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GEOMETRIC MORPHOMETRIC AND VOLUMETRIC ANALYSIS OF LUMBAR VERTEBRAE FOR FORENSIC ANTHROPOLOGY AND CLINICAL APPLICATIONS: A MINI REVIEW

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ABSTRACT

Geometric morphometric and volumetric analysis are important methods to analyse bone shape, size, and structural variations among populations, sexes, and ages. Geometric morphometric methods use two- or three-dimensional landmark coordinates to study the shape and form of biological or geometric structures. Volumetric analysis aims to determine the density of the bone or structure in three dimensions. This article is a review of 12 studies that have been done regarding the morphometric and volumetric analysis of lumbar vertebrae, and how they can be applied to forensics and clinical application. Google Scholar and PubMed were used to search for articles from (2010-2024) using Lumbar Vertebrae, Geometric Morphometrics, Volumetric Analysis, Forensic Anthropology, and Spinal Surgery keywords. Medical research shows, the size of lumbar vertebrae males have bigger vertebrae than females. Age, ethnicity, and morphometric data are crucial in designing implants for forensic anthropology and spinal surgery. They play an important role in improving clinical outcomes through CT-based models and 3D printing. These studies highlight the importance of morphometric data for understanding spinal anatomy and enhancing preoperative planning. This paper applies population data to refine morphometric techniques used in both fields.

Introduction

Geometric morphometric and volumetric analysis represent tools for assessing shape and anatomical structure including the lumbar vertebrae. The lumbar vertebrae support the vertebral column and protecting the cord. Such differences in the shape and size of the lumbar vertebrae may originate from age, sex, and populations with specific morphological variations, which can be very important in different areas, such as forensic anthropology and clinical medicine (Slice, 2007). In forensic anthropology, the shape and structure of bones examined with the help of the GM technique help in providing individual characteristics of identification and biological profile reconstruction. On other hands, volumetric analysis may be used in the quantification of bone density and pathological changes across the thickness or volume of bones (Bookstein, 1997).

In clinical cases, geometric morphometric and volumetric analyses have thus been performed to diagnose and monitor degenerative disc disease, scoliosis, and spinal stenosis amongst others that affect the lumbar spine (Adams & Dolan, 2005). The capturing of the complex three-dimensional shape data provides a more detailed assessment of anatomical changes that may form the basis for the development of targeted therapeutic approaches. Further, volumetric data allow the evaluation of bone quality and density, which is useful in studies related to osteoporosis-related diseases. Such analyses can enhance preoperative planning and postoperative assessment in spinal surgeries by giving the surgeon accurate anatomical information. (White & Panjabi, 1990).

The geometric morphometric (GM) method is often used by forensic anthropologists to estimate age, sex, and ancestry from skeletal remains. In this technique, a landmark-based application was used to analyze the shape of bones that can reveal morphological variations related to the population (Zelditch, Swiderski, & Sheets, 2012). Volumetric analysis is utilized to determine the specificity of the vertebrae for understanding the circumstances surrounding death, especially in cases involving trauma (Ogden, 2000). GM and volumetric methods enhance the ability to accurately identify human remains and give valuable information for forensic investigations.

The lumbar spine is very important because it does a lot of movement, it carries a lot of weight, and it also protects the spinal cord (Boszczyk et al., 2001). Morphometrics, one of branches of morphology, that uses statistical procedures to analyze variability in the shape and size of organisms and organs (Reyment, 2010) (Zelditch et al., 2004) . It focuses on the study of biological forms' size and shape components and their variation in the population. Morphometric analysis requires describable and repeatable terms to represent shape variation (Reyment, 2010).

Forensic anthropologists and clinicians use morphometric and volumetric analysis of lumbar vertebrae for many purposes, from identifying a person in a forensic case to preparing for surgical procedures. This paper aims to survey articles that use geometric morphometrics and volumetric analysis to study variation among populations, sexual dimorphism, and age-related alterations in the lumbar spine.

Methodology

This narrative review aimed to identify research studies that focused on using morphometric and volumetric analysis of lumbar vertebrae for biological profiling and its clinical application. Pubmed and Google Scholar were used to search for the articles from health science journals published between 2010 and 2024. The findings were taken from articles written in English, including their summaries. The chosen studies used different methods to analyze the shapes of human vertebrae for determining gender, age, and gender such as X-ray, CT scans, MRI, and examining dry bones.

The review included articles that had undergone three stages. Initially, the title screening was conducted to ensure that unsuitable articles were not included. The remaining articles' abstracts were analyzed next, and any that didn't meet the criteria were excluded. Excluded articles were reviews, news, editorials, letters, or case reports. Finally, the other papers were screened for any that were not within the scope of the literature and the duplicates were removed.

Almost all studies used landmark-based techniques of shape analysis, in which precise anatomical measures were taken to compare different populations and age groups. The correlation between these findings and statistical analyses was established through the use of sexual dimorphism, population variation based on age-related degenerative changes.

Results and Discussion

This study synthesized morphometric data from various studies focusing on the lumbar vertebrae across different populations and genders. This result section highlights the findings from each study, focusing on the morphometric data, differences between genders, and implications for surgery and spinal implants (Table 1). The studies examined offer comprehensive knowledge of vertebral morphometry and the influence of sexual dimorphism across diverse populations. The outcomes collectively highlight several significant aspects of the variability in vertebral dimensions influenced by gender, demographic history, and chronological age, as well as their implications for both scientific and medical research.

In the literature, there appears to be sexual dimorphism: males always have a larger number of spine sizes than females. The L1 vertebra is notably distinct from females, as per Bozdag & Karaman (2021), and Turkish males possess larger male vertebrae in all areas. The study highlights this feature. A similar pattern was observed in other Western populations. Grivas et al., (2019) found marked differences in both the male and female dimensions of the Greek population's bodies and those of their females.

Males in all populations tend to have larger vertebral features, which suggests a common biological tendency that is influenced by both genetics and environmental factors. However, these studies also point out the need for population-specific data when estimating sex from vertebral measurements, as absolute sizes and predictive models vary across ethnic groups. According to Zlolniski et al., (2017), the Mediterranean sample demonstrated greater lumbar lordosis and spine curvature in comparison to the South African sample, indicating that sexual dimorphism can occur independently in different populations.

Another important factor is the variability that exists between populations, not just sex differences. According to Alam et al., (2014), the dimensions of the lumbar vertebrae in Pakistani and Indian populations were similar but not significant, and different from those of Iranian, Israeli, or American populations. The values were compared in a study on cervical spines by researchers at Qil International (Kostan). Vertebral morphology is thought to be affected by population-specific genetic backgrounds, lifestyle, and environmental factors. The impact of inter-population differences is significant, not only for forensic anthropology but also for clinical purposes. In forensic contexts, it is suggested that vertebral morphometry for sex estimation or identification may need to be modified for different populations.' The clinical application of the findings underscores the significance of adjusting surgical interventions like pedicle screw placement and vertebral augmentation to the distinct physical traits of those patients. Additionally, Indian lumbar vertebrae are compared to Western and other Asian populations, as evidenced by Singh et al., (2022), who argue that spinal surgeries should consider population differences, particularly when designing implants like pedicle screws.

Studies have investigated the impact of age on vertebral morphometry, and they suggest that changes in vertebrate dimensions may affect both forensic investigations and clinical procedures. Azu et al., (2016) demonstrated that age has a significant impact on specific vertebral measurements in determining population sizes, indicating that vertebrate dimensions can change throughout time. This discovery is especially important for the forensic context where it may not be possible to accurately estimate how many sex individuals are, given the lack of careful age consideration. This age-related variation is of clinical importance, especially in ageing populations where degenerative changes to the vertebral column are common. Observing how the size of each vertebra is different with age can assist in planning surgery, especially for older people and may help design age- appropriate spinal implants or support systems.

Vertebral morphology can be examined using volumetric and stereological techniques, as well as linear measurements of vertebrae. Karabekir et al., (2011) and Limthongkul et al., (2010) are volumetric studies that highlight the significance of measuring vertebral body volumes and intervertebral disc in spinal structure. Accurate measurements in clinical settings, including augmentation and vertebral surgery, are

crucial to prevent complications such as cement leakage during kyphoplasty and other procedures. Moreover, an accurate understanding of the size of your body is crucial to filling well cement.

Another aspect of sexual dimorphism is also examined through volumetric measurement. The use of linear measurements like vertebral height or pedicle dimensions consistently exposes the gender distribution, but volumetric data can provide a more detailed representation of the overall size and capacity of each vertebra, which may improve sex estimation models. Volumetric methods may be supported by traditional morphometric approaches, as Karabekir et al., (2011) found no significant differences between males and females in terms of vertebral body volumes except at L1.

Implications for Forensic and Clinical Practice

The results hold both forensic and clinical significance. Studies conducted in forensic anthropology confirm the usefulness of vertebral morphometry for estimating sex, especially when combined with population-specific data. The accuracy of sex prediction in studies such as Bozdag and Karaman (2021) and Grivas et al., (2019) is supported by the evidence that vertebral dimensions are reliable for forensic identification purposes. Despite this, the substantial inter-population disparities, as observed by Alam et al., (2014) and Singh drew attention to the need for creating regionally tailored models for forensic purposes.

The direct use of morphometric and volumetric data in spinal surgery, particularly for implant placement, such as pedicle screws, is prevalent in clinical practice. Grivas et al., (2019) state that the pedicle dimensions are a crucial factor in surgical planning, while Limthongkul et al., (2010) suggest that volumetric data can assist in determining the appropriate amount of material for vertebral augmentation. Also, findings of sexual dimorphism and age-related changes can inform personalized surgical procedures that are tailored to the patient's specific anatomy.

Further studies are needed to explore ways of using morphometric and volumetric data to improve models used in clinical trials for sexual estimation. The reason is that the integration of 3D geometric morphometrics and machine learning-based models, new imaging techniques could potentially enhance both clinical and scientific assessment with improved accuracy and efficiency. Additionally, broadening research to encompass more diverse populations, including those with subsets of ethnic backgrounds, would facilitate the development of morphometric databases that can be used worldwide.

Sexual Dimorphism

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Age-Related Variations

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Volumetric and Morphometric Approaches

Vertebral morphology can be examined using volumetric and stereological techniques, as well as linear measurements of vertebrae. Karabekir et al., (2011) and Limthongkul et al., (2010) are volumetric studies that highlight the significance of measuring vertebral body volumes and intervertebral disc in spinal structure. Accurate measurements in clinical settings, including augmentation and vertebral surgery, are crucial to prevent complications such as cement leakage during kyphoplasty and other procedures. Moreover, an accurate understanding of the size of your body is crucial to filling well cement.

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Future Research Directions

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Table 1. Summary of Studies Included in the Review based on PICO Framework

Study	Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
Zlolniski et al. (2017)	Mediterranean (Spain & Israel) and South African adults (31 participants)	3D geometric morphometric analysis of lumbar vertebrae using CT images	Sexual dimorphism and genetic variation between populations	Mediterranean individuals showed greater lumbar lordosis and curvature. Female vertebrae were more elongated, demonstrating significant sexual dimorphism
Bozdag and Karaman (2021)	241 Turkish adults (121 females, 120 males)	CT-based 3D morphometric measurements of the L1 vertebra	Male versus female vertebral morphometry	Males had significantly larger vertebral measurements. Multivariate analysis achieved a sex classification accuracy of 72.6%
Grivas et al., (2019)	100 Greek adults (79 males, 21 females) without spinal pathology	CT morphometric analysis of thoracolumbar and lumbar vertebrae (T9–L5)	Male versus female morphology and comparison with Western populations	Significant sex-related differences were observed in vertebral and pedicle dimensions, providing useful information for spinal surgery and pedicle screw selection
Singh et al., (2022)	Indian adults (20–40 years) with no spinal pathology	CT morphometric assessment of lumbar vertebral body and pedicle dimensions	Comparison between genders and different populations	Morphometric differences were identified across populations and between sexes, supporting the design of spinal implants and surgical planning
Alam et al., (2014)	Pakistani adults (18–60 years) undergoing lumbar CT examination	Thin-slice CT morphometric analysis of lumbar vertebrae	Male versus female measurements and comparison with Pakistani, Indian, Iranian, American, and Israeli populations	Males demonstrated larger vertebral dimensions. Significant differences were observed among several populations, although Pakistani and Indian populations showed similar measurements

Table 1. Summary of Studies Included in the Review based on PICO Framework (*continued…*)

Study	Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
Atta-Alla et al., (2014)	Lebanese females aged 18–22 years without spinal disorders	Radiographic assessment of lumbar vertebrae, intervertebral discs, and lumbar lordosis	Observational evaluation across lumbar vertebral levels	Vertebral body height and pedicle dimensions increased progressively from L1 to L5. Consistent lumbar lordosis and inter-pedicular relationships were also identified
Azu et al., (2016)	South African skeletal sample comprising 170 individuals (103 males, 67 females)	Morphometric measurements of lumbar vertebrae using digital calipers	Male versus female dimensions and age-related variation	Significant sex differences were observed at selected lumbar levels, with several measurements showing age-related correlations. Baseline morphometric data were established for clinical practice
Güleç et al., (2017)	240 adults who underwent lumbar 3D-CT examination	3D-CT morphometric measurements of pedicle dimensions and vertebral parameters	Comparison according to sex, age, and height	Significant differences were identified in pedicle diameter and axis length according to sex, age, and height. Findings support appropriate pedicle screw selection for lumbar surgery
Karabekir et al., (2011)	100 dry lumbar vertebrae from adult cadavers and MRI scans of 21 healthy adults (11 males, 10 females)	Stereological morphometric analysis of lumbar vertebrae (L1–L5), vertebral bodies, pedicles, and intervertebral space volumes using MRI and cadaveric specimens	Comparison between males and females and across lumbar vertebral levels	No significant sex differences were found except for the anterior height of L1. Variations were observed in vertebral body and intervertebral space volumes
Gocmen-Mas et al., (2010)	25 healthy adults (13 males, 12 females), aged 22–49 years	MRI-based stereological morphometric analysis of lumbar vertebrae (L1–L5) and intervertebral discs, including vertebral body and disc dimensions	Comparison of morphometric measurements between males and females	Established baseline morphometric data for vertebral bodies and intervertebral discs, supporting surgical planning and implant sizing

Table 1. Summary of Studies Included in the Review based on PICO Framework (*continued…*)

Study	Population (P)	Intervention (I)	Comparison (C)	Outcome (O)
Limthongkul et al., (2010)	40 healthy adults (20 males, 20 females), aged 18–50 years, with no spinal pathology	CT-based volumetric analysis of thoracic and lumbar vertebrae to determine vertebral body volume and safe working distances for vertebral augmentation	Comparison between thoracic and lumbar vertebrae and between male and female participants	Vertebral body volume increased from T1 to L4, with L5 slightly smaller than L4. Findings support optimal cement volume selection and safer vertebral augmentation procedures
Kanawati et al., (2021)	Six human cadaveric lumbar spines	Comparison of manual measurements, CT-based models, and 3D-printed lumbar vertebral models	Comparison between actual vertebrae, CT-based models, and 3D-printed models	No significant differences were found for most measurements. CT-based models showed high accuracy and may be used for anatomical replication and surgical planning

Conclusion

The use of volumetric analysis in this field enhances the understanding of morphometric data and its relevance to surgical procedures. These models need to be improved, further imaging methods should be developed, and more research needs to focus on the genetic-environmental interactions affecting vertebral development. Animal studies must take into account this aspect as well.

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