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Geometric Morphometric Analysis in Human Craniofacial Research: Diagnostic Value and Clinical Implications – A Systematic Review

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ABSTRACT

Background: Geometric morphometric analysis has become an essential quantitative approach for evaluating complex craniofacial morphology beyond traditional linear measurements. Advances in three-dimensional imaging have expanded its application in diagnosis, treatment planning, and outcome assessment in craniofacial and dental practice. However, a comprehensive synthesis of its clinical relevance remains limited. Method: This systematic review was conducted in accordance with PRISMA 2020 guidelines. Literature searches were performed in PubMed, Scopus, and Google Scholar for articles published between 2019 and 2024. Eligible studies included original research involving human subjects that applied geometric morphometric analysis to craniofacial structures with reported diagnostic or therapeutic relevance. Study selection, data extraction, and qualitative synthesis were performed independently. Results: Eight studies met the inclusion criteria. The findings demonstrated that geometric morphometrics is widely applied in odontological analysis and orthognathic surgery. Applications in forensic and anthropological research further highlighted its utility in population and individual identification. Conclusion: Geometric morphometric analysis provides a objective framework for craniofacial diagnosis and treatment planning. Its integration with three-dimensional imaging technologies enhances diagnostic accuracy and supports data-driven clinical decision-making. Future studies should focus on protocol standardization and large-scale clinical validation to facilitate broader implementation in routine practice.

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INTRODUCTION

Craniofacial morphology plays a critical role in diagnosis, treatment planning, and outcome evaluation across multiple disciplines, including dentistry, orthodontics, maxillofacial surgery, otolaryngology, and forensic science.[1] Accurate assessment of craniofacial form and variation is essential for understanding growth patterns, developmental anomalies, functional adaptation, and pathological conyditions.[1,2] Conventional morpheme tric approaches, which rely primarily on linear and angular measurements, are limited in their ability to capture complex three-dimensional shape variation and spatial relationships inherent to craniofacial structures.[2] Geometric morphometric analysis has emerged as a powerful quantitative framework that overcomes these limitations by integrating landmark-based shape analysis with multivariate statistical techniques.[3] Unlike traditional methods, geometric morphometrics preserves the geometric properties of anatomical structures, allowing precise comparison of shape independent of size, orientation, and position.

The rapid advancement of three-dimensional imaging modalities, such as computed tomography (CT), cone-beam CT (CBCT), magnetic resonance imaging (MRI), and micro-computed tomography, has further expanded the applicability of geometric morphometrics in both research and clinical settings.[4,5] In recent years, geometric morphometric techniques have been increasingly applied to human craniofacial analysis, including the evaluation of dental morphology, enamel-dentin junction configuration, cranial base development, facial asymmetry, and soft tissue structures.[2] Clinically, these applications have demonstrated potential value in improving diagnostic accuracy, optimizing orthodontic and orthognathic treatment planning, predicting surgical outcomes, and supporting individualized patient care.[2] Moreover, geometric morphometrics has shown relevance in non-dental clinical contexts, such as assessing anatomical risk factors for otitis media, as well as in forensic and anthropological identification.[2] Despite the growing body of literature, evidence regarding the diagnostic and therapeutic utility of geometric morphometric analysis in craniofacial practice remains fragmented across disciplines and methodologies. To date, no comprehensive systematic review has synthesized recent human-based studies focusing specifically on its clinical implications for craniofacial diagnosis and treatment planning. Therefore, this systematic review aims to critically evaluate current evidence on the role of geometric morphometric analysis in human craniofacial research, with particular emphasis on its diagnostic value, clinical applications, and potential for integration into routine practice.

METHODS

Study Design and Reporting Guidelines

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines. The review protocol was developed a priori to ensure methodological transparency and reproducibility.

Eligibility Criteria

Studies were selected based on predefined inclusion and exclusion criteria. Inclusion criteria were: (1) original research articles published between January 2019 and December 2024; (2) studies involving human subjects; (3) application of geometric morphometric analysis to craniofacial or dental structures; and (4) reported relevance to diagnosis, treatment planning, or clinical decision-making. Exclusion criteria included: review articles, conference abstracts, animal or in vitro studies, case reports, non-English publications, and studies lacking clinical or diagnostic relevance.

Information Sources and Search Strategy

A comprehensive literature search was performed in PubMed, Scopus, and Google Scholar. The search strategy combined controlled vocabulary and free-text terms using Boolean operators as follows: ("craniofacial" OR "facial morphology" OR "dental morphology") AND ("geometric morphometrics" OR "morphometric analysis") AND ("diagnosis" OR "treatment planning" OR "clinical application"). Reference lists of eligible studies were also manually screened to identify additional relevant articles.

Study Selection

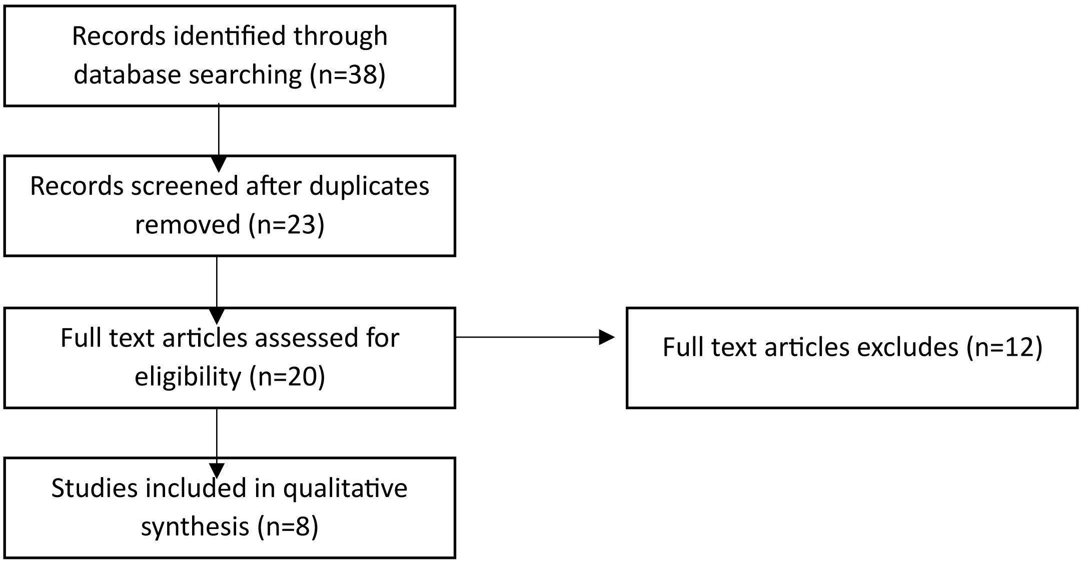
All identified records were imported into reference management software, and duplicate entries were removed. Two independent reviewers screened titles and abstracts for relevance, followed by full-text evaluation of potentially eligible articles. Discrepancies were resolved through discussion and consensus.

Data Extraction and Synthesis

Data extracted included authorship, publication year, study population, imaging modality, morphometric methodology, anatomical focus, and reported clinical implications. Due to methodological heterogeneity among studies, a qualitative narrative synthesis was conducted without statistical meta-analysis.

PRISMA Flow Diagram

The study selection process is illustrated using a PRISMA flow diagram.



A total of 38 records were identified through database searching. After screening titles and abstracts, 20 full-text articles were assessed for eligibility. Twelve articles were excluded due to not meeting the inclusion criteria, resulting in 8 studies included in the qualitative synthesis.

RESULTS

Study Selection

The literature search identified a total of 38 records across all databases. After screening titles and abstracts, 20 articles were selected for full-text assessment. Twelve studies were excluded due to insufficient clinical relevance, non-human subjects, or incomplete morphometric methodology. Ultimately, 8 studies met the eligibility criteria and were included in the qualitative synthesis. The study selection process is illustrated in the PRISMA flow diagram.

Characteristics of Included Studies

The included studies were published between 2019 and 2024 and involved human craniofacial structures across diverse age groups. Imaging modalities predominantly included computed tomography (CT), cone-beam computed tomography (CBCT), magnetic resonance imaging (MRI), and micro-computed tomography. Geometric morphometric analysis was primarily conducted using landmark- and semi-landmark–based approaches to assess three-dimensional craniofacial shape variation.

Clinical Applications of Geometric Morphometrics

Across the included studies, geometric morphometric analysis demonstrated broad applicability in craniofacial diagnosis and treatment planning. In odontological research, geometric morphometrics was used to evaluate dental morphology, particularly enamel–dentin junction configuration and tooth crown shape, providing insights into developmental variation and informing restorative and orthodontic planning.[2,3]

In clinical settings, several studies applied MRI-based geometric morphometrics to assess soft tissue and airway-related craniofacial structures, including the Eustachian tube, contributing to improved understanding of anatomical risk factors for otitis media and related conditions.[4–7]

Within maxillofacial surgery, geometric morphometric techniques were employed to model craniofacial shape changes following orthognathic procedures, supporting data-driven surgical planning and postoperative outcome evaluation.[8,9] Additionally, applications in forensic and anthropological contexts highlighted the method's utility for population-based analysis and individual identification through craniofacial shape assessment.[5,6]

Methodological Trends

Most studies emphasized the advantage of geometric morphometrics over traditional linear measurements in capturing complex shape variation while preserving anatomical relationships. However, heterogeneity was noted in landmark selection, imaging protocols, and analytical workflows, which limited direct comparison across studies.

Discussion

This systematic review synthesizes recent evidence on the application of geometric morphometric analysis in human craniofacial diagnosis and treatment planning. The findings demonstrate that geometric morphometrics provides a robust quantitative framework capable of capturing complex three-dimensional craniofacial shape variation, which cannot be adequately assessed using traditional linear or angular measurements. By preserving geometric relationships among anatomical landmarks, this approach offers enhanced diagnostic resolution and supports more precise clinical decision-making.

In odontological applications, geometric morphometric analysis has proven particularly valuable for evaluating dental morphology, including enamel–dentin junction configuration and crown shape variation.[10,11] These insights contribute to improved understanding of craniofacial growth and development and have direct implications for orthodontic diagnosis and restorative treatment planning.[12–14] Importantly, the ability to distinguish developmental morphology from surface-level variation may reduce diagnostic ambiguity and minimize the risk of treatment misclassification.[15,16]

Beyond dental structures, several studies highlighted the clinical relevance of geometric morphometrics in assessing non-dental craniofacial anatomy, such as the Eustachian tube and cranial base. The integration of MRI-based morphometric analysis enables non-invasive evaluation of soft tissue morphology and functional anatomy, supporting risk stratification and early identification of predisposition to conditions such as otitis media.12,13,17 In maxillofacial surgery, geometric morphometrics facilitates objective assessment of craniofacial shape changes following orthognathic procedures, thereby enhancing surgical planning and postoperative evaluation.16,18,19

Despite these advantages, methodological heterogeneity remains a key limitation. Variations in imaging modalities, landmark definitions, and analytical workflows restrict cross-study comparability and hinder translation into standardized clinical protocols. Additionally, most included studies focused on methodological feasibility rather than direct correlations with long-term clinical outcomes.

Future research should prioritize protocol standardization, integration with artificial intelligence–based modeling, and prospective clinical validation to fully realize the translational potential of geometric morphometric analysis in routine craniofacial practice.

CONCLUSION

Geometric morphometric analysis represents a powerful and objective approach for craniofacial diagnosis and treatment planning. Its integration with advanced three-dimensional imaging enhances the precision of morphological assessment across dental, clinical, surgical, and forensic contexts. While current evidence supports its diagnostic and planning utility, further standardization and clinical validation are essential to facilitate widespread implementation in everyday practice.

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