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Transformative Digital Innovations in Orthodontics: The Role of Artificial Intelligence, 3D Printing, and Facial Recognition in Enhancing Diagnostic and Treatment Approaches

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Abstract

Background: The integration of digital technologies in orthodontics, particularly artificial intelligence (AI), 3D printing, and facial recognition, is transforming diagnostic and treatment methodologies. This paradigm shift emphasizes a patient-centered approach that prioritizes aesthetic outcomes and individualized care.

Methods: This scoping review examines the current literature on the application of AI, 3D printing, and facial recognition technologies in orthodontics. A comprehensive search was conducted using the Scopus database, focusing on English-language publications from 2018 to 2023. The review evaluates the impact of these technologies on treatment planning, patient outcomes, and the overall efficiency of orthodontic practice.

Results: The findings indicate that AI enhances diagnostic accuracy and treatment planning through automated analysis of cephalometric data and facial structures. 3D printing facilitates the creation of customized orthodontic appliances, improving fit and comfort. Facial recognition technologies offer innovative solutions for assessing craniofacial aesthetics and treatment outcomes. Despite the benefits, challenges such as data privacy, algorithm transparency, and the need for clinical validation remain significant.

Conclusion: The adoption of digital technologies in orthodontics is revolutionizing the field by enhancing precision and personalization in treatment. However, ongoing research is essential to address the limitations and ensure the successful integration of these innovations into clinical practice. Future studies should focus on the long-term impact of these technologies on patient care and outcomes.

Keywords: Orthodontics, artificial intelligence, 3D printing, facial recognition, digital technology.

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1. Introduction

Contemporary orthodontics has transitioned from a "occlusion-driven" approach to a "face-driven" paradigm. The phrase "soft tissues paradigm" originated in the late 20th century, emphasizing the necessity of treating each orthodontic patient as a distinct individual with a particular appearance, unique facial structure, and personal expectations, while prioritizing aesthetics [1]. Conversely, the Angle paradigm saw the optimal dental occlusion as crucial. The significance of soft tissues was entirely overlooked or, at best, minimized. The continuous advancement of computer technology and artificial intelligence, alongside established aesthetic principles grounded in anatomical and physiognomic evaluation, heralds the emergence of sophisticated diagnostic techniques and innovative treatment options [2].

Historically, an orthodontic therapy plan was exclusively based on hard tissue interactions assessed using dental cast models and two-dimensional cephalometric X-ray evaluations [3]. At the conclusion of the 20th century, cone-beam computed tomography (CBCT), with a cone-shaped X-ray beam and a reciprocating detector spinning around the patient, was developed, facilitating the acquisition of 3D images with reduced radiation exposure relative to traditional CT scans [4]. The proliferation of cameras, particularly digital ones, has made it standard practice in orthodontics to capture intraoral and extraoral photographs before and after treatment, facilitating the evaluation of treatment effects on patients' dental arches and, to a degree, their facial aesthetics. Nonetheless, some constraints exist inside the two-dimensional "reality." Three-dimensional and four-dimensional imaging techniques have been created to address the absence of depth in conventional photographs. Active stereophotogrammetry relies on the examination of an image projected onto the scanned item. Passive stereophotogrammetry integrates numerous images captured from various perspectives to generate a singular 3D object [5]. Incorporating the temporal dimension into diagnostics facilitates more comprehensive studies, particularly in individuals with cleft lip and/or palate or facial asymmetries, with age serving as a significant diagnostic variable [6,7].

Intraoral imaging, laser examination, cone-beam computed tomography (CBCT), stereophotogrammetry, and three-dimensional imaging are essential components of contemporary orthodontics. Notwithstanding their limits and shortcomings, 3D technologies are emerging as the predominant choice, particularly in more intricate scenarios [8]. They provide comprehensive and accurate input data to testing and treatment-planning systems [9-11]. Data from intraoral and/or face scanners may be integrated with CBCT scans to enhance the comprehension of underlying clinical problems [12,13]. Artificial intelligence enables automated cephalometric recording that is both exact and accurate, hence enhancing the efficiency of treatment planning [14,15]. The examination of 3D pictures acquired from face 3D scanners may be automated via the use of curvature mapping and sagittal aspect analysis [16]. Moreover, intraoral scanners provide data to specialized software that facilitates the planning of alterations in tooth locations, the configuration of dental arches, and interdental relationships. Integrating this software with many dental aligner manufacturers finalizes a comprehensive digital process in orthodontic treatment planning [17,18].

Contemporary techniques using pre- and post-treatment intraoral scans with an initial pretreatment CBCT scan may precisely forecast the ultimate post-treatment root position, hence obviating the need for recurrent X-ray exposure [12]. Despite the reduced radiation dosage of contemporary CBCT scanners compared to historical cephalostats, adherence to the ALARA (as low as reasonably possible) concept necessitates that each CBCT scan acquisition be thoroughly justified, particularly in the treatment of developing patients [12,19,20]. MRI scans may be used in some individuals; nonetheless, they are still suboptimal for orthodontic cephalometric analysis [21]. Similarly, digital photography may be used, to a certain degree, for landmark recognition and face analysis, hence reducing the need for more intrusive examinations [22,23].

Technological advances have been used in orthodontics for several decades. Deriving lengths and angles using standardized cephalometry and/or measuring dental plaster models facilitates data quantification. These may undergo further processing, facilitating the objective identification of malocclusions according to several indices and norms [24]. Artificial intelligence (AI) has garnered significant interest in recent years. The phrase denotes intelligent behavior shown by computers that simulate human performance in cognitive activities [25]. Artificial Intelligence in medicine can be classified into two categories: virtual AI, encompassing electronic health record systems and decision-support systems for treatment, including surgical procedures and predictive models for disease states; and physical AI, which pertains to advanced prosthetics, biomedical implants for health monitoring, and robot-assisted surgeries [26-29]. In the context of AI-assisted decision-making, it is essential to highlight that although evidence-based dentistry informs the everyday choices of dental practitioners, machine-learning models derive insights from human knowledge, enabling AI to function as an effective adviser that assimilates all pertinent information accessible [30]. This may benefit less-experienced doctors; nonetheless, other writers emphasize the need of an individualized approach facilitated by the human element [31,32].

Machine learning algorithms and the development of evidence-based orthodontics are fundamentally interconnected. Given the vast quantity of digital data accessible, AI is anticipated to play a pivotal role in generating innovative discoveries, which will eventually transform treatment planning and diagnostics in the future [33]. This research aims to discover the most-cited papers on digital advancements in orthodontics, sorted by the field-weighted citation impact ratio from Scopus, and to examine the most-cited technology within contemporary orthodontics and dentistry.

2. Methods

This review examines the extent of existing research on the use of digital technology in orthodontic treatment guided by facial features. A literature search was performed using the Scopus search engine to discover pertinent research, including articles, reviews, conference papers, and brief surveys. The search was restricted to articles authored in English and published between 2018 and 2023.

3. Artificial intelligence, 3D printing, and face recognition

Artificial intelligence, 3D printing, and face recognition are the three technological advances with the most research perspective, as demonstrated by the FWCI values of the analyzed publications. The following sections address their use in orthodontics and the constraints of this scoping study.

The literature review indicates that radiology is the medical discipline now reaping the most advantages from AI technology [34]. A significant number of research focused on evaluating the quality of acquired pictures or detecting CT, MRI scans, and X-rays that exhibited no abnormalities [35,36]. Conversely, AI methodologies may identify pathological conditions, such as dental caries on radiographs, with an escalating degree of precision [37].

Artificial intelligence and machine learning—a subset of AI that allows robots to enhance their functionalities via self-adaptive algorithms—are used in several domains of orthodontics [38]. Orthodontists, residents, and general dentists may use artificial intelligence for diagnosis, decision-making, treatment planning, and patient monitoring. An AI feature assesses the quality of 2D cephalometric X-rays, potentially excluding lower-quality images from further processing owing to probable distortion. [39] Furthermore, machine learning has been used in both lateral and 3D cephalogram analysis to enhance the precision of landmark localization.

Recent research on the integration of radiomics and AI analysis with radiologists' expertise in dentomaxillofacial imaging is very promising, suggesting that this paradigm change will significantly influence daily clinical practice and dental school curriculum [37]. Furthermore, recent research indicates that healthcare professionals favor the complete replacement of manual and semi-automatic methods in cephalometry with AI algorithms, as this would enhance time efficiency and potentially improve the accuracy of analysis results [39]. Currently, the inquiry is not about the accuracy of CBCT scans, but rather how automated processes may assist experts in landmark identification, skeletal categorization, scan interpretation, and CBCT processing [40,41]. Current study concludes that AI is very beneficial for evaluating mandibular shape asymmetry and screening upper airways to test various factors [42,43].

Artificial intelligence has emerged as a highly investigated domain during the last 10 years [37]. In addition to CBCT assessment and automated teeth classification, AI assists clinicians in treatment planning, including choices on tooth extractions [43,44]. Despite recent studies indicating that AI technology in the aforementioned domains, including the assessment of cervical vertebra maturation and the prediction of postoperative facial aesthetics, demonstrates remarkable performance and achieves precision and accuracy comparable to that of trained professionals, additional research is anticipated to clarify and further examine the advantages and disadvantages of this innovative technology [43,45,46]. It is extremely likely that, within a few years, the benefits of AI applications, particularly in orthodontics, will be undeniable. The expert opinion varies based on the facts, experience, and evidence available. Only a few years before, several writers asserted that a lateral cephalogram was more precise and precise than a 3D CBCT scan [47]. No one advocates for it now. Demystifying AI algorithms, sometimes referred to as "the black box," to enhance their comprehensibility for humans might be a method to increase AI's believability; nevertheless, this task may prove extremely tough due to the increasing complexity of the algorithms used. Another method to establish confidence in an AI system is its resilience, namely via effective practices across diverse topic populations.

Artificial intelligence is used at every tier of decision-making in orthodontics and medicine, including specializations like radiation, encompassing data collecting, storage, administration, in-depth processing, analysis, communication, and teaching [48,49]. Comprehensive study includes automated face assessment and the use of AI in identifying craniofacial anomalies and syndromes in facial scans, as well as forecasting illnesses [27,36,37,39]. Research has been conducted on evaluating face attractiveness concerning facial dimensions and profiles [50,51]. AI is expected to soon facilitate automated aesthetic assessment, smile design, and treatment planning. Utilizing machine-learning techniques, AI can accurately forecast the time of orthodontic treatment based on pretreatment data [52]. Additionally, dental monitoring software utilizing AI has demonstrated efficacy in tracking progress during the treatment phase and in identifying relapse and evaluating the consistency of treatment outcomes during the retention phase, while also assessing patient compliance without necessitating regular in-office visits [41]. The objective of contemporary technology is to enhance dental care by ensuring it is high-quality, seamless, time-efficient, and cost-effective, while also improving treatment planning and risk management; artificial intelligence undoubtedly contributes to this aim.

Artificial intelligence has been used in human gene sequencing and in the analysis of extensive datasets that provide invaluable insights into many biological processes. Data about genes that researchers are now collecting and analyzing will be essential in the shift towards really personalized therapy. These omics data are expected to become a fundamental component of orthodontic medical records, widely used in treatment planning and diagnosis. Consequently, it is essential to revise orthodontic residency programs to ensure the provision of superior orthodontic treatment.

AI algorithms are being used for automated landmark identification, cephalometric analysis, skeletal maturation staging, face recognition, syndrome detection, automatic segmentation of CBCT images, and forecasting the need for orthognathic operations or extractions, among other applications. Recent studies indicate that the accuracy of the examined techniques is clinically acceptable, making them very beneficial in orthodontic treatment [53-62]. Recent advancements in automated 3D landmarking have resulted in enhanced accuracy [63]. Nonetheless, several writers underscore the need for human interaction to mitigate mistakes in automated cephalometric analysis [64]. Further study is required to enhance the precision and accuracy of AI systems. Moreover, elucidating and clarifying the mechanisms of AI will significantly enhance its credibility.

The rapid development of AI has resulted in the creation of many AI tools, each with distinct functionalities and uses in orthodontics. These technologies may be categorized into three main types: supervised learning, unsupervised learning, and reinforcement learning. Supervised learning methods are programmed on labeled data, whereby the right output for each input is predetermined. This learning approach is particularly effective for tasks like cephalometric analysis, which involves identifying landmarks and measuring face measurements. Prominent supervised learning methods in orthodontics involve support vector machines, random forests, and neural networks. Unsupervised techniques for learning are taught on unlabeled data, aiming to identify patterns or structures without the assistance of labeled samples. This learning method is beneficial for tasks like face recognition and syndrome identification, concentrating on recognizing patterns that differentiate various facial traits. Prevalent unsupervised learning methods in orthodontics include k-means clustering, principal component analysis, and autoencoders.

Reinforcement learning algorithms engage with an environment to optimize a reward signal. This learning approach is particularly effective for activities like treatment planning, aimed at optimizing orthodontic treatment outcomes. Prominent reinforcement education methods in orthodontics include advanced Q-learning and regulatory gradient techniques. The selection of an AI tool is contingent upon the particular job and the data at one's disposal. Supervised methods of learning are often used for projects with substantial labeled data, whereas unsupervised methods of learning are better appropriate for problems with less labeled data or where the objective is to identify patterns rather than generate predictions. Reinforcement learning algorithms are especially adept at problems requiring sequential decision-making, such as treatment planning. The caliber and volume of data employed to train AI systems significantly influence the precision and efficacy of such algorithms. In orthodontics, datasets may be sourced from several sources, notably cephalometric X-rays, 3D CBCT examinations face pictures, and clinical records. The assessment of AI systems in orthodontics often entails quantifying their precision and accuracy using a reserved test dataset. Accuracy quantifies the ratio of accurate forecasts, while precision quantifies the ratio of right positive predictions.

4. Three-Dimensional Fabrication

Additive manufacturing, or three-dimensional printing, is a method that constructs structures by incrementally adding material, in contrast to subtractive manufacturing, commonly known as milling operations, which produces products by eliminating surplus material from a solid block. In dentistry, 3D printing is used in maxillofacial surgery, implantology, prosthodontics, and orthodontics. Metals, ceramics, polymers, and hydrogels are used for 3D printing applications. Recently, (bio)printing using cells, matrices, and growth factors to fabricate tissues, including dental, jawbone, and periodontal tissues, has garnered increasing interest. Numerous processes are used in 3D printing, including stereolithography, laser-based technologies, electron beam melting, fused deposition modeling, laminated item production, and inkjet printing [65]. Similar to other technologies, 3D printing has both merits and drawbacks. The drawbacks include elevated expenses and considerable time requirements for postprocessing. The benefits include the substantial yield of utilized resources, the capability to construct intricate structures, and the exceptional precision and correctness of 3D-printed items [42,66].

3D-printing techniques have revolutionized orthodontics and orthognathic surgery. Additive manufacturing is used to produce research models, clear aligners (either by direct printing or using 3D-printed models), various surgical guides (including those for mini-implant placements), components for permanent or removable appliances, and occlusal splints [18]. Highly individualized lingual appliances seem to have the additional benefit of superior results [32,67]. Similarly, efforts have been made to advocate for in-office custom-fabricated brackets for vestibular equipment [68]. In patients with unilateral full cleft lip and palate, a 3D-printed nasoalveolar molding appliance was used preoperatively to enhance treatment outcomes [50].

Given the many facets of additive manufacturing, it is feasible to assert that its use will expand in personalized orthodontics, regenerative dentistry, implantology, and maxillofacial surgery. Consequently, the information and abilities essential for understanding digital workflow in everyday practice must be developed in pre- and postgraduate students, residents, and experts. To ensure the provision of excellent treatment to patients, dental curriculum and elective courses must promptly adapt to technological advancements [69,70].

5. Facial Recognition

A prominent subject in a contemporary study on digital technology in orthodontics is face scanning. Similar to other innovative diagnostic or therapeutic approaches, one must first go outside their comfort zone to contemplate them, then examine the supporting data, and ultimately choose to adopt contemporary trends and technology advancements in clinical environments. A solid theoretical foundation and relevant practical experience are crucial before engaging with patients to mitigate potential mistakes arising from a complete absence of competence. Modernized formal education, lectures, study groups, and diverse practical courses are essential.

The fundamental need for the digital revolution is the objective of the alteration. It was observed that advancement for the mere sake of advancement is unwise. Reliability, precision, and time efficiency are among the factors that may catalyze the transformation. Facial scans acquired with the 3D light scanner Artec Eva were juxtaposed with direct craniofacial measurements taken with a caliper. The research demonstrated the superior precision of the digital approach. Nonetheless, the digital approach necessitated double the time in comparison to the direct technique [71].

Numerous studies have assessed the precision and dependability of lower-cost devices. Stereophotogrammetry appears to have significant promise as a substitute for laser imaging in medical applications [72]. A meta-analysis indicates that professional 3D imaging systems exhibit more precision than contemporary face scanning software in portable smart devices [8]. Nonetheless, the disparities seem to be clinically tolerable [73]. Kinect devices provide an economical 3D imaging method applicable in orthodontics and surgery planning [74]. The Bellus3D and Capture programs seem advantageous relative to the stereophotogrammetry approach used by a 3dMD system; yet they want much more patience from the patient, since both the capturing and processing durations are markedly extended [34]. A further research contrasted Bellus3D pictures with facial surfaces delineated from CBCT scans. The scientists determined that Bellus3D has some practical applications in orthodontics; nonetheless, existing technologies exhibit limits regarding accuracy [49]. Further research is required to elucidate the degree to which disparities across different face-scanning technologies affect therapeutic results and their correlation with pre- and post-treatment CBCT scans. A particular investigation indicated that collection methods do not significantly influence measurement variances [75].

A question persists: Is it possible to recreate faces using existing photographs? The methodology for generating 3D facial representations from 2D images is confirmed, since the obtained measures are clinically satisfactory. Nevertheless, this technique requires significant time and labor [76]. The benefits of this radiation-free screening tool, particularly for developing individuals, must be underscored. Studies indicate that face scans and subsequent soft tissue studies may effectively assess the results of removal or orthognathic surgery, demonstrating both adequate repeatability and reliability [77,78].

This study emphasized the capacity of AI to transform the fields in which it is used. The study illustrates the adaptability and versatility of this technology. In the realm of bioelectronics, artificial intelligence is assisting in addressing the issues related to material development, manufacturing techniques, and system integration. In orthodontics, AI facilitates face analysis that transcends basic symmetry and proportionality, offering a more thorough comprehension of facial anatomy and its influence on tooth alignment. Artificial intelligence facilitates the customization of treatment techniques to meet the specific demands of individual patients. Artificial intelligence may customize device design and selection according to patient-specific attributes in bioelectronics. In orthodontics, AI-facilitated face analysis may discern distinctive facial characteristics and enhance treatment strategies appropriately. Data-driven decision-making is essential for directing AI-based decision-making processes. In bioelectronics, artificial intelligence algorithms analyze extensive datasets to discern trends and enhance device efficacy. Facial analysis techniques in orthodontics use patient data, including 2D or 3D scans, to provide insights for arranging treatment [79].

6. Conclusions

The use of AI, 3D printing, and face scanning in orthodontics is affecting a paradigm change in the discipline. These technologies are revolutionizing orthodontic practice, enhancing accuracy, efficiency, and patient-centeredness. As these technologies advance, they will significantly influence the future of orthodontics. The use of AI in orthodontics has unveiled a realm of opportunities and is poised to revolutionize the discipline and enhance patient care. Although AI remains in its nascent phase of research, its capacity to enhance diagnosis, treatment planning, and patient outcomes is indisputable. As artificial intelligence progresses, it is essential for orthodontists and dental students to be informed about the newest developments and have a robust foundation in digital technology. This will guarantee that orthodontics harnesses the capabilities of AI and facilitates a new epoch of individualized, data-driven treatment.

This study indicates that face-guided orthodontics is gaining prominence and is integral to a multifaceted AI revolution in the profession, resulting in an unparalleled paradigm change. Artificial intelligence will enable the management of challenging activities, like the analysis of intricate face traits and simulations. We are now in the first stage of integrating AI into routine orthodontic treatment.

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الابتكارات الرقمية التحويلية في تقويم الأسنان: دور الذكاء الاصطناعي، الطباعة ثلاثية الأبعاد، والتعرف على الوجه في تحسين التشخيص والعلاجات

الملخص

الخلفية:

يُحدث دمج التقنيات الرقمية في تقويم الأسنان، ولا سيما الذكاء الاصطناعي(AI) ، والطباعة ثلاثية الأبعاد، وتقنيات التعرف على الوجه، تحولًا كبيرًا في أساليب التشخيص والعلاج. ويؤكد هذا التغيير على نهج يركز على المريض، مع إعطاء الأولوية للنتائج الجمالية والرعاية الفردية.

المنهجية:

تبحث هذه المراجعة الاستكشافية في الأدبيات الحالية حول تطبيق الذكاء الاصطناعي، الطباعة ثلاثية الأبعاد، والتعرف على الوجه في مجال تقويم الأسنان .تم إجراء بحث شامل باستخدام قاعدة بيانات Scopus، مع التركيز على المنشورات باللغة الإنجليزية بين عامي 2018و2023 .تُقيّم المراجعة تأثير هذه التقنيات على تخطيط العلاج، نتائج المرضى، وكفاءة ممارسات تقويم الأسنان.

النتائج:

تشير النتائج إلى أن الذكاء الاصطناعي يُحسن دقة التشخيص وتخطيط العلاج من خلال التحليل الآلي لبيانات السيفالومتري (الأشعة الرأسية) وهياكل الوجه .الطباعة ثلاثية الأبعاد تُسهم في تصنيع أجهزة تقويم مخصصة، مما يحسن من الملاءمة والراحة .تقنيات التعرف على الوجه توفر حلولًا مبتكرة لتقييم الجماليات القحفية الوجهية ومتابعة نتائج العلاج .ورغم الفوائد الكبيرة، لا تزال هناك تحديات مثل حماية البيانات، شفافية الخوارزميات، والحاجة إلى التحقق السريري.

الاستنتاج:

يُحدث اعتماد التقنيات الرقمية في تقويم الأسنان ثورة في المجال من خلال تحسين الدقة والتخصيص في العلاج .ومع ذلك، تظل البحوث المستمرة ضرورية لمعالجة التحديات وضمان التكامل الناجح لهذه الابتكارات في الممارسات السريرية. ينبغي أن تركز الدراسات المستقبلية على التأثير طويل المدى لهذه التقنيات على رعاية المرضى ونتائج العلاج.

الكلمات المفتاحية :تقويم الأسنان، الذكاء الاصطناعي، الطباعة ثلاثية الأبعاد، التعرف على الوجه، التكنولوجيا الرقمية.