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THE SCIENTIFIC BASIS AND PRACTICAL SIGNIFICANCE OF APPLYING ARTIFICIAL INTELLIGENCE TECHNOLOGIES IN THE DIAGNOSIS OF DENTO-MAXILLARY SYSTEM ANOMALIES AND DEFORMATIONS

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Relevance: Traditional diagnosis of dento-maxillary anomalies is a laborious, subjective, and error-prone process. The analysis of radiographs and 3D models depends on the clinician's experience, which can lead to diagnostic discrepancies among different specialists. Artificial intelligence (AI) technologies offer immense potential to address these challenges by enhancing diagnostic accuracy, automating processes, and facilitating the development of personalized treatment plans for each patient. The integration of AI into orthodontics and dentistry holds significant scientific and practical relevance for improving treatment outcomes and increasing clinical efficiency.

Keywords: artificial intelligence, orthodontics, dento-maxillary anomalies, diagnosis, deep learning, machine learning, cephalometric analysis, CBCT, 3D modeling.

НАУЧНЫЕ ОСНОВЫ И ПРАКТИЧЕСКОЕ ЗНАЧЕНИЕ ПРИМЕНЕНИЯ ТЕХНОЛОГИЙ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В ДИАГНОСТИКЕ АНОМАЛИЙ И ДЕФОРМАЦИЙ ЗУБОЧЕЛЮСТНОЙ СИСТЕМЫ

Актуальность: Традиционная диагностика аномалий зубочелюстной системы является трудоемким, субъективным и подверженным человеческим ошибкам процессом. Анализ рентгеновских снимков и 3D-моделей зависит от опыта клинициста, что может приводить к расхождениям в диагнозах у разных специалистов. Технологии искусственного интеллекта (ИИ) предоставляют огромные возможности для решения этих проблем, повышая точность диагностики, автоматизируя процесс и способствуя разработке индивидуализированных планов лечения для каждого пациента. Интеграция ИИ в ортодонтию и стоматологию имеет актуальное научное и практическое значение для улучшения результатов лечения и повышения эффективности работы клиницистов.

Ключевые слова: искусственный интеллект, ортодонтия, зубочелюстные аномалии, диагностика, глубокое обучение, машинное обучение, цефалометрический анализ, КЛКТ, 3D-моделирование.

TISH-JAG' TIZIMI ANOMALIYALARI VA DEFORMATSIYALARINI TASHXISLASHDA SUN'IY INTELLEKT TEXNOLOGIYALARINI QO'LLASHNING ILMIY ASOSLARI VA AMALIY AHAMIYATI

Dolzarbligi: Tish-jag' tizimi anomaliyalarini an'anaviy tashxislash ko'p vaqt talab qiladigan, sub'ektiv va inson xatolariga moyil bo'lgan jarayondir. Rentgen suratlari va 3D modellarni tahlil qilish klinisyenning tajribasiga bog'liq bo'lib, bu turli mutaxassislar o'rtasida tashxisda farqlarga olib kelishi mumkin. Sun'iy intellekt (SI) texnologiyalari ushbu muammolarni hal qilish uchun ulkan imkoniyatlar yaratadi, diagnostika aniqligini oshiradi, jarayonni avtomatlashtiradi va har bir bemor uchun individual davolash rejasini ishlab chiqishga yordam beradi. SI ning ortodontiya va stomatologiyaga integratsiyasi davolash natijalarini yaxshilash va klinisyenlar ish samaradorligini oshirish uchun dolzarb ilmiy va amaliy ahamiyatga ega.

Kalit so'zlar: sun'iy intellekt, ortodontiya, tish-jag' anomaliyalari, diagnostika, chuqur o'rganish, mashinali o'rganish, sefalometrik tahlil, KLLT, 3D modellashtirish.

INTRODUCTION

The complexity of traditional orthodontic diagnosis - The diagnosis of dento-maxillary anomalies and deformations is the cornerstone of effective orthodontic treatment. This process requires a meticulous and simultaneous evaluation of a patient's skeletal, dental, and soft tissue structures from multiple perspectives. Traditionally, clinicians have relied on a combination of patient interviews, clinical examinations, and the analysis of diagnostic records, including dental impressions and radiographic images. Cephalometric analysis, a foundational technique involving the manual tracing of anatomical landmarks on lateral skull radiographs, has been the gold standard for assessing skeletal patterns and planning treatment for decades.

However, these conventional methods are fraught with inherent limitations. Manual landmark identification is a laborious and time-consuming task that is highly dependent on the clinician's experience and expertise, leading to significant inter- and intra-observer variability. The interpretation of 2D radiographs can be challenging due to overlapping anatomical structures and geometric distortions, which may not fully capture the three-dimensional reality of a patient's craniofacial morphology. Similarly, the analysis of physical dental models is a manual process prone to measurement errors. These challenges underscore a critical need for diagnostic tools that can enhance accuracy, improve consistency, and streamline the clinical workflow.

The emergence of artificial intelligence in dentistry - In recent years, Artificial Intelligence (AI) has emerged as a transformative technology across numerous medical fields, and dentistry is no exception. AI, particularly its subfields of machine learning (ML) and deep learning (DL), involves the development of algorithms that enable computers to learn from data, identify complex patterns, and make predictions or decisions without being explicitly programmed for each task. These technologies excel at analyzing vast and complex datasets, such as medical images, with a level of speed and precision that can surpass human capabilities.

Deep learning models, especially Convolutional Neural Networks (CNNs), are inspired by the structure of the human brain and are exceptionally proficient at processing visual data. In dentistry, this has opened up new frontiers for automating image-based diagnostic tasks. AI systems can be trained on thousands of annotated radiographs and 3D scans to recognize anatomical structures, detect pathologies like caries or periapical lesions, and perform complex measurements with high accuracy. This technological revolution promises to move orthodontic diagnosis from a subjective art to a data-driven science, providing clinicians with powerful decision-support tools.

Objectives of the review - The rapid evolution of AI technologies presents both immense opportunities and significant challenges for the field of orthodontics. As these tools become more integrated into clinical software and workflows, it is imperative for clinicians to understand their underlying scientific principles, current capabilities, and practical implications. This article aims to provide a comprehensive overview of the scientific basis and practical significance of applying AI in the diagnosis of dento-maxillary system anomalies. Specifically, this review will: 1) Explore the core AI technologies being applied to orthodontic imaging. 2) Detail the key applications of AI in 2D cephalometric and 3D model analysis. 3) Discuss the impact of AI on diagnostic accuracy, efficiency, and treatment planning. 4) Examine the current challenges and future directions for AI in orthodontics.

By synthesizing the current body of research, this article seeks to provide a clear framework for understanding how AI is reshaping the landscape of orthodontic diagnosis and care.

Key AI applications in dento-maxillary diagnosis - Artificial intelligence is being applied across the entire spectrum of orthodontic diagnosis, from foundational 2D analysis to complex 3D simulations. These applications are not merely automating old processes but are enabling new levels of precision and insight.

Automated cephalometric analysis - Cephalometric analysis remains a fundamental diagnostic tool in orthodontics, and its automation has been a primary focus of AI research. Deep learning algorithms, particularly CNNs, have demonstrated remarkable success in automatically identifying cephalometric landmarks on lateral radiographs.

These AI systems are trained on large datasets of cephalograms that have been manually annotated by expert orthodontists. The model learns to recognize the complex patterns and anatomical features associated with each landmark. Studies have shown that modern AI models can achieve a success detection rate (SDR) of 75-90% within a clinically acceptable 2mm error range, a performance level that is comparable, and in some cases superior, to that of human examiners. The practical benefits are substantial: automated analysis drastically reduces the time required for manual tracing from minutes to seconds, eliminates subjective operator error, and provides a consistent, reproducible basis for diagnosis and treatment planning.

3D model analysis and anomaly detection - The advent of Cone-Beam Computed Tomography (CBCT) and intraoral scanners (IOS) has shifted orthodontic diagnosis towards a three-dimensional paradigm, offering a more complete and accurate representation of a patient's anatomy. However, the manual analysis of these large 3D datasets can be exceedingly complex and time-consuming. AI is proving indispensable in this area.

AI-powered software can automatically perform 3D segmentation, which involves isolating individual teeth, skeletal structures (maxilla, mandible), and airways from a CBCT scan. This process, which would take a human expert hours to complete manually, can be done by an AI in minutes, with high accuracy. Once segmented, these 3D models can be used for a variety of diagnostic tasks :

Malocclusion Classification: AI algorithms can analyze digital models from intraoral scans to automatically determine Angle classification and measure parameters like overjet, overbite, and tooth size discrepancies (Bolton analysis).

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Skeletal Analysis: By identifying landmarks on 3D CBCT reconstructions, AI can perform comprehensive 3D cephalometric analysis, providing a more accurate assessment of skeletal discrepancies than 2D methods.

Data Fusion: Advanced AI models can fuse data from different sources, such as the high-resolution crown data from an intraoral scan with the root and bone data from a CBCT scan. This creates a complete and highly accurate 3D digital patient, enabling precise treatment planning and simulation.

Growth prediction and treatment planning support - One of the most challenging aspects of orthodontics, particularly in adolescent patients, is predicting future craniofacial growth. AI is beginning to offer powerful tools to address this challenge. By training on large longitudinal datasets of cephalometric images, deep learning models can learn to predict mandibular growth patterns with a high degree of accuracy, outperforming junior clinicians in some studies. This capability is critical for determining the optimal timing and strategy for interventions like functional appliances or orthognathic surgery.

Furthermore, AI serves as a powerful decision-support system for treatment planning. Algorithms can analyze a patient's diagnostic data and help determine the need for tooth extractions or predict the final outcome of different treatment modalities. By simulating tooth movement, AI can help orthodontists visualize and plan the most efficient and stable treatment path, moving the field closer to truly personalized and predictable care.

Table 1.

Summary of Key AI applications in dento-maxillary diagnosis.

AI Application	**Diagnostic task**	**Key technologies**	**Primary benefit**
2D Cephalometry	Automated landmark identification and analysis	Deep Learning, Convolutional Neural Networks (CNNs)	Increased speed, accuracy, and consistency; elimination of manual tracing errors.
3D Model analysis	Segmentation of teeth and bone from CBCT, malocclusion classification, 3D cephalometry	Deep Learning, CNNs, Data Fusion Algorithms	Comprehensive 3D visualization, precise measurement of complex structures, improved surgical planning.
Growth prediction	Forecasting mandibular and maxillary growth patterns in adolescents	Deep Learning, Longitudinal Data Analysis	Improved timing of treatment, more accurate planning for growth-dependent therapies.
Treatment	Decision support for	Machine Learning,	Enhanced personalization

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planning	extractions, outcome prediction, tooth movement simulation	Predictive Modeling	of treatment, optimization of clinical decisions, improved predictability.

MATERIAL AND METHODS

The power of AI in diagnosing dento-maxillary anomalies is rooted in sophisticated computational models that are trained to learn from clinical data. Understanding these foundational concepts is key to appreciating their application and limitations.

Machine learning and supervised learning - Most AI applications in orthodontic diagnosis are based on machine learning (ML), a field of computer science where algorithms learn patterns from data without being explicitly programmed. The predominant approach is supervised learning. In this paradigm, the ML model is trained on a large dataset where the "correct answers" (or labels) are already known. For example, to train an AI to identify cephalometric landmarks, developers use thousands of radiographs where experts have already marked the precise location of each landmark. The algorithm processes these examples, learning the statistical relationships between the image pixels and the landmark locations, and adjusts its internal parameters to minimize the difference between its predictions and the expert labels.

Deep learning (DL) is a more advanced subset of ML that uses multi-layered artificial neural networks, allowing it to learn from data in a more hierarchical and complex manner. For image analysis, the most effective DL architecture is the Convolutional Neural Network (CNN). CNNs are uniquely designed to process grid-like data, such as images. They employ specialized layers called convolutional layers that act as feature detectors, automatically learning to identify relevant features ranging from simple edges and textures in the initial layers to complex anatomical shapes like teeth or jaws in deeper layers. This ability to automatically extract features from raw image data is what makes CNNs so powerful and accurate for tasks like landmark detection, object classification (e.g., identifying a specific anomaly), and image segmentation.

The performance of any AI model is fundamentally dependent on the quality and quantity of the data used for its training. To build a robust and generalizable diagnostic AI, several data-related factors are critical:

Large Datasets: ML models, especially deep learning ones, require thousands of examples to learn effectively and avoid errors.

High-Quality Annotations: The "ground truth" labels used for training (e.g., landmark locations, segmented areas) must be accurate and consistent, often requiring input from multiple calibrated experts.

Data Diversity: The training data must be representative of the diverse patient population on which the AI will be used, encompassing variations in age, ethnicity, sex, and image quality to ensure the model is not biased and performs well in real-world scenarios.

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Once trained, a model must be rigorously validated on a separate, unseen "test" dataset to assess its true performance. Metrics such as accuracy, sensitivity, and precision are used to quantify its effectiveness. This validation process is crucial for ensuring the clinical reliability and safety of AI diagnostic tools.

PRACTICAL SIGNIFICANCE AND FUTURE OUTLOOK

The integration of AI into the diagnosis of dento-maxillary anomalies is not a futuristic concept but a present-day reality that is already beginning to reshape clinical practice. The practical implications are profound, offering benefits to both clinicians and patients, though important challenges remain.

Impact on clinical practice - The most immediate and significant impact of AI is the enhancement of diagnostic accuracy and efficiency. By automating repetitive and time-consuming tasks like cephalometric tracing and model analysis, AI dramatically reduces the diagnostic workload, allowing clinicians to dedicate more time to critical thinking, treatment strategy, and patient communication. Moreover, AI acts as a "second opinion," providing an objective and consistent analysis that minimizes the subjective variability inherent in human interpretation. This leads to a more standardized and reliable diagnostic process, particularly for less experienced practitioners, whose precision and accuracy can be significantly improved with AI augmentation. This synergy between human expertise and artificial intelligence elevates the quality and consistency of care.

Toward personalized orthodontics - Beyond improving current diagnostic methods, AI is paving the way for truly personalized medicine in orthodontics. By integrating and analyzing multimodal data—including 3D imaging, patient health records, and even genetic information—AI can help create comprehensive digital models of each patient. These models can be used to simulate different treatment options and predict their outcomes with a high degree of accuracy. This predictive capability allows clinicians to design treatment plans that are not only tailored to the patient's unique anatomy but also optimized for efficiency, stability, and long-term periodontal health. This data-driven approach moves orthodontics from a reactive to a proactive discipline, where potential risks can be identified and mitigated before treatment even begins.

Challenges and the path forward - Despite its immense potential, the widespread adoption of AI in dento-maxillary diagnosis faces several hurdles. A primary challenge is the need for large, diverse, and well-curated datasets for training and validation, which requires significant collaboration among institutions. The "black box" nature of some complex deep learning models—where it is difficult to understand exactly how the AI arrived at a decision—raises questions of interpretability and trust that must be addressed.

Furthermore, regulatory approval (e.g., from bodies like the U.S. Food and Drug Administration) is essential for ensuring the safety and efficacy of AI-enabled medical devices. Finally, it is crucial to emphasize that AI is a tool to **augment, not replace, the clinician**. The final diagnostic and treatment decisions must always rest with the human expert, who can integrate the AI's output with their clinical judgment, patient context, and ethical considerations. The future of orthodontics lies in a collaborative synergy where the computational power of AI enhances the irreplaceable wisdom and empathy of the clinician.

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CONCLUSION

The application of artificial intelligence technologies marks a pivotal moment in the evolution of diagnosing dento-maxillary anomalies and deformations. We are transitioning from an era defined by manual, subjective, and time-intensive methods to one characterized by automated, objective, and highly efficient data-driven analysis. This review has illuminated the scientific foundations of AI, particularly machine and deep learning, and detailed their transformative applications in automating cephalometric analysis, interpreting complex 3D imaging, and providing powerful decision support for treatment planning.

The clinical implications of this technological shift are profound. For clinicians, AI offers the promise of enhanced diagnostic accuracy, reduced variability, and a streamlined workflow, freeing them to focus on the strategic aspects of patient care. For patients, it translates to more precise diagnoses, personalized treatment plans, and potentially more predictable and stable outcomes.

While challenges related to data standardization, clinical validation, and regulatory oversight must be diligently addressed, the trajectory is clear. Artificial intelligence is set to become an integral and indispensable component of the orthodontic toolkit. The future will be defined by a powerful synergy between the analytical prowess of AI and the indispensable clinical judgment of the practitioner, working in concert to advance the science of orthodontics and deliver a higher standard of care to patients worldwide.

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