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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.

Keywords: *Lumbar Vertebrae, Geometric Morphometrics, Volumetric Analysis, Forensic Anthropology, Spinal Surgery*

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 a. (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 & Co. (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.

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Population-Specific Variability

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Age-Related Variations

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Volumetric and Morphometric Approaches

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Future Research Directions

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Table 1: The summary of the articles is presented in Table 1 into four categories: population, intervention, comparison and outcome

	STUDY/PICO	P (Population)	I (Intervention)	C (Comparison)	O (Outcome)
1	(Zlolniski SL et al., 2017)	The study analyzed 390 semi landmarks of the CT scan of lumbar spine of seven males, nine females from a Mediterranean population (Spain, Israel) and seven males, eight females from a South African population.	The research focused on using 3D geometric morphometrics to analyze the 3D morphology of the lumbar spine in selected population	Sexual dimorphism and variation in genetic backgrounds were considered as factors influencing lumbar vertebral morphology in the study	The study found that the Mediterranean sample had greater lordosis and lumbar spine curvature, while sexual dimorphism significantly influenced lumbar spine variation, with female vertebrae being more elongated.
2	(Bozdag & Karaman, 2021)	The study population consists of 241 Turkish individuals (121 females and 120 males) who had CT scans for sex estimation	Computed tomography (CT) scan-based 3D modeling and morphometric measurements of the L1 vertebra. Twenty-two linear measurements were taken to evaluate sex differences.	Morphometric measurements between males and females to identify statistically significant differences and predict sex based on L1 vertebral measurements, and intra- and inter-observer measurement consistency was	Males exhibited significantly larger measurements than females in most parameters, with prediction rates for sex classification ranging from 50.2% to 73.9%, depending on the discriminant function analysis. Multivariate analysis resulted in a correct prediction rate of 72.6% when all variables were included.

				calculated.	
3	(Grivas et al., 2019)	Adult Greek individuals (100 total; 79 males, 21 females), aged 33 to 87 years (mean 70 ± 8.73 years), without spinal pathology.	Morphometric analysis of thoracolumbar and lumbar vertebrae (T9–L5) using computed tomography (CT) scans. Measurements included anterior vertebral body height (AVBH), posterior vertebral body height (PVBH), pedicle height, pedicle width, pedicle axis angle (PAA), and postero-anterior trajectory length of the pedicle (PTLP).	Comparison of morphometric characteristics between males and females in the Greek population, as well as with morphometric data from other Western populations.	A morphometric database for thoracolumbar and lumbar vertebrae in the Greek population. Findings highlight significant sex-dependent differences in vertebra and pedicle dimensions, with implications for the selection of transpedicular screws and operative planning. Additionally, pedicle dimensions (especially at T9 and T10) may influence surgical decisions.
4	(Singh et al., 2022)	Indian population aged 20-40 years with no gross spinal pathology, undergoing computed tomographic (CT) evaluation for abdominal/genitourinary complaints.	Computed tomography morphometry of the lumbar spine, specifically measuring vertebral body and pedicle dimensions	Comparison of lumbar spine morphometric data with different populations (Western, other Asian populations) and between genders (male vs. female).	Determination of differences in vertebral body and pedicle dimensions across populations and genders, with implications for spinal surgery, particularly for the development of spinal implants like pedicle screws.
5	(Alam et al., 2014)	Pakistani population, adults (aged 18-60), undergoing CT scans of the lumbar spine for various reasons (trauma, chronic backache, suspected tumors, spondylolisthesis).	Analysis of lumbar vertebrae morphometry through thin-cut CT images (3 mm), comparing dimensions between males and females, as well as between Pakistani and other populations.	Gender-based differences in lumbar vertebrae morphometry (male vs. female), and inter-population comparison (Pakistani vs. Indian, Iranian, American, and Israeli populations).	Significant differences in vertebral dimensions (e.g., vertebral body height, pedicle dimensions, canal diameters, lamina dimensions) between genders and across populations. The study found larger lumbar vertebral dimensions in males and significant differences between Pakistani and certain other populations (USA,

					Iran, Israel) but no differences between Pakistan and India.
6	(Atta-Alla et al., 2014)	Lebanese adult females, aged 18-22 years, with no prior spine surgery, no history of low back pain, no pregnancy, and no diagnosed lumbar spinal pathology or deformities.	Radiographic (X-ray) assessment (antero-posterior and lateral views) of lumbar vertebrae and intervertebral disc morphometry, including measurements of vertebral body height, pedicle dimensions, inter-pedicular distance, intervertebral disc height, and lumbar lordosis angles.	This is an observational study	The study found a gradual increase in anterior height of lumbar vertebrae from L1 to L5 and a decrease in posterior height after L2. Pedicle dimensions increased in a craniocaudal direction, while inter-pedicular distance and transverse diameter of lumbar vertebrae increased from L1 to L5. Additionally, the study identified patterns in lumbar lordosis, sacral inclination, and lumbosacral angles, with notable consistency in the ratio of inter-pedicular distance to transverse diameter across the lumbar vertebrae.
7	(Azu et al., 2016)	Sample includes 107 individuals (103 males and 67 females), aged between 21 and 80 years, who died during the apartheid era (1908-1970). The total lumbar vertebrae measured was 298 across five lumbar segments (L1 to L5).	Measurement of lumbar vertebrae dimensions (anteroposterior body diameter, interpedicular distance, midsagittal diameter, pedicle length, and MSD/APD ratio) using digital calipers. The study aims to assess differences between males and females as well as correlations with age.	Comparison of lumbar vertebrae dimensions between males and females, as well as evaluation of the relationship between these dimensions and the subjects' age.	Baseline data on lumbar vertebrae dimensions in South African males and females to guide clinical and diagnostic practices (for orthopedic surgeons, radiologists, clinicians). Key results include significant differences between genders at certain lumbar levels and correlations between age and specific measurements.
8	(Güleç et al., 2017)	240 patients who underwent 3D-CT for lumbar vertebrae analysis (no spinal pathologies) at a radiology department	Morphometric measurements of transverse pedicle diameter (TPD), vertical	Variations in morphometric parameters analyzed based on sex, age, and	Significant differences in TPD, VPD, and PAL by sex, age, and height. TPA varied with age but not sex or height. Findings similar to

		between 2008 and 2012. Divided by sex, age (20–59 years), and height groups (<160 cm, 160–169 cm, 170–179 cm, >179 cm).	pedicle diameter (VPD), pedicle axis length (PAL), and transverse pedicle angle (TPA) using 3D-CT.	height.	Western populations, influencing screw choice for lumbar surgeries.
Volumetric analysis					
1	(Karabekir et al., 2011)	100 dry lumbar vertebrae from adult cadavers and MRI scans of 21 healthy adults (11 men, 10 women)	Morphometric analysis of lumbar vertebrae (L1-L5) and intervertebral space volumes using stereological methods, with a focus on pedicles, vertebral bodies, and intervertebral spaces.	Differences in morphometric measurements between male and female subjects, and across various lumbar vertebral levels.	No significant differences were found between males and females, except for the anterior height of L1. Variations noted in vertebral body and intervertebral space volumes
2	(Gocmen-Mas et al., 2010)	25 healthy, right-handed adult individuals (13 males, 12 females) aged between 22 and 49	Utilization of MRI imaging to analyze lumbar vertebrae (L1-L5) and intervertebral discs. Application of stereological morphometric techniques to measure dimensions such as length, height, width, and volume of vertebral bodies and discs.	Comparison of morphometric measurements between male and female participants. Evaluation of differences in anterior-posterior diameter (APD), transverse diameter (TD), and intervertebral disc height and volume.	Assessment of the average dimensions of lumbar vertebrae and intervertebral discs. Identification of any statistically significant differences in measurements between sexes. Establishment of baseline morphometric data to guide surgical approaches and implant sizing in spinal procedures.
3	(Limthongkul et al., 2010)	40 individuals (20 men, 20 women), aged 18-50, with no spinal pathologies, undergoing CT scans of thoracic and lumbar vertebrae.	CT scans to calculate vertebral body volumes, measuring vertebral working distances, and defining "safe zones" for vertebral augmentation procedures like kyphoplasty and	Volume comparisons between thoracic vs. lumbar vertebrae, between male and female participants. Results of volumetric analysis with	Vertebral body volume increases from T1 to L4, with L5 being slightly smaller than L4. Findings help optimize cement volume in vertebral augmentation, reducing risks like cement leakage.

			vertebroplasty	previous studies.	
4	(Kanawati et al., 2021)	Six human cadaveric lumbar spines	Comparison of manual measurements of lumbar vertebrae, CT-based models, and 3D-printed models.	Differences between actual vertebra, CT-based measurements, and 3D-printed models.	No significant differences were found between the models for most measurements except vertebral width. CT-based models were slightly larger than 3D-scanned models, with a mean volumetric difference of 4.3 ml ($p < 0.001$).

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.

Conflict of Interest

Authors declares no conflict of interest in publishing this article.

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