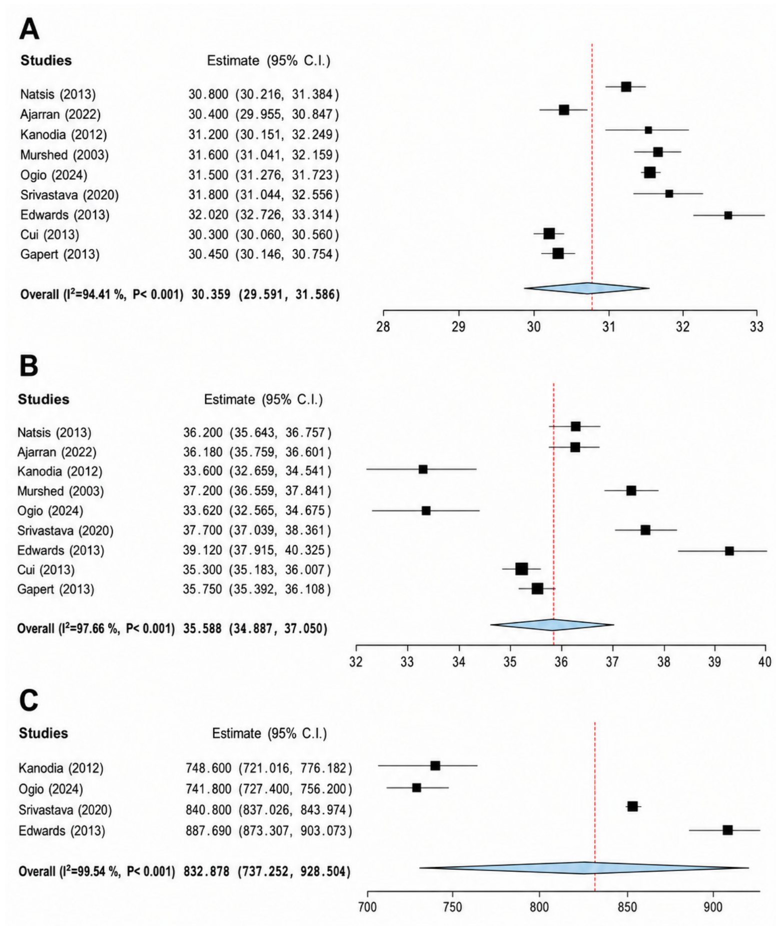


**Fig. 4 Pooled estimates for the male population: (a) width; (b) length; (c) area**

**Table 2. Prevalence of foramen magnum morphological shapes across included studies**

| Study (Year) | Sex | Two Semicircles | Pear | Oval | Egg | Round | Rhomboid | Irregular | Triangular | Tetragonal | Pentagonal | Hexagonal | Rectangular | Drop Shaped |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Natsis (2013) | **Overall** | 37 | 32 | 21 | 30 | 2 | 20 | 1 | - | - | - | - | - | - |
| | **Female** | 22 | 15 | 11 | 12 | 0 | 6 | 0 | - | - | - | - | - | - |
| | **Male** | 15 | 17 | 10 | 18 | 2 | 14 | 1 | - | - | - | - | - | - |
| Dulkadir (2025) | **Overall** | 66 | 2 | 26 | 15 | 10 | 0 | 10 | 1 | 24 | 1 | 31 | - | 15 |
| | **Female** | 26 | 0 | 12 | 7 | 4 | 0 | 3 | 0 | 11 | 0 | 12 | - | 9 |
| | **Male** | 40 | 2 | 14 | 8 | 6 | 0 | 7 | 1 | 13 | 1 | 19 | - | 6 |
| Degno (2019) | **Overall** | - | - | 10 | 11 | 12 | - | 7 | 2 | - | 6 | 4 | 2 | - |
| Avci (2011) | **Overall** | - | - | - | 17 | - | - | - | - | - | - | - | - | - |
| Aljarrah (2022) | **Overall** | - | - | 72 | 27 | 35 | - | 158 | - | 15 | 20 | 145 | - | - |
| | **Female** | - | - | 35 | 18 | 21 | - | 71 | - | 8 | 11 | 72 | - | - |
| | **Male** | - | - | 37 | 9 | 14 | - | 87 | - | 7 | 9 | 73 | - | - |
| Murshed (2003) | **Overall** | - | - | 9 | 7 | 24 | - | 22 | - | 14 | 15 | 19 | - | - |
| Srivastava (2020) | **Overall** | - | - | 17 | 2 | 2 | - | 4 | - | 14 | 4 | 17 | - | - |
| | **Female** | - | - | 7 | 0 | 2 | - | 3 | - | 6 | 2 | 10 | - | - |
| | **Male** | - | - | 10 | 2 | 0 | - | 1 | - | 8 | 2 | 7 | - | - |
| Edwards (2013) | **Overall** | - | - | 61 | 8 | 65 | - | 31 | - | 11 | 21 | 41 | - | - |
| | **Female** | - | - | 28 | 5 | 29 | - | 13 | - | 3 | 11 | 15 | - | - |
| | **Male** | - | - | 33 | 3 | 36 | - | 18 | - | 8 | 10 | 26 | - | - |
| Cui (2013) | **Male** | - | - | - | - | - | - | - | - | - | - | - | - | - |
| Moodley (2019) | **Overall** | - | - | 1 | 3 | 5 | - | 5 | - | 7 | 8 | - | - | - |
| Kumar (2022) | **Overall** | - | - | 125 | 5 | 71 | - | 25 | - | 38 | 17 | 33 | - | - |
| Aragão (2014) | **Overall** | - | 41 | 6 | - | 17 | - | 7 | - | 12 | 3 | 10 | - | - |
| | **Female** | - | 21 | 3 | - | 6 | - | 2 | - | 2 | 0 | 7 | - | - |
| | **Male** | - | 20 | 3 | - | 11 | - | 5 | - | 10 | 3 | 3 | - | - |

Less frequent morphologies included the tetragonal shape, with a prevalence of 10.2% (95% CI: 6.3–15.0), based on 135 out of 1,567 skulls; the egg-shaped form, showing a prevalence of 10% (95% CI: 3.7–18.7), with 125 out of 1,684 specimens; and the pentagonal shape, estimated at 6.3% (95% CI: 3.3–10.1), with 95 out of 1,621 specimens. Finally, the hexagonal shape presented a proportion of 16.8% (95% CI: 11.9–22.4), corresponding to 311 out of 1,621 skulls. Significant heterogeneity was identified ($p < 0.01$), evidencing substantial inconsistency in the magnitude or direction of effects among the studies. The high $I^2$ value indicates that most of the observed variability arises from true differences between studies rather than from chance. The prevalence of the different FM shapes reported in the articles is summarized in Table 2. The most frequent configurations include two semi-circumferences, oval, round, irregular, pentagonal, tetragonal, and rhomboid shapes.

# DISCUSSION

The study of morphological variables of the foramen magnum (FM) is of fundamental importance for a better understanding of craniocervical junction pathologies and for optimizing surgical procedures in this region, aiming to minimize potential damage to the involved tissues (Ogolo *et al*. 2024; Demir *et al*. 2023).

In this context, the present article highlighted the morphological and morphometric differences of the FM, particularly considering sex-based variation, in addition to comparing findings reported in studies conducted across different countries, seeking to ensure that the research encompasses populations with diverse ethnological characteristics (Table 1). The dimensions of the FM exhibit relative consistency, although with variations among populations and measurement methods. In morphometric terms, mean anteroposterior diameter values of approximately 34–34.5 mm and mean transverse diameter close to 29 mm were observed in adult skulls, as described in classical osteological analyses (Avci *et al*. 2011; Berge and Bergman 2001). The FM area also presents considerable variation, with an approximate mean of 758.71 mm² when calculated using image analysis software, although higher mean values may be achieved depending on the formula employed, as demonstrated by the Radinsky and Teixeira formulas (Aragão *et al*. 2020). Regarding morphology, different studies indicate a predominance of oval or ovoid shapes, with round, tetragonal, pentagonal, or irregular forms also being described, evidencing the broad anatomical variability of this structure (Dulkadir *et al*. 2025; Avci *et al*. 2011). Furthermore, some authors report the presence of asymmetries or irregularities in a small proportion of specimens, a finding that reinforces the morphological complexity of the occipital bone region (Avci *et al*. 2011).

When elaborating a comparative table with information from all selected studies, it was observed that there was no significant variation in the morphological expression of the FM between sexes, as both present a predominance of the same shapes. This result is consistent with the most frequently reported finding in the literature (Dulkadir *et al*. 2025; Edwards *et al*. 2013), although it is necessary to acknowledge the existence of studies that point to pronounced sexual dimorphism regarding FM shape (Wang *et al*. 2026). The diversity of data obtained in this review evidenced that population and regional factors exert a significant influence on FM dimensions and morphology (Natsis *et al*. 2013; Mehta *et al*. 2014; Moodley *et al*. 2019). By encompassing studies conducted in different countries and regions, including five continents (Africa, North America, South America, Asia, and Europe), it becomes possible to observe a representation of varied ethnological characteristics that directly impact skull base anatomy (Cui and Zhang 2013). The main impact of this inter-locality variation is the impossibility of establishing a universal anatomical standard, as measurements considered normal in one population may not be applicable to another without compromising diagnostic accuracy (Natsis *et al*. 2013; Mehta *et al*. 2014; Moodley *et al*. 2019). Thus, it is concluded that regional heterogeneity requires both clinical and forensic practice to utilize population-specific databases, aiming to ensure safety in surgical procedures and accuracy in identification processes (Moodley *et al*. 2019; Edwards *et al*. 2013). Therefore, these findings reinforce that geographic variability is a determining factor that demands an individualized clinical approach and the development of further research with broad and diverse population samples.

In the context of sexual dimorphism and population differences, several studies indicate that FM measurements may present statistically significant differences between males and females, although there is considerable overlap between the values observed in both sexes, which limits their isolated use for sex determination (Edwards *et al*. 2013; Toneva *et al*. 2018). The accuracy for sex estimation based on these dimensions is typically moderate, with values close to 66–67% when multiple variables are analyzed together (Edwards *et al*. 2013). Moreover, investigations in specific populations demonstrate that population and regional factors may influence these measurements. For example, studies in Chinese populations have demonstrated correlations between FM dimensions and anthropometric characteristics such as stature, albeit with variable intensity (Cui and Zhang 2013). Similarly, analyses based on tomographic images in children and adolescents indicate morphological and dimensional variations throughout development, evidencing that age-related and population factors may contribute to the observed anatomical diversity (Dulkadir *et al*. 2025). These findings reinforce the importance of considering population and methodological differences in the morphological and morphometric interpretation of the FM, particularly in anthropological, forensic, and clinical applications. The morphological variability of the FM, represented in this study by the predominance of oval (20.12%), hexagonal (17.35%), and grouped irregular shapes (15.60%), constitutes a determining factor for understanding craniocervical junction pathologies. The identification of these shapes and their anatomical variations, such as the presence of asymmetries, carries direct clinical implications for the diagnosis of compressive conditions and malformations of the occipital region (Kumar *et al*. 2022; Edwards *et al*. 2013). In this regard, the morphometric detailing presented, with observed mean diameters of 35 mm (AP) and 29 mm (transverse), proves indispensable for the optimization and planning of surgical procedures, with the objective of minimizing iatrogenic damage to tissues in the area. The correlation between these shapes and FM dimensions is fundamental for defining neurosurgical approaches, such as the transcondylar approach, in which the specific morphology of the skull base determines the feasibility and safety of the surgical corridor (Dulkadir *et al*. 2025; Moodley *et al*. 2019). Finally, the existence of less common variations and irregular forms found expressively reinforces the need for individualized and precise anatomical assessment, an essential condition for the success of interventions at the craniovertebral junction.

The clinical relevance of FM morphometry extends to several pathological conditions. In achondroplasia, the most common form of dwarfism, foramen magnum stenosis represents a life-threatening complication. Zhang *et al.* (2023) recently characterized the pathogenesis of severe FM stenosis using CT, revealing that patients with grades 3 and 4 of the achondroplasia foramen magnum stenosis (AFMS) scale present a surface area 3.4 times smaller than age-matched controls (mean sagittal diameter: 16.2 ± 2.4 mm vs. 31.7 ± 2.4 mm in controls, $p < 0.001$). The study identified premature fusion of the anterior and posterior interoccipital synchondroses and the presence of opisthion bone spicules projecting into the FM, creating characteristic crescent and cloverleaf shapes (Zhang *et al.* 2023). These findings are crucial for quantitatively evaluating emerging medical therapies for achondroplasia. In Chiari type I malformation, patients with non-syndromic craniosynostosis exhibit significantly reduced FM anteroposterior diameter (33.4 mm vs. 36.7 mm in controls, $p = 0.023$) (Leikola *et al.* 2012). Additionally, in patients with Chiari type I and hypoplastic posterior fossa, tonsillar descent correlates negatively with posterior fossa height ($r = -0.498$, $p \leq 0.001$) and clivus length ($r = -0.325$, $p \leq 0.001$) (Nair and Rajshekhar 2022), highlighting the complex interplay between FM dimensions and craniovertebral junction pathology (Friedlander 2024).
Beyond anatomical description, FM morphometry carries direct surgical implications. Muthukumar *et al.* (2005) demonstrated that the occipital condyle can be safely drilled up to 12 mm from its posterior margin before encountering the hypoglossal canal, a critical parameter for the transcondylar approach to craniocervical junction pathologies. Occipital condyle protrusion into the FM occurs in 20–86.7% of skulls, significantly influencing surgical corridor planning (Natsis *et al.* 2013; Muthukumar *et al.* 2005). The transcondylar approach, frequently employed for lesions of the anterior craniocervical junction, requires precise knowledge of FM dimensions and condylar anatomy to minimize iatrogenic neurovascular injury (Natsis *et al.* 2013; Page *et al.* 2021). Three-dimensional CT-based analysis has further refined surgical planning by identifying eight main FM morphological types: round (18.8%), two semicircles (17.8%), ovoid (14.9%), hexagonal (13.9%), tetragonal (10.9%), oval (10.9%), pentagonal (8.9%), and irregular (4%) (Göçmez *et al.* 2014). This morphological diversity reinforces the necessity for individualized preoperative assessment.

Among the limitations identified in the analyzed studies, methodological differences between research projects stand out, such as the use of dry skulls, tomographic images, or digital photographs, as well as the use of different calculation and measurement methods for FM dimensions, which may hinder direct comparison between results. Some investigations also presented sample limitations, including populations restricted to certain groups or an absence of sex balance, as observed in samples composed only of male individuals or with a reduced number of participants. Additionally, the morphological variability of the FM itself, including cases of asymmetry or irregular shapes, may hinder the standardization of morphological classifications and reduce the precision of comparative analyses. Thus, future studies should seek broader and more diverse population samples, standardization of measurement methods, and greater integration between morphometric, morphological, and imaging techniques, with the purpose of improving the understanding of anatomical variations of the FM and their potential for application in anthropological, clinical, and forensic contexts.

**Declarations**

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**Competing interests** The authors have no relevant financial or non-financial interests to disclose.

**Ethics approval** This systematic review was registered with PROSPERO (CRD420261349646). The study involved analysis of previously published data and did not require institutional ethics approval. All included studies had obtained appropriate ethical clearance from their respective institutions.

**Consent to participate** Not applicable (this study is a systematic review and meta-analysis of published data).

**Consent to publish** Not applicable.

**Data availability** All data generated or analyzed during this study are included in this published article and its supplementary information files.

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