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Dental and Craniofacial Anatomical Variations and Their Impact on Orthodontic Diagnosis and Treatment Planning: A Systematic Review

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Article Info	ABSTRACT
Keywords: anatomical variation; cone-beam computed tomography; craniofacial abnormalities; dental anatomy; anatomymalocclusion; malocclusionorthodontics : treatment planning	Background: Dental and craniofacial anatomical variations are fundamental determinants of orthodontic diagnosis and treatment planning. Variability in tooth morphology, skeletal relationships, and alveolar bone anatomy may influence biomechanical feasibility, treatment selection, and the risk of complications. Objective: This systematic review aimed to synthesize current evidence on dental and craniofacial anatomical variations and to evaluate their impact on orthodontic diagnosis and treatment planning. Methods:A systematic literature search was conducted in PubMed, Scopus, and Web of Science in accordance with the PRISMA 2020 guidelines. Studies published in English within the last 10 years and involving human subjects with permanent dentition were considered. Data extraction and study selection were performed independently, and findings were synthesized narratively due to methodological heterogeneity. Results: Twenty studies were included in the qualitative synthesis. Dental anatomical variations, particularly root morphology and tooth anomalies, were associated with biomechanical limitations and increased risk of root resorption. Craniofacial skeletal variations influenced malocclusion patterns, growth assessment, and decisions between orthodontic camouflage and combined orthodontic surgical treatment. Alveolar bone anatomical variability defined the biological limits of orthodontic tooth movement and was closely linked to periodontal risk. 3D imaging techniques, especially cone-beam computed tomography, enhanced the identification of clinically relevant anatomical constraints. Conclusions: Dental, craniofacial, and alveolar anatomical variations play a critical role in orthodontic diagnosis and treatment planning. An anatomy driven approach supported by appropriate imaging improves diagnostic accuracy, facilitates individualized treatment strategies, and reduces the risk of adverse outcomes. These findings support the integration of comprehensive anatomical assessment into precision orthodontic practice.
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INTRODUCTION

Accurate orthodontic diagnosis and effective treatment planning rely heavily on a comprehensive understanding of dental and craniofacial anatomy.[1] The craniofacial complex is characterized by intricate structural relationships among teeth, alveolar bone, maxilla, mandible, and associated skeletal components, all of which exhibit considerable anatomical variability.[1,2] These variations play a critical role in the development of malocclusion, facial asymmetry, and skeletal discrepancies, thereby influencing orthodontic treatment strategies and outcomes.[3,4]

Dental anatomical variations, including differences in tooth size, shape, root morphology, and eruption patterns, can substantially affect orthodontic biomechanics and treatment feasibility.[5] Variations in root length, root angulation, and root proximity may alter the response to orthodontic forces and increase the risk of adverse effects such as root resorption or alveolar bone dehiscence. Similarly, anomalies such as supernumerary teeth, tooth agenesis, and ectopic eruption present diagnostic and therapeutic challenges that require careful anatomical assessment.[6–8]

Beyond individual tooth morphology, craniofacial skeletal anatomy exhibits significant interindividual and population-specific variation.[1] Differences in maxillomandibular relationships, cranial base morphology, vertical facial dimensions, and transverse skeletal width are well recognized determinants of malocclusion patterns and facial esthetics. Growth related changes further complicate diagnosis and treatment planning, particularly in growing patients, where timing and modality of orthodontic intervention are closely linked to craniofacial developmental stages.[1]

Advancements in diagnostic imaging, especially cone-beam computed tomography (CBCT) and three-dimensional (3D) cephalometric analysis, have transformed the evaluation of dental and craniofacial anatomy in orthodontics.[9] These technologies enable detailed visualization of skeletal and dental structures beyond the limitations of conventional two-dimensional radiography, facilitating more precise assessment of anatomical boundaries, root positions, alveolar bone thickness, and airway dimensions. Consequently, an expanding body of literature has emerged documenting clinically relevant anatomical variations using advanced imaging techniques.[9]

Despite the growing volume of research, the available evidence on dental and craniofacial anatomical variations in orthodontic contexts remains heterogeneous and fragmented. Studies differ in anatomical definitions, imaging modalities, measurement protocols, and outcome reporting, limiting direct comparison and clinical translation. Moreover, while numerous studies describe anatomical variations, fewer systematically evaluate their implications for orthodontic diagnosis, treatment planning, and risk assessment.

Therefore, this systematic review aims to comprehensively synthesize the current evidence on dental and craniofacial anatomical variations and to critically evaluate their impact on orthodontic diagnosis and treatment planning. By integrating findings from diverse populations, anatomical regions, and imaging approaches, this review seeks to provide an evidence-based anatomical framework to support precision orthodontics, optimize treatment outcomes, and identify gaps for future research.

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. The focus of this review was to synthesize existing evidence regarding dental and craniofacial anatomical variations and their implications for orthodontic diagnosis and treatment planning.

Eligibility Criteria

The eligibility criteria were defined based on the Population-Concept-Context (PCC) framework. Studies were included if they met the following criteria:

1. Population: Human subjects with permanent dentition, orthodontic patients or populations relevant to orthodontic diagnosis and treatment planning
2. Concept: Dental anatomical variations (e.g., tooth size, shape, root morphology, eruption pattern), Craniofacial anatomical variations (e.g., skeletal relationships, cranial base morphology, alveolar bone characteristics), Anatomical factors influencing orthodontic diagnosis, biomechanics, treatment planning, or outcomes
3. Context: Orthodontic, dentofacial orthopedic, or craniofacial clinical settings
4. Study Design: Observational studies (cross-sectional, cohort, case–control), Imaging-based anatomical studies (CBCT, CT, 3D cephalometry), Systematic anatomical analyses with clinical orthodontic relevance

Studies were excluded if they were conducted on animals, cadavers only, or in vitro models, focused exclusively on primary or mixed dentition, were case reports, case series, editorials, letters, narrative reviews, or expert opinions, did not explicitly relate anatomical variations to orthodontic diagnosis or treatment planning, lacked sufficient methodological or anatomical detail. A comprehensive literature search was conducted in the following electronic databases PubMed/MEDLINE, Scopus, Web of Science. Additional manual searches were performed by screening the reference lists of included studies to identify potentially relevant articles not captured by the electronic search.

Search Strategy

The search strategy combined controlled vocabulary (MeSH terms) and free-text keywords related to dental anatomy, craniofacial anatomy, and orthodontics. Boolean operators (AND, OR, NOT) were used to maximize sensitivity while maintaining specificity. The term that we used are "Dental Anatomy"[Mesh] OR "Tooth Anatomy"[Mesh] OR tooth morphology OR dental morphology AND "Craniofacial Abnormalities"[Mesh] OR "Craniofacial Anatomy"[Mesh] OR craniofacial morphology AND "Orthodontics"[Mesh] OR orthodontic diagnosis OR treatment planning AND "Anatomical Variation"[Mesh] OR anatomical variation* OR morphological variation* OR anomaly* AND Humans[Mesh] AND (CBCT OR "cone beam computed tomography" OR "three-dimensional imaging" OR "3D cephalometry").

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Study Selection

All retrieved records were exported to a reference management software, and duplicates were removed. Two independent reviewers screened titles and abstracts to assess eligibility. Full-text articles were subsequently evaluated for inclusion based on the predefined criteria. Any disagreements were resolved through discussion and consensus.

Data Extraction

Data were independently extracted using a standardized data extraction form, including: Author(s) and year of publication, Study design and population characteristics, Type of dental and/or craniofacial anatomical variation, Imaging modality or assessment method, Orthodontic diagnostic implications, Impact on treatment planning or biomechanics.

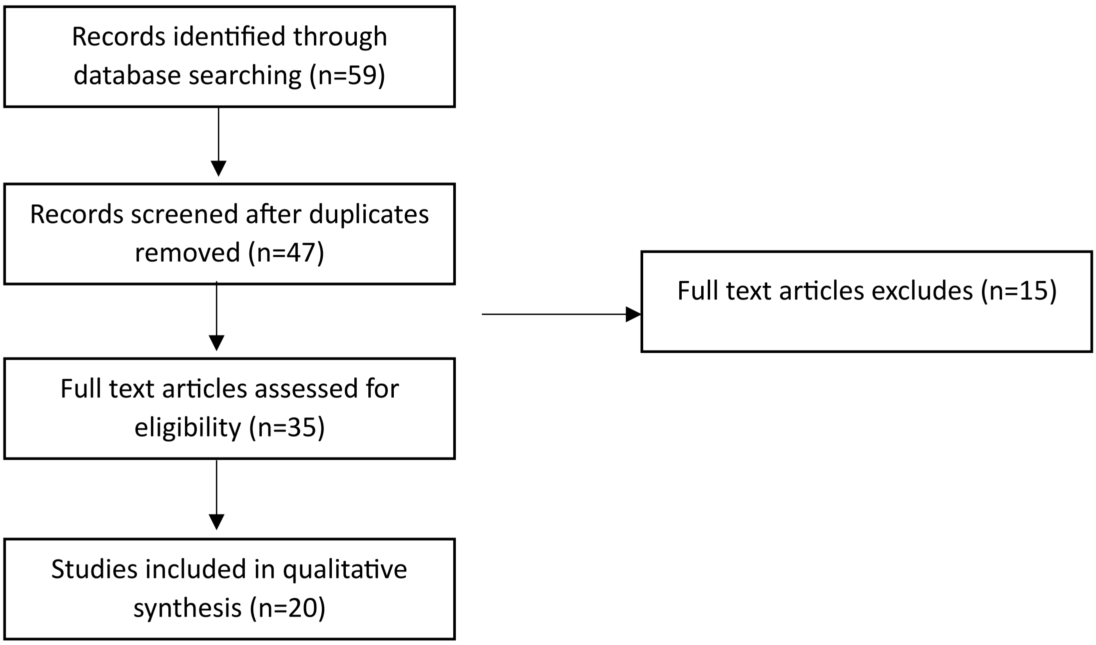
Data Synthesis

Given the heterogeneity of study designs, anatomical variables, and outcome measures, a narrative synthesis was performed. Findings were organized thematically according to dental anatomical variations, craniofacial skeletal variations, alveolar and dentoalveolar anatomy and clinical implications for orthodontic diagnosis and treatment planning.

RESULTS

PRISMA Flow Diagram

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



Study Selection

Following database searching and screening procedures, a total of 59 articles were initially identified. After removal of duplicates and assessment of titles, abstracts, and full texts based on eligibility criteria, 20 studies were included in the final qualitative synthesis. The included studies predominantly employed cross-sectional and observational designs, with

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most utilizing cone-beam computed tomography (CBCT) or three-dimensional imaging for anatomical assessment.

Dental Anatomical Variations and Orthodontic Implications

The included studies consistently reported substantial variability in dental anatomy, particularly regarding tooth size, crown morphology, root length, root angulation, and root number. Variations in root morphology, such as dilacerations, divergent roots, short roots, and proximity between adjacent roots, were frequently highlighted as clinically relevant findings in orthodontic patients.[10,11] Several studies emphasized that root length and root morphology significantly influence orthodontic diagnosis and risk assessment.[10,12] Teeth with short or atypically shaped roots were associated with an increased susceptibility to orthodontically induced root resorption, necessitating modifications in force magnitude, treatment duration, and monitoring protocols.[10] Additionally, variations in crown–root angulation affected bracket positioning and torque expression, directly impacting treatment planning and biomechanical control.[6,13] Dental anomalies, including tooth agenesis, supernumerary teeth, ectopic eruption, and transposition, were recurrently reported across different populations.[3,8] These anomalies posed diagnostic challenges and often required interdisciplinary decision-making. In orthodontic treatment planning, such variations influenced decisions regarding space management, extraction strategies, anchorage requirements, and sequencing of tooth movement. Overall, the evidence indicated that comprehensive evaluation of dental anatomical variations enhances diagnostic accuracy and supports individualized orthodontic treatment planning aimed at minimizing complications and optimizing outcomes.[3,14,15]

Craniofacial Skeletal Anatomical Variations and Orthodontic Implications

Across the included studies, marked craniofacial skeletal variability was observed in maxillomandibular relationships, cranial base morphology, vertical facial dimensions, and transverse skeletal width.[16] These variations were closely associated with different malocclusion patterns, including skeletal Class I, II, and III discrepancies, facial asymmetry, and vertical growth patterns.[6,12,17] Variations in cranial base angle and length were reported to influence sagittal jaw relationships, affecting cephalometric interpretation and orthodontic diagnosis.[18] Differences in mandibular morphology, such as ramus height, mandibular plane angle, and symphyseal thickness, were shown to affect growth prediction and treatment timing, particularly in adolescent patients.[17] Several studies highlighted the role of skeletal anatomy in determining the limits of orthodontic camouflage versus the need for orthognathic surgery. [2]Severe skeletal discrepancies, identified through detailed anatomical assessment, necessitated combined orthodontic, surgical approaches rather than orthodontic treatment alone. Furthermore, skeletal asymmetries required careful diagnosis to avoid compensatory tooth movements that could compromise facial esthetics or functional stability. The findings underscore that understanding craniofacial skeletal anatomical variations is essential for accurate orthodontic diagnosis, growth assessment, and the selection of appropriate treatment modalities.[12,16]

Alveolar and Dentoalveolar Anatomical Variations and Orthodontic Implications

Alveolar bone anatomy emerged as a critical determinant of orthodontic treatment feasibility and safety.[17] The included studies consistently reported variations in alveolar bone thickness, height, cortical bone density, and alveolar housing dimensions around anterior and posterior teeth.[17] Reduced alveolar bone thickness, particularly in the labial and lingual cortical plates of anterior teeth, was associated with an increased risk of alveolar dehiscence, fenestration, and gingival recession during orthodontic tooth movement.[17] These findings were particularly relevant in cases requiring extensive incisor proclination or retraction. Variations in dentoalveolar inclination and alveolar envelope were shown to influence the permissible range of tooth movement.[17] Studies utilizing CBCT demonstrated that exceeding anatomical boundaries of the alveolar housing could result in periodontal compromise, emphasizing the importance of three-dimensional anatomical assessment during treatment planning.[10,12,19] In the context of orthodontic diagnosis, alveolar anatomical evaluation informed decisions regarding extraction versus non-extraction therapy, anchorage planning, and the use of auxiliary devices such as temporary anchorage devices (TADs). The evidence suggests that incorporating alveolar anatomical considerations into treatment planning enhances treatment predictability and reduces iatrogenic risks.[6,15]

Summary of Clinical Implications

Collectively, the included studies demonstrate that dental, skeletal, and alveolar anatomical variations are integral to orthodontic diagnosis and treatment planning.[20,21] Dental anatomy influences biomechanical control and risk management, skeletal anatomy determines growth patterns and treatment modality selection, and alveolar anatomy defines the biological limits of tooth movement.[20,21] Integrating these anatomical domains through advanced imaging and comprehensive assessment supports a precision orthodontics approach, enabling individualized, safe, and effective treatment strategies.[2,10,20]

Discussion

This systematic review highlights the critical role of dental and craniofacial anatomical variations in shaping orthodontic diagnosis and treatment planning. By synthesizing evidence across dental, skeletal, and alveolar domains, the findings reinforce the concept that orthodontic treatment is fundamentally constrained and guided by individual anatomical characteristics rather than standardized protocols. The heterogeneity observed among the included studies reflects the biological diversity inherent in craniofacial structures and underscores the necessity for individualized, anatomy-driven orthodontic care.

Dental Anatomy as a Determinant of Orthodontic Risk and Biomechanics

Dental anatomical variations, particularly in root morphology and crown–root relationships, emerged as pivotal factors influencing orthodontic biomechanics and treatment safety. [1,16,22] Variations such as short roots, root dilacerations, and atypical root angulations have been consistently associated with an elevated risk of orthodontically induced root resorption. These findings support the growing emphasis on pre-treatment risk stratification, wherein detailed dental anatomical assessment informs force selection, treatment duration, and monitoring frequency.[12,23,24] Moreover, dental anomalies such as tooth agenesis, supernumerary teeth, and ectopic eruption extend beyond localized morphological differences and often signal broader developmental disturbances within the dentofacial complex. From a diagnostic standpoint, these variations necessitate comprehensive assessment to determine their impact on occlusal relationships and space management.[1,24,25]

In treatment planning, they frequently require interdisciplinary coordination and may fundamentally alter extraction patterns, anchorage strategies, and sequencing of orthodontic mechanics.[5,21]

Craniofacial Skeletal Anatomy and Diagnostic Decision-Making

Craniofacial skeletal variations were shown to exert a dominant influence on orthodontic diagnosis, particularly in differentiating dental from skeletal components of malocclusion. Variations in cranial base morphology, sagittal jaw relationships, and vertical facial dimensions directly affect cephalometric interpretation and growth prediction.[20,26,27] Misinterpretation of these anatomical features may lead to inaccurate diagnosis and suboptimal treatment strategies. The reviewed evidence underscores the importance of skeletal anatomical assessment in determining the feasibility of orthodontic camouflage versus combined orthodontic, surgical approaches. Severe skeletal discrepancies and asymmetries, when inadequately recognized, may prompt compensatory dental movements that compromise facial esthetics, periodontal health, and long-term stability. Consequently, detailed evaluation of craniofacial skeletal anatomy serves as a cornerstone for ethical and evidence-based orthodontic treatment planning.[2,10,12,20]

Implications for Precision Orthodontics

Collectively, the findings of this review support a paradigm shift toward precision orthodontics, wherein diagnostic and therapeutic decisions are guided by individualized anatomical profiles. Advanced imaging modalities, such as CBCT, facilitate comprehensive assessment of dental, skeletal, and alveolar structures, enabling clinicians to identify anatomical constraints and opportunities that may not be evident with conventional diagnostic tools.[9] However, the routine use of three-dimensional imaging must be justified by clear diagnostic benefits and balanced against considerations of radiation exposure.[28,29] The reviewed studies suggest that selective, indication-based use of advanced imaging is most appropriate, particularly in complex cases where anatomical variations are likely to influence treatment outcomes.

CONCLUSION

This systematic review demonstrates that dental, craniofacial skeletal, and alveolar anatomical variations play a fundamental role in orthodontic diagnosis and treatment planning. Variability in tooth morphology and root anatomy influences biomechanical control and risk assessment, particularly with regard to root resorption and treatment safety. Craniofacial skeletal anatomy determines malocclusion patterns, growth behavior, and the appropriateness of orthodontic camouflage versus combined orthodontic–surgical approaches. Meanwhile, alveolar bone anatomy defines the biological limits of orthodontic tooth movement and directly impacts periodontal outcomes. The findings underscore the necessity of comprehensive anatomical evaluation as a cornerstone of evidence-based orthodontic care. Incorporating detailed assessment of dental, skeletal, and alveolar structures enhances diagnostic accuracy, supports individualized treatment planning, and reduces the risk of iatrogenic complications. Advanced imaging modalities, particularly three-dimensional techniques, have significantly improved the visualization of anatomical variability

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and contributed to more precise orthodontic decision-making when used judiciously. Overall, an anatomy-driven approach to orthodontics aligns with the principles of precision medicine and promotes safer, more predictable, and patient-centered treatment outcomes. Future research should focus on standardizing anatomical assessment protocols and exploring the integration of advanced imaging analytics to further optimize orthodontic diagnosis and treatment planning. This review has several limitations. The heterogeneity in study designs, imaging protocols, and anatomical measurement methods precluded quantitative synthesis. Additionally, most included studies were observational in nature, limiting causal inference. Future research should aim to standardize anatomical definitions and measurement techniques to enhance comparability across studies. Prospective studies investigating the direct relationship between specific anatomical variations and orthodontic outcomes are warranted. Furthermore, the integration of artificial intelligence and automated image analysis holds promise for improving anatomical assessment and supporting personalized orthodontic treatment planning.

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