

Shaping the future of orthodontics with artificial intelligence: An overview of innovations today, insights for tomorrow

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Orthodontics is a specialised discipline of dentistry with a rich history dating back over 3,000 years. Ancient civilisations attempted tooth alignment using materials such as metal bands and catgut. Since its inception, orthodontics has made remarkable advances. Today, with artificial intelligence (AI) emerging as a transformative technology, the industry has shifted dramatically. The present study explores the interaction between orthodontics and artificial intelligence by focusing on its applications in diagnostic methods, treatment planning, and clinical practice. AI has demonstrated tremendous potential for enhancing the accuracy of cephalometric analysis, dental evaluations, facial assessments, and overall treatment outcomes through techniques related to deep learning and neural networks. Despite the promising results of existing applications, significant challenges remain, including algorithmic biases, ethical issues, and data privacy concerns. The present review underscores the limitations while also highlighting opportunities for incorporating AI into orthodontic treatment and emphasising the need for improved datasets and a better understanding of clinical implications. Ultimately, while AI integration has the potential to transform orthodontics, its implementation must be approached with caution in order to uphold ethical principles and promote patient-centred care. (Aust Orthod J 2025; 41: 88 - 99. DOI: 10.2478/aoj-2025-0007)

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Introduction

Orthodontics is a subspecialty of dentistry which focuses on the treatment of dentofacial deformities, including occlusal disharmony and jaw malalignment.¹ The formal recognition of the field as an academic branch dates back to the 18th century, particularly following Pierre Fauchard's systematic assessment.²

Much later, Edward Angle, the pioneering figure of modern orthodontics, made significant contributions by publishing the first edition of his book "Malocclusion of the Teeth" in the 1880s. Angle's contribution continued with the introduction of his classification of malocclusion in 1899 which established a revolutionary system for regulating the

teeth that remains in use today. He also founded a school that trained many of the most notable orthodontists of the time, thereby shaping the field's distinct professional identity.^{2,3}

Artificial intelligence (AI) is a rapidly expanding subfield of computer science that aims to program machines to simulate human cognitive processes in order to make appropriate decisions.⁴ Dentistry is not exempt from the rapid changes brought about by this technology, which offers substantial benefits. Recent advances in machine learning and data analytics have created the potential to transform a dental professional's approach to diagnosis, treatment, and oral health management.^{4,5} Recent research indicates

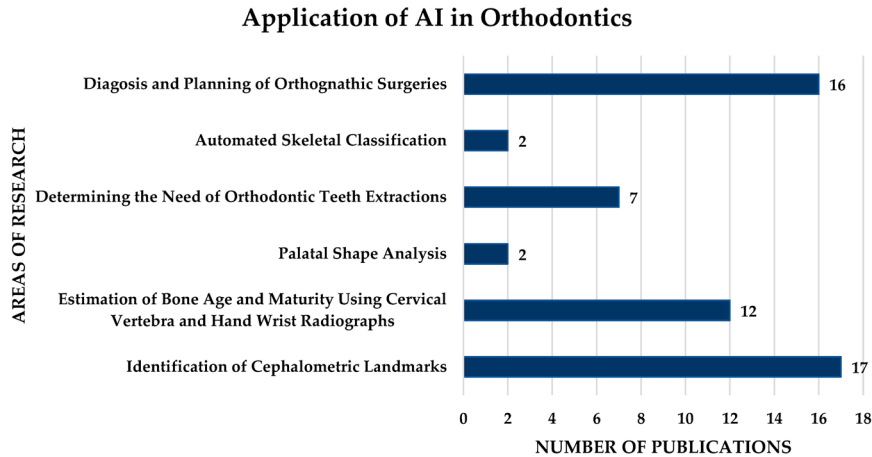


Figure 1. Recent research on the application of AI in orthodontics.⁶

that AI has significantly enhanced the efficiency of clinical orthodontic practice (Figure 1).⁶

However, understanding the core aspects of AI is critical before exploring its orthodontic implications. Machine learning is the fundamental principle of AI, as it involves programming machines without prior knowledge to perform intelligent tasks or to manually establish operational rules, thereby eliminating the need for direct human intervention. Instead, the machines identify patterns contained in large datasets.⁷ Deep learning, which is a subdiscipline of machine learning, employs multi-layered neural networks to interpret input data thereby aiming to create networks with enhanced feature recognition and precise pattern identification.^{7,8}

Neural networks are collections of algorithms that interpret input data by simulating the behaviour of human neurons.⁸ In medicine and dentistry, convolutional neural networks (CNNs) are commonly-used types of artificial neural networks (ANNs) and are designed to analyse digital signals, including sounds, images, and video materials, through a unique neuron connection structure combined with convolutional mathematics.⁹

Given the continuous evolution of the field, staying updated on the latest advancements is crucial for developing a better understanding of AI applications and therefore enhancing a patient's experience. Although recent developments have yielded positive outcomes, there remains significant scope for the increased orthodontic application of AI.¹⁰ The present study aims to provide a comprehensive overview of

current orthodontic AI applications, with a focus on diagnosis, treatment planning, and clinical practice. Furthermore, the current limitations and challenges associated with AI in orthodontics will be explored, in an effort to provide useful insights into how AI can be more effectively integrated into future practice.

Applications of AI in orthodontics

Diagnosis

The primary concern of orthodontists is ensuring that their patient's craniofacial complexes are correctly aligned; therefore, accurate and detailed documentation is essential to prevent suboptimal treatment outcomes.¹¹ The rapid advancement of technology has significantly enhanced diagnostic capabilities across multiple domains, including cephalometric analysis, dental evaluations, facial assessments, palatal shape determination, skeletal maturation assessments, and upper airway patency evaluations. By incorporating these advanced tools into their practice, orthodontists can improve treatment planning and make better decisions regarding complex procedures such as orthognathic surgery.¹¹

Cephalometric analysis

Due to its critical role in evaluating craniofacial skeletal profiles, cephalometric analysis is an orthodontic application of AI that has been extensively researched and supported by a substantial

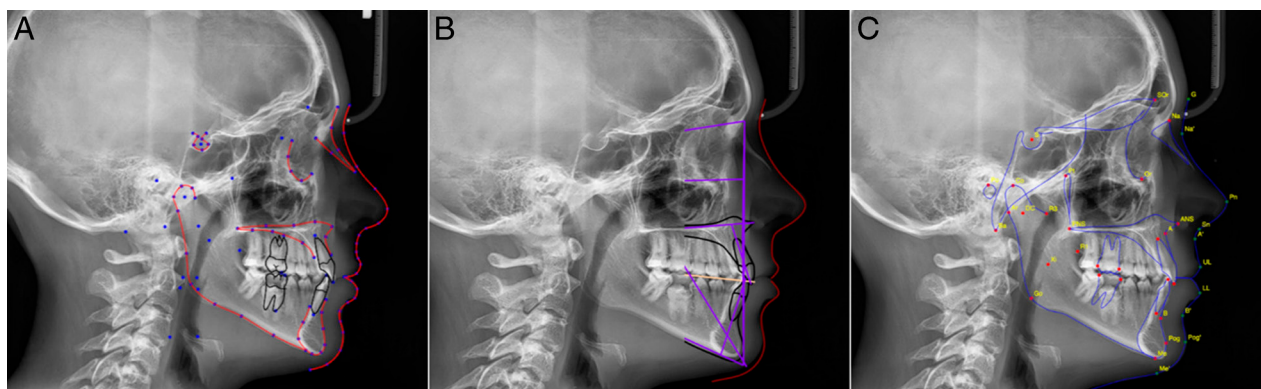


Figure 2. Comparison of superimposed cephalometric landmarks on sample patient: (A) CephX, (B) AudaxCeph, (C) WebCeph.¹³

body of literature.¹² Traditionally, the manual tracing of anatomical landmarks is a time-consuming and skill-intensive process. However, recent advances in AI technology, particularly those involving deep learning neural networks, have enabled the development of automated models that can accurately predict landmarks with minimal user intervention and perform at a level similar to highly skilled manual tracers, thereby increasing clinical practice efficiency and accuracy.¹² In contrast to manual tracing, automated cephalometric analysis methods demonstrate greater stability and repeatability. Studies have shown near-perfect agreement in the accuracy of repeated measurements between the CephX (Orca Dental AI Ltd., Las Vegas, NV, USA), WebCeph (Gyeonggi-do, Republic of Korea), and

AudaxCeph (Audax, Ljubljana, Slovenia) programs (Figure 2), indicating that these automated systems yield consistent results when re-analysing the same radiographs, and therefore confirming the accuracy of their algorithms. This highlights the promise of AI-powered tools as reliable alternatives to traditional approaches while offering the advantages of speed and consistency.¹³ Consequently, cephalometric superimposition is utilised to assess changes related to growth and the outcomes of orthodontic treatment.¹⁴ The machine learning superimposition method is a newly developed framework for automating the superimposition process and it has been proposed for immediate implementation after the automatic identification of landmarks. A key advantage of the machine learning (ML) approach

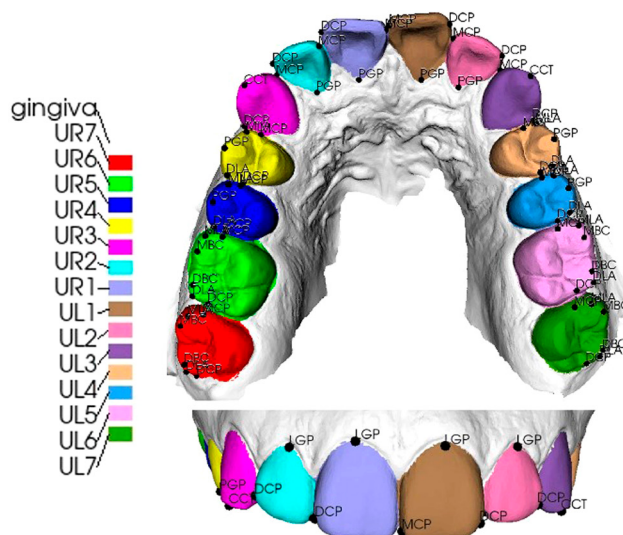


Figure 3. Sixty-six anatomical landmarks were identified on 14 teeth, representing the central contact areas of the mesial and distal contact points on the upper right and upper left teeth. The top and bottom graphics depict occlusal and frontal views, respectively.¹⁵

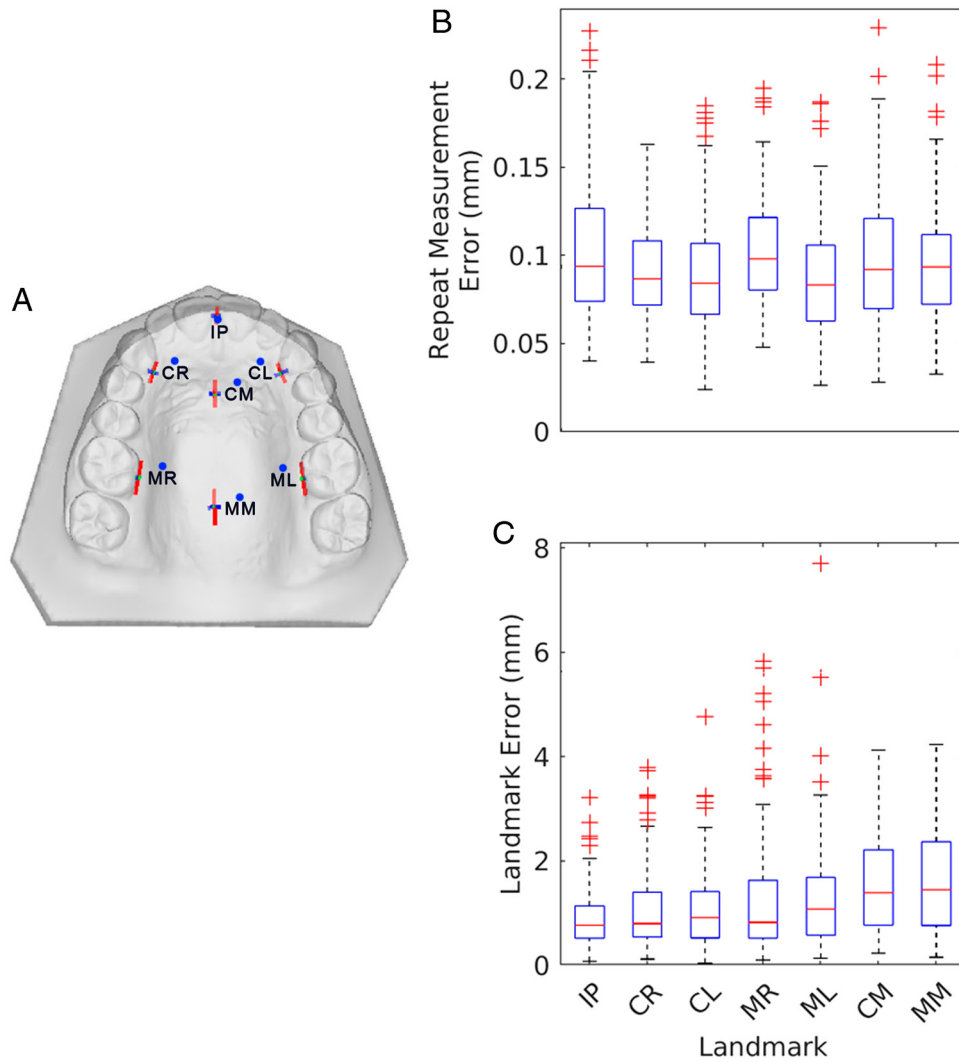


Figure 4. Accuracy (A and C) and repeat measurement error (B) of the automatic landmarking method.¹⁷

is its potential for automatic application, which may provide reliability comparable to that of traditional manual superimposition methods. To overcome the limitations associated with the traditional Sella-Nasion (SN) superimposition technique, the new method relies on six landmarks: Sella, Nasion, Porion, Orbitale, Basion, and Pterygoid. These landmarks reflect precise changes in growth over time instead of the dependence on Sella and Nasion points as they continue remodelling throughout growth until early adulthood. Although this method works effectively with computer-aided cephalometrics and produces more accurate findings than the standard SN approach, it appears beneficial for the examination of post-treatment outcomes in individuals who have

completed their growth, while its efficacy regarding growing patients remains to be explored.¹⁴

Dental evaluation

The widespread use of digital 3D dental models (Figure 3) to generate personalised treatment plans demonstrates their effectiveness and safety.¹⁵ Identifying key anatomical landmarks is a crucial step in this process, which combines computer vision and medical imaging analysis.¹⁵ While automated segmentation in dental intraoral scans presents challenges, due to individual patient variation, these models are more efficient and accurate at identifying a landmark using only the mesh of the

Table 1. Definition of the landmarks.¹⁷

Landmark	Definition
Bilateral Landmarks	
CL, CR	The deepest point of the gingival crevice on the palatal surface of the canine. If there was gingival recession and the cemento-enamel junction was visible, this was defined as the deepest point of the cemento-enamel junction. If the canines were malpositioned, the tooth in the more correct position within the dental arch was used.
ML, MR	The deepest point of the gingival crevice or the cemento-enamel junction on the palatal surface of the first molar. If there was gingival recession and the cemento-enamel junction was visible, this was defined as the deepest point of the cemento-enamel junction.
Midline Landmarks	
IP	The tip of the incisive papilla.
CM	The point on the palatal raphe between the CL and CR landmarks, indicated while viewing the casts perpendicular to the anterior-incisal-occlusal plane.
MM	The point on the palatal raphe, between the ML and MR landmarks indicated while viewing the casts perpendicular to the anterior-incisal-occlusal plane.

specific tooth rather than the entire dental arch model. Furthermore, the models have proven useful for overlaying images and tracking tooth movements before and after treatment. When evaluated from the occlusal and frontal perspectives, the models significantly improve accuracy within clinically acceptable error limits while substantially reducing computational demands.¹⁵

Facial assessment

Since the perception of beauty is a complex and multifaceted concept, many patients seek orthodontic treatment for cosmetic reasons.¹⁶ Numerous factors related to jaw prominence, overall facial height, and facial symmetry, have been linked in studies of attractiveness.¹⁶ To assist orthodontists in achieving better facial harmony for their patients, AI technologies have the potential to enhance facial images. AI advancements have focused primarily on the lower third of the face, which is a region particularly responsive to orthodontic alterations.

Moreover, recent image editing applications that integrate AI have provided users with different tools to apply filters and effects. Image enhancement approaches have been thoroughly and intensively researched, and advances have been made related to wavelet transforms, histogram equalisation, the

algebraic reconstruction mode and cellular neural networks.¹⁶ For example, 'FaceApp' (FaceApp Technology Ltd., Limassol, Cyprus) is revered for its realism and ease of use; however, it features convoluted algorithms paired with multiclass CN networks that enhance image quality through statistical analysis of vast amounts of facial data.

At present, AI-powered facial enhancement combines machine learning and image processing, which allows complex facial feature refinements through an extensive process. Face detection is the first step in which algorithms identify facial boundaries and landmarks. Thereafter, a comprehensive analysis of facial features is performed, taking into consideration skin geometry, plus the mouth and eyes. The analysis has been further improved by the application of deep learning models, especially convolutional neural networks, trained over large collections of facial image data to identify complex facial patterns. The algorithm then performs feature augmentation of the patterns to enhance characteristics of the images that may involve the reduction of wrinkled features or shrinkage in the size of the nose.

Generative Adversarial Networks (GANs) are used to generate increasingly realistic images in which these models collaborate to produce authentic-looking results by competing against each other during the

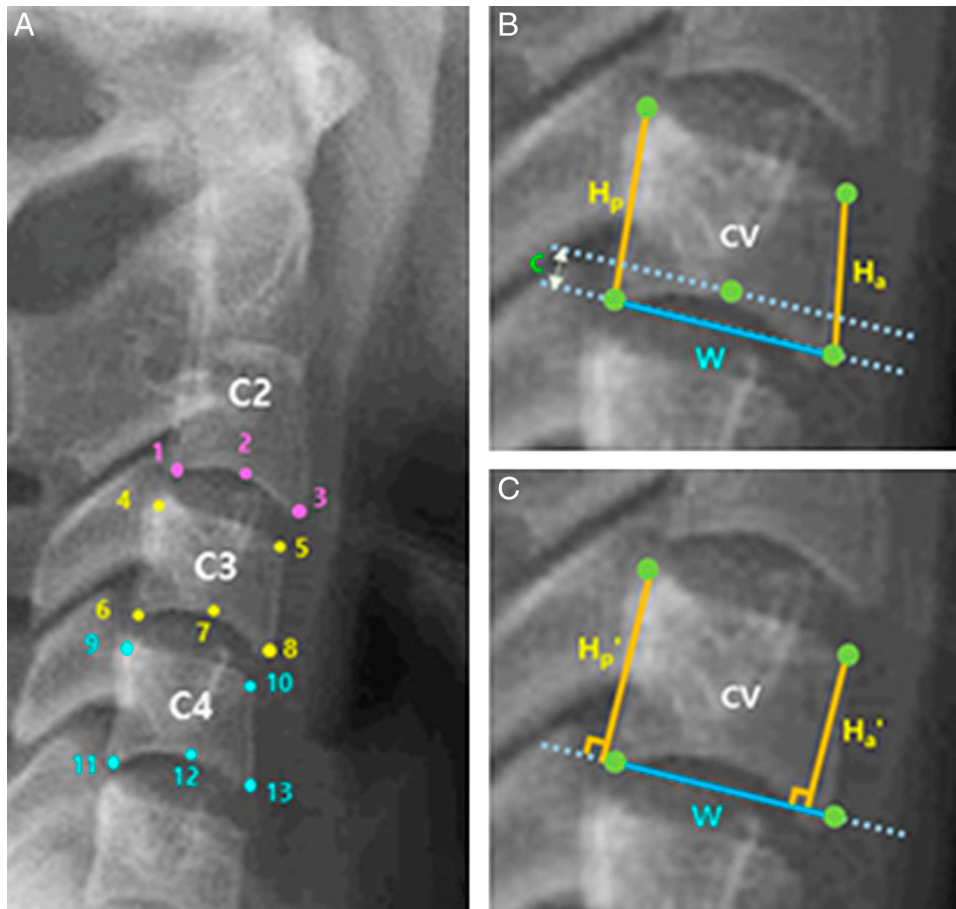


Figure 5. Morphometric assessment of the second (C2), third (C3) and fourth (C4) cervical vertebrae (CVs).¹⁹

evaluation process. It also allows personalisation, enabling enhancements to be made at an individual level in such a way that the output will meet the user's requirements. It also supports real-time processing, thereby enabling a variety of enhancing operations to be performed simultaneously.

However, it is essential to acknowledge limitations, and patients must be aware of the realistic scope of changes that AI technologies propose because the software cannot assess the plausibility of the suggested alterations, especially in non-surgical orthodontic effects on the face or factors beyond the clinician's control. Ultimately, decisions regarding treatment plans must always rest with the treating professional, who should account for each patient's unique circumstances. As the field evolves, it is crucial that clinicians and patients maintain an open dialogue about the innovations and their potential effects on treatment outcomes, ensuring that expectations

remain grounded in reality.¹⁶ This collaborative approach will empower patients to make informed decisions and foster trust in the treatment process.

Palatal shape determination

The palate provides a framework for essential functions such as speaking and mastication. Multiple factors, including the developmental stages, breathing patterns, tongue size and posture, the types of malocclusions, and numerous health conditions explain individual shape variations. Additionally, orthodontic procedures such as palatal expansion, tooth extraction, and tooth inclination changes can further shape the palate.¹⁷ Recent progress in geometric deep learning has led to automated landmark identification techniques (Figure 4) (Table I), which offer a more comprehensive method for mapping specific points across the palate's anatomical features. Although this method

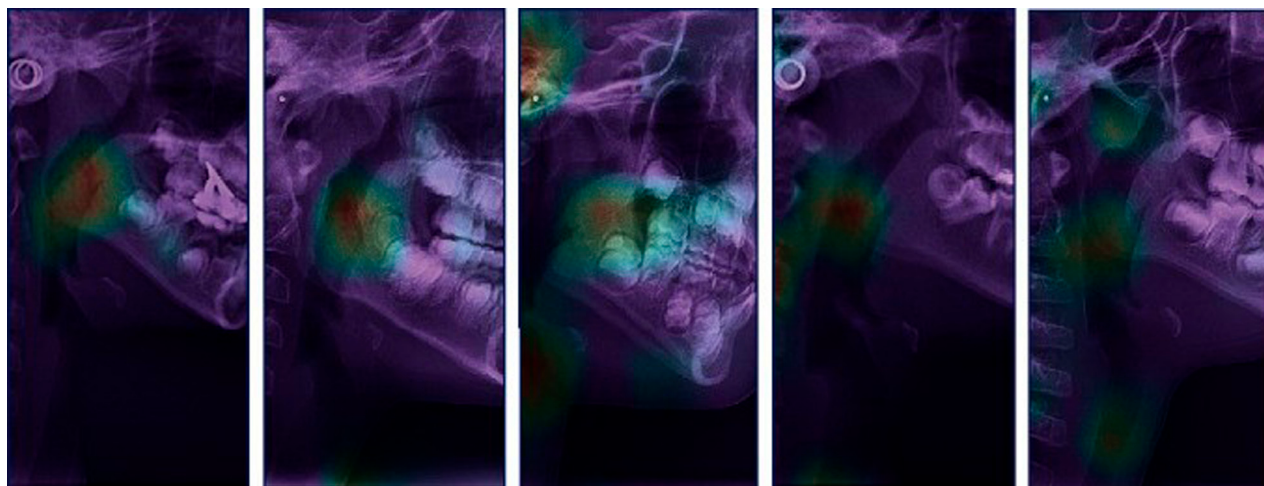


Figure 6. A heatmap generated via class activation maps, which visualises information from a cephalogram. In this depiction, the red shade highlights the upper area activated when the model processes a sample indicating airway obstruction.²⁰

shows promise regarding accuracy and reliability in repeated measurements, it may encounter difficulties when applied to a palate of atypical shape.¹⁷

Skeletal maturation assessment

Accurately determining an individual's developmental stage or biological maturity is orthodontically crucial, as skeletal age and chronological age can differ significantly.¹⁸ Traditionally, hand-wrist radiographs are used to assess skeletal maturation based on the correlation between osseous bone growth in the hand and wrist and overall development.¹⁸ In parallel, lateral cephalograms offer a compatible, cost-effective method of measuring cervical vertebrae maturation without exposing patients to additional radiation (Figure 5).¹⁹ Given the strong correlation between cervical vertebral and the skeletal maturation of hand and wrist bones, AI techniques based on machine learning algorithms have been developed to predict the skeletal maturation stages from lateral cephalograms, demonstrating enhanced accuracy when incorporating chronological age, gender, and certain characteristics of the cervical vertebrae as input variables.¹⁹

Upper-airway patency evaluation

There is substantial evidence that links dentofacial anomalies to upper airway obstruction.²⁰ Conditions that hinder breathing, such as nasal polyps, environmental irritants, allergic rhinitis,

and adenotonsillar hypertrophy, can elevate nasal resistance. This may lead to mouth breathing, resulting in dental complications noted as maxillary narrowing, tooth crowding, an increased overjet, and an anterior open bite.²⁰ Currently, clinicians can assess patients more accurately and efficiently due to advancements in deep learning models designed to automatically detect upper airway obstructions (Figure 6).²⁰

Treatment planning

Orthodontic treatment plans are uniquely tailored to each patient's specific needs, emphasising the field's individualised nature. To simplify this complex process, multilayer artificial neural networks (ANNs) suggest treatment protocols and probabilities for numerous alternative options. These decisions encompass critical elements such as extraction versus non-extraction strategies, extraction patterns, and methods of anchorage.²¹

The decision of tooth extraction

Decisions regarding tooth extraction are guided by diagnostic clinical assessments, radiographs, dental study models, and patient photographs.²² However, the decision is widely debated due to the irreversible consequences of extraction and the potential for complications, which include an unfavourable facial profile, a poor occlusion, and difficulties in closing the resulting spaces, all of which can impair aesthetic

outcomes. The complications may sometimes hinder the course of treatment.²³ Currently, there is no universally accepted method for identifying the need for extraction, and decisions are typically influenced by the treating orthodontist's experience and proficiency. However, the incorporation of AI models shows promise in reducing errors in making these critical decisions and provides comprehensive assessments of extraction patterns which potentially leads to improved treatment outcomes by employing a template-matching system that identifies similar cases from an established database.²³

Many studies have reported improvements in facial morphology following orthodontic treatment involving tooth extraction.²⁴ Consequently, premolar extraction is often the preferred approach for managing cases. Understanding the relationship between hard and soft tissues, as well as accurately estimating post-treatment facial morphology is vital.

Recent advancements in AI-based three-dimensional (3D) facial prediction systems have demonstrated that the pre-treatment facial shape plays a critical role in predicting the post-treatment facial outcome.²⁴ This suggests that identifying the pre-treatment profile pattern is invaluable in determining the appropriate ratios of soft tissue to hard tissue movements, ultimately leading to a moderate to high correlation in estimating the post-treatment facial outcome.

In practice, orthodontists focus on the position of the lower lip to determine the placement of the mandibular incisors, rather than relying solely on upper lip position.²⁴ Furthermore, in cases involving premolar extractions, the repositioning of the upper and lower lips can be predicted with moderate to high accuracy through regression models based on AI-determined profile patterns. Notably, changes in incisor inclination after orthodontic treatment significantly affects soft tissue facial configurations. Importantly, the specific pattern of facial change varies according to the pre-treatment nasal-lip-chin profile.

Decision-making in orthognathic surgery

Determining the most effective strategic approach for borderline cases which fall between orthodontic camouflage and orthognathic surgery remains a challenging aspect of treatment planning.²⁵ Establishing precise diagnostic measures is critical

for navigating complex clinical scenarios.²⁶ An advanced AI-based machine learning model has demonstrated remarkable accuracy in distinguishing between cases requiring surgical intervention and those who can be treated non-surgically. The model is also highly accurate in determining the type of surgery required and whether extractions are necessary. Furthermore, researchers have developed an AI model capable of predicting facial morphology following orthognathic surgery and assessing the soft tissue profiles (Figure 7).^{26,27} Using three-dimensional facial images, the model achieves an impressive average system error. However, the model tends to underestimate dysplasias associated with asymmetrical cases and those characterised by cranial or caudal displacement.²⁶

Treatment outcome prediction

The use of digital setup models provides orthodontists with a detailed visualisation of potential treatment plan alterations (Figure 8), which significantly enhances their abilities. Throughout the therapy process, the models assist practitioners in making informed judgments by displaying projected outcomes.²⁸ Simultaneously, an AI model built on the Convolutional Neural Network (CNN) architecture has demonstrated an ability to predict changes in the soft tissues, skeletal structure, and dental structure, as well as visually displaying the expected alterations.²⁹ Furthermore, an AI-powered system combining deep learning approaches with Gaussian Mixture Models (GMMs) can reliably predict 3D facial topography after orthognathic surgery and orthodontic therapy.³⁰ Together, these advancements in digital modelling and AI technology not only improve the accuracy of treatment outcome predictions but also enhance communication between orthodontists and their patients, resulting in more effective discussions about treatment plans, increased patient co-operation, and improved satisfaction.^{28–30}

Clinical Practice

Research indicates that incorporating AI into clinical practice opens opportunities for the development of precise solutions that enhance therapeutic care and outcomes, particularly for less experienced orthodontists. Notably, AI can serve as a valuable resource for seeking a second opinion.³¹

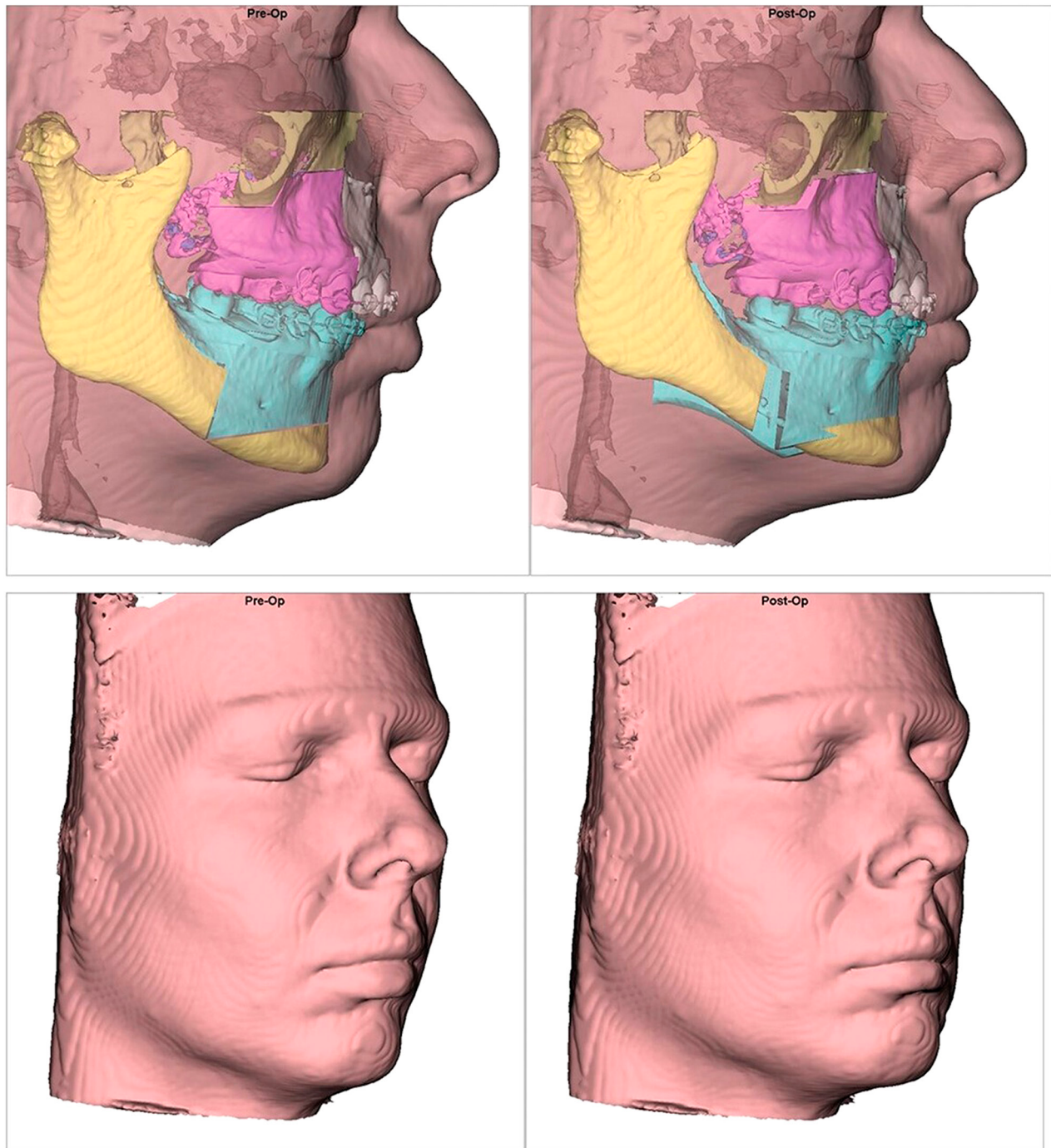


Figure 7. The prediction of facial morphology after orthognathic surgery and orthodontic treatment.²⁷

Practice guidance

The implementation of a computer-based AI decision support system (DSS) has shown promising outcomes. The algorithm's conclusions have demonstrated remarkable precision and a high level of agreement with actual therapy modifications.³²

This degree of accuracy indicates how AI-driven solutions can enhance clinical judgment.

Remote care

Remote monitoring is an intriguing new concept that has the potential to revolutionise orthodontic

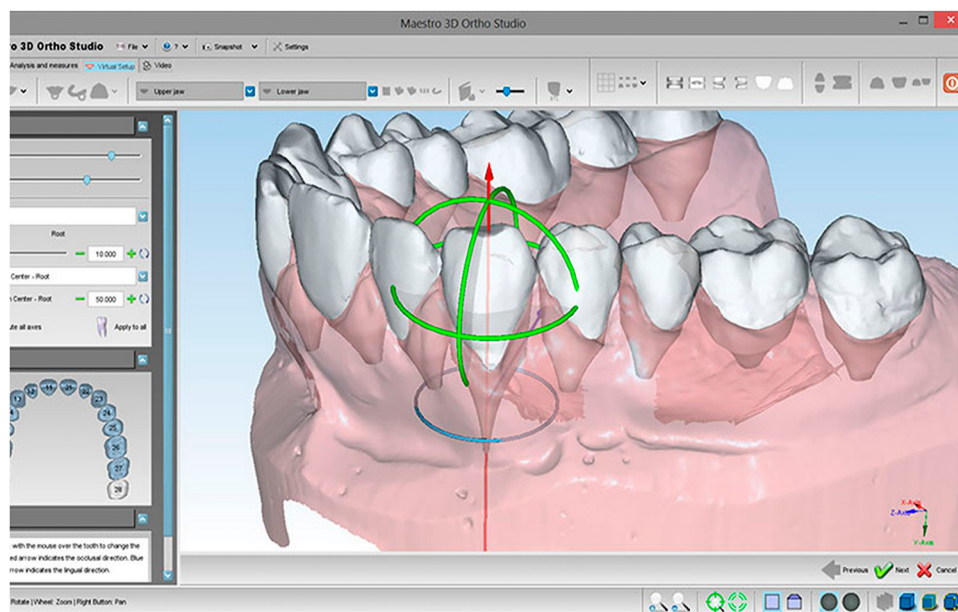


Figure 8. Detailed digital setup.²⁸

practice.³³ This breakthrough concept, known as AI-driven Remote Monitoring (AIRM), allows clinicians to remotely monitor their patients by scanning and capturing images of their dentition via a smartphone. Accordingly, AIRM may significantly reduce the frequency of in-person appointments required for patients undergoing clear aligner treatment, thereby increasing flexibility and convenience, with participants generally expressing a positive perception of the experience.³³ Remote monitoring strengthens the doctor-patient relationship by enabling professionals to communicate and closely monitor patient progress. Additionally, patients receive regular updates on their treatment progress and feedback through the software.³³ Overall, the advantages of AI-driven remote monitoring include enhanced patient care for fixed appliances, aligners and other mechanics, thereby making orthodontics more effective and responsive.

Clinical documentation

As orthodontic treatment necessitates continuous image collection, practitioners have increasingly relied on automated categorisation and monitoring systems that utilise deep learning techniques.³⁴ Traditional methods of photography and radiography often encounter problems related to missing and

duplicate images, which necessitate manual data storage for each patient.³⁴

To address the issue, a deep learning algorithm based on DeepID (Abacus Research AG, Wittenbach, Switzerland) has been developed to classify and efficiently archive orthodontic images. The findings indicate that deep learning algorithms can automatically categorise, archive, and monitor orthodontic images with greater accuracy and speed than traditional methods and facilitate the quick retrieval of important data within a large library of photographs. Furthermore, the innovations enhance the effectiveness of dental follow-up and treatment processes, thereby reducing the orthodontic workload.³⁴

Education and training

Virtual reality (VR), augmented reality (AR), and AI are revolutionary technological advancements that have the potential to transform orthodontic teaching and research.³⁵ Intelligent tutoring systems (ITSs), when integrated with laboratory and pre-clinical training, as well as patient-centred interactive instruction, can significantly improve learning outcomes. AI-enabled simulators are particularly effective in enhancing motor skills and student efficiency while reducing the time required by teachers and tutors.³⁵

Limitations

The future of AI in orthodontics is promising and diverse, with applications ranging from accurate diagnostic and guidance systems to improved patient communication. However, a considerable number of challenges must be addressed before AI can be widely and completely implemented in practice.

The current AI systems often overlook the existence of oral diseases, inadequately incorporate facial analysis into their algorithms, and fail to sufficiently consider the detrimental effects of functional problems on treatment outcomes.³⁶ Additionally, while AI systems can provide valuable insights, they cannot fully comprehend the unique demands of each patient, as they lack the clinical background of a professional orthodontist. The integration of AI into healthcare also raises ethical concerns, including biased algorithms and the potential for automation to replace human labour. Moreover, data privacy and transparency are critical considerations, especially since orthodontic datasets pose significant privacy and security risks due to their sensitive nature, including clinical images that can identify patients. Furthermore, different data modalities are often stored in separate repositories, known as ‘data silos’ which complicates access and integration.^{37,38}

Consequently, most currently-used orthodontic AI algorithms are trained and evaluated on unicentric datasets. This reliance on limited datasets introduces inherent risks, such as poor predictive performance with new data and significant biases, leading to variations across diverse patient populations. To ensure the development of equitable and generalisable algorithms, expanding the datasets used for training and testing is essential.³⁸ By recognising and addressing the challenges, the orthodontic community can better leverage the potential of AI technologies and develop solutions that improve care while adhering to ethical standards and prioritising patient safety.

Conclusion

The integration of artificial intelligence into orthodontics has significantly improved diagnostic accuracy, treatment planning, and clinical efficiency. AI-powered technologies currently enhance cephalometric analysis, facial assessment, and skeletal maturation evaluation, which are important tools that

support clinicians in decision-making. Furthermore, the translation of AI into clinical practice in areas such as remote monitoring, practice optimisation, and automated documentation, amongst others, has eased workflows and improved patient care. However, in parallel with these promising trends, challenges related to algorithmic bias, ethical considerations, and data privacy concerns remain critical obstacles to widespread implementation. In this respect, the orthodontic role of AI should be regarded as a complementary tool in continuous evolution that enhances, rather than replaces clinical expertise, thereby ensuring that patient-centred care and ethical standards remain at the core of orthodontic practice.

Conflict of interest

The authors declare that there is no conflict of interest.

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