AIMS Biophysics, 9(3): 182–197.
DOI: 10.3934/biophy.2022016
Received: 18 March 2022
Revised: 29 May 2022
Accepted: 13 June 2022
Published: 08 July 2022

http://www.aimspress.com/journal/biophysics

Review

Artificial intelligence and 3D printing technology in orthodontics: future and scope

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Abstract: New digital technologies, like in other fields, have revolutionized the health care field and orthodontic practice in the 21st century. They can assist the health care professionals in working more efficiently by saving time and improving patient care. Recent advances in artificial intelligence (AI) and 3D printing technology are useful for improving diagnosis and treatment planning, creating algorithms and manufacturing customized orthodontic appliances. AI accomplishes the task of human beings with the help of machines and technology. In orthodontics, AI-based models have been used for diagnosis, treatment planning, clinical decision-making and prognosis prediction. It minimizes the required workforce and speeds up the diagnosis and treatment procedure. In addition, the 3D printing technology is used to fabricate study models, clear aligner models, surgical guides for inserting mini-implants, clear aligners, lingual appliances, wires components for removable appliances and occlusal splints. This paper is a review of the future and scope of AI and 3D printing technology in orthodontics.

Keywords: orthodontics; artificial intelligence; artificial neural network; 3D printing

1. Introduction

Artificial intelligence (AI) is a general term coined during a Dartmouth summer research project [1]. AI is the study of an equipment/machine that senses its environment and takes measures to increase its chances of reaching its objectives [2,3]. AI accomplishes the task of human beings with the help of machines and technology [4,5]. AI is currently being applied in health care, the automobile industry, economics, video games, smartphones, etc. [6].

Orthodontics is a branch of dentistry that focuses on diagnosing malocclusions and other irregularities of the dentofacial region and preventing and correcting them. So, it deals with the parameters applied to biological systems. AI applications such as machine learning, artificial neural networks (ANNs), convolutional neural networks (CNNs) and deep learning (DL) are used for diagnosis and treatment planning, the prognosis of malocclusion in orthodontics with high accuracy, and to reduce human error [5,7]. In addition, AI can document and send data to clinicians faster and more efficiently than humans [8].

Three-dimensional (3D) printing, which is also known as additive manufacturing (AM), is a fabrication procedure that empowers the layer-by-layer development of 3D objects from the computer-aided design (CAD) data [9]. The final product is obtained by the union of multiple subunits, instead of via the subtraction of the material. This concept helps lower the consumption of raw materials and provide high-quality products [10,11]. The advantages of AM include lower time cost, reduced financial costs, less human interaction and the creation of a product with any complex shape [12]. In orthodontics, 3D printing technology is used to fabricate study models, clear aligner models, surgical guides for inserting mini-implants, clear aligners, lingual appliances, wires components for removable appliances and occlusal splints [13].

Digital technology, like as in other fields, has revolutionized the orthodontic practice of the 21st century. With the advances in 3D imaging techniques, 3D printing and AI technology, the orthodontist can improve diagnosis and treatment planning, and create algorithms for the manufacture of customized orthodontic appliances. This article is a review of the scope of AI and 3D printing technology in orthodontics.

2. Artificial intelligence and its applications in orthodontics

AI is a science concerned with the computational understanding of intelligent behavior and creating artifacts that demonstrate it. AI permits accurate patient examination, organization of the clinical data and treatment planning [14,15]. AI technology works by imitating human intelligence through a machine that can think and act rationally. Many subfields of AI that have been commonly used in different areas, mainly biological and medical diagnostics, including machine learning, ANNs, CNNs and DL. Some of these subfields of AI have been widely used in various sectors, primarily in biological and medical diagnostics [16]. Machine learning combines factual and probabilistic tools, and the machines learn from past models and progress their activities when new information is presented [17]. ANNs are numerical computing models that can re-enact human brain processes and accomplish different tasks like classification, estimation, design acknowledgment, picture coordination, chance forecasting and memory simulation [18,19].

New digital technologies have revolutionized the orthodontic practice. They can assist the health care professionals with working more efficiently by saving time and in improving patient care. AI-based models have been used in orthodontic diagnosis, treatment planning, clinical decision-making and prognosis prediction. It minimizes the required human resources and speeds up the diagnosis and treatment procedure [20,21].

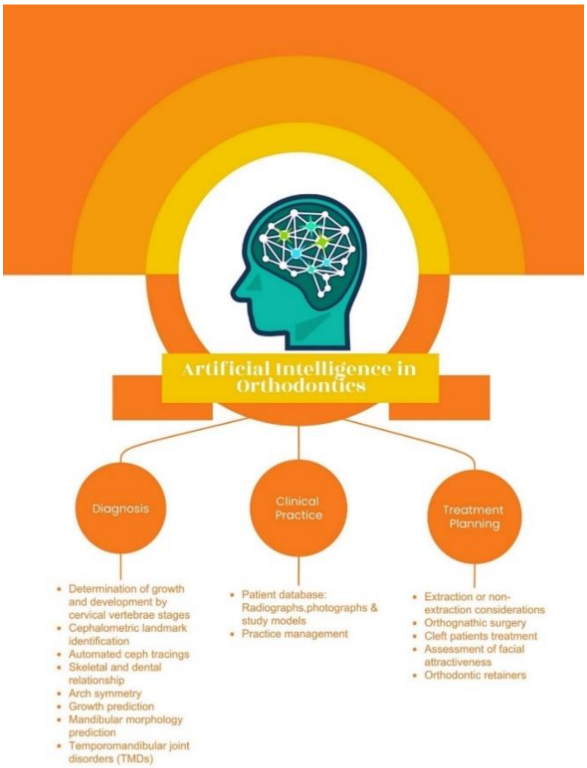

Figure 1. Applications of AI in orthodontics.

Table 1. Literature showing the applications of AI in orthodontics.

Year	Article	Applications	AI technology	Reference
2010	Artificial neural network modeling for deciding if extractions are necessary prior to orthodontic treatment	Extraction and non-extraction therapy in orthodontics	Machine learning through a 2-layer neural network	[22]
2016	New approach for the diagnosis of extractions with neural network machine learning	Extraction and non-extraction therapy in orthodontics	Machine learning through a 2-layer neural network	[23]
2017	Moving towards precision orthodontics: an evolving paradigm shift in the planning and delivery of customized orthodontic therapy	Diagnosis and treatment planning	Fuzzy logic software was used for the diagnosis and treatment planning	[24]
2017	Use of automated learning techniques for predicting mandibular morphology in skeletal classes I, II, and III	Mandibular morphology	An ANN with unidirectional and basic elements of support vector regression and support vector machines were used	[25]

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Year	Article	Applications	AI technology	Reference
2019	Artificial intelligent model with neural network machine learning for the diagnosis of orthognathic surgery	Orthognathic surgery	Neural network machine learning with various cephalometric software programs	[26]
2019	A computer-assisted optimization approach for orthognathic surgery planning	Orthognathic surgery	Neural network machine learning with various cephalometric software programs	[27]
2019	Facial attractiveness of cleft patients: a direct comparison between artificial-intelligence-based scoring and conventional rater groups	Cleft patients and facial attractiveness	An algorithm consisting of a face detector and CNNs with visual cortex/vision processing was used	[28]
2019	Deep learning and artificial intelligence for the determination of the cervical vertebra maturation degree from lateral radiography	Growth and development determination using cervical vertebrae	CNN and ANN methods, models and algorithms were used	[29]
2019	Usage and comparison of artificial intelligence algorithms for determination of growth and development by cervical vertebrae stages in orthodontics	Growth and development determination using cervical vertebrae	CNN and ANN with DL methods were implemented	[30]
2019	Minimally invasive approach for diagnosing TMJ osteoarthritis	Temporomandibular disorders	Deep convoluted neural network	[31]
2019	Compliance monitoring via a Bluetooth-enabled retainer: a prospective clinical pilot study	Orthodontic retention	AI with micro-sensor scanning was used	[32]
2020	Automated detection of TMJ osteoarthritis based on artificial intelligence	Temporomandibular disorders	AI with a region of interest	[33]
2021	A review of the use of artificial intelligence in orthodontics	Diagnosis and treatment planning	Fuzzy logic software was used for the diagnosis and treatment planning	[34]
2021	Determination of growth and development periods in orthodontics with artificial neural network	Growth prediction	ANN models were based on cervical vertebrae algorithms like scaled conjugate gradient back propagation and tan-sigmoid transfer function	[35]
2021	Orthodontic retention: What's on the horizon?	Orthodontic retention	Smartphone-enabled temperature sensor was incorporated	[36]

AI plays an important role in orthodontics, and it is thought to have the most promising future in diagnosis and treatment planning. Hence, the present paper was purposed to review the following applications of AI technology in orthodontics (Figure 1 and Table 1).

2.1. Diagnosis and treatment planning

Diagnosis and treatment planning in orthodontics involve the data obtained from clinical examinations, photographs, radiographs and study models. All of these investigations involve operator skills and patient cooperation. AI facilitates the preparation of patients' diagnostic records and helps to understand the etiology of malocclusion [34]. AI converts the patient information to suit a natural language processing-based of AI system, which stores the patient data and problems list in the order of their treatment priority [24,37]. The AI-based treatment prioritization models can obtain high-performance feature vectors for a more precise treatment plan.

2.2. Cephalometric landmark identification and automated cephalometric tracing

Cephalometry is the measurement of facial and skull bones and the soft tissue profile, and it is important for diagnosis and treatment planning in orthodontics. Cephalometric tracing can be done manually or by using computer software [38,39]. Manual cephalometric tracing is time-consuming, and there is a risk of human error in the landmark identification and measurement of the cephalometric parameters. The major errors in manual tracing tend to involve radiograph unpredictability in the landmark identification and measurements [40,41]. Using computers for cephalometric tracing helps to save time by reducing manual errors and increasing the diagnostic value of the cephalometric analysis [42]. Existing literature shows that AI-based automated cephalometric tracing has a high success rate (over 90%) when applied for the differential diagnosis of cephalometric landmarks using computerized cephalometric software and web-based software [43,44].

To overcome these human errors and increase time efficiency, AI can identify cephalometric landmarks via a DL method. The You Only Look Once algorithm is an AI-based systems for identifying cephalometric landmarks [45].

2.3. Extraction and non-extraction therapy in orthodontics

Orthodontic extraction is a major and important decision that significantly impacts the prognosis and outcome of the treatment. It is based on the orthodontist's clinical experience and expertise, and the correctness of the diagnostic test results [46]. AI technology based on an ANN algorithm produced impressive results, ranging from 80% to 92% accuracy, and it was proved to be a useful tool for extraction decision-making. This can be additional support for clinicians with relatively less clinical experience [23]. Literature reviews showed that the success rate of the AI models was 93% for the diagnosis of extraction or non-extraction therapy, and 84% for the selection of extraction patterns [22].

2.4. Growth prediction

The growth and development rate of the face is important for achieving good orthodontic therapy, as they play a crucial role in the treatment of skeletal discrepancies associated with growth spurts and physiological facial growth [35]. The ANN has been created to be comparable to the biological structure of the human brain, and it mimics the way nerve cells work in the human brain. The hand-wrist and lateral cephalometric radiographs (for cervical vertebrae) are commonly used to predict growth and development. Using ANN algorithms, AI technology accurately determines the growth and development rate based on hand-wrist radiographs and the cervical vertebrae.

2.5. Orthognathic surgery

AI has tremendous potential for application in the diagnosis of dentofacial deformities and treatment planning of orthognathic surgeries. A CNN algorithm revealed that orthognathic surgery significantly improved most patients' profiles and facial attractiveness [26]. AI intervenes at various levels to optimize the data acquisition, processing and pre-analysis of maxillofacial imagery [47]. AI systems facilitate diagnostic precision for orthognathic surgeries, treatment planning using 3D models (3D printing of surgical splints) and enhanced therapeutic follow-up and image superimposition [27,48]. The use of AI in intraoral scanner software allows faster and more efficient data procurement, which results in higher-quality images with lower radiation and is thus beneficial for the 3D reconstructions of images [49].

2.6. Cleft patients and facial attractiveness

Although AI has not been broadly connected to assessing facial attractiveness, it enables the single-face image assessment of attractiveness based on the attractiveness of facial attributes and combinations [50]. Using a CNN trained on large data and mirroring relevant opinions may be useful for objectively and reproducibly interpreting facial appearance [51]. One of the most obvious advantages of a single AI-based score would be eliminating the variability and subjectivity associated with flexible panel-based ratings. The AI-based results are comparable, but they require further improvement and refinement to distinguish facial cleft features, which negatively impact the human perception of attractiveness [28,52].

Machine learning algorithms are also used to build predictive models with single nucleotide polymorphisms (SNPs). SNPs are the most common type of genetic variation among people. Therefore, machine learning methods such as the support vector machine, logistic regression, naive Bayesian classification, random forests, the k-nearest neighbor method, decision trees and ANN-based methods are used to evaluate the genetic risk assessment in cleft lip and palate etiology [53].

2.7. Mandibular morphology

The mandible plays a key role in decisions for occlusion, treatment planning and growth prediction applications in orthodontics because its morphology influences facial aesthetics. In addition, identification of the mandibular morphology becomes important in forensic dentistry when a facial reconstruction is performed, as in the case of a missing person whose mandibular bone has been lost [54]. In the absence of the mandible, AI has significant potential in mandibular prediction because ANN can be used in the facial reconstruction [25].

2.8. Growth and development determination using cervical vertebrae

In orthodontics, the right treatment timing and jawbone growth and development are important for successful treatment. The stages of growth can be studied by using the cervical vertebra maturation (CVM) stages [29]. AI technology, such as CNN and DL methods, models and algorithms, can be used to determine CVM stages. AI algorithms such as k-nearest neighbors, naive Bayes, decision trees, ANNs, support vector machines, random forests and logistic regression are available for CVM determination [30].

2.9. Temporomandibular disorders

Temporomandibular joint (TMJ) disorders constitute the second-most common musculoskeletal condition; they cause pain and disability and affect approximately 5% to 12% of the population. Using a deep neural network model, AI can aid in automatically detecting TMJ osteoarthritis (TMJOA) [33]. It might as well be used to help clinicians diagnose and decide on the treatment of TMJOA. In the future, an AI model that incorporates data other than images, such as signs, symptoms and patient demographic data, would tremendously increase diagnostic accuracy [31]. Furthermore, AI-based TMJ images shed light on the clinical phenotypes of TMJOA and their possible links to etiologic factors such as biomarkers, genetic variations and immunologic responses.

2.10. Orthodontic retention

After the active phase of orthodontic treatment, retainers are passive orthodontic appliances that maintain and stabilize the position of teeth. AI can help with retention monitoring, the fabrication of different types of retainer materials and the digital workflow to design customized retainers. AI-based DentalMonitoring (Paris, France) software has been introduced to monitor the retention protocol, including factors such as stability, retainer adjustment problems and oral hygiene maintenance. This software makes use of intraoral photographs captured by patients' smartphones. This is useful for the clinician, as it reduces the chair time and preferences for patients and motivates patients to maintain and follow the instructions on using the retainer [32,36,55].

Advances in digital technologies made it possible to fabricate retainers by using a digital workflow. An intraoral scan of the dentition can be used to plan the customized nickel-titanium retainer digitally. It is then precision-manufactured by using a CAD-Computer aided manufacturing (CAM) process, ensuring a close fit to the palatal and lingual surfaces of the teeth [56]. The clear plastic retainers were fabricated using 3D-printed models created from intraoral scans, and they are just as the accurate as retainers made using traditional impressions [57,58].

3. Three-dimensional printing and its applications in orthodontics

Three-dimensional printing technology, also known as AM, is constructed by the addition of a material layer-by-layer in a specific pattern using a CAD/CAM design [59]. Charles Hull invented 3D printing, and the standard tessellation language (STL), or stereolithography, is the most commonly used file format for editing and preparing objects for 3D printing [60]. Additive techniques enable the creation of complex and difficult structures and geometries with undercuts or hollows that would be impossible to create using traditional methods [61,62].

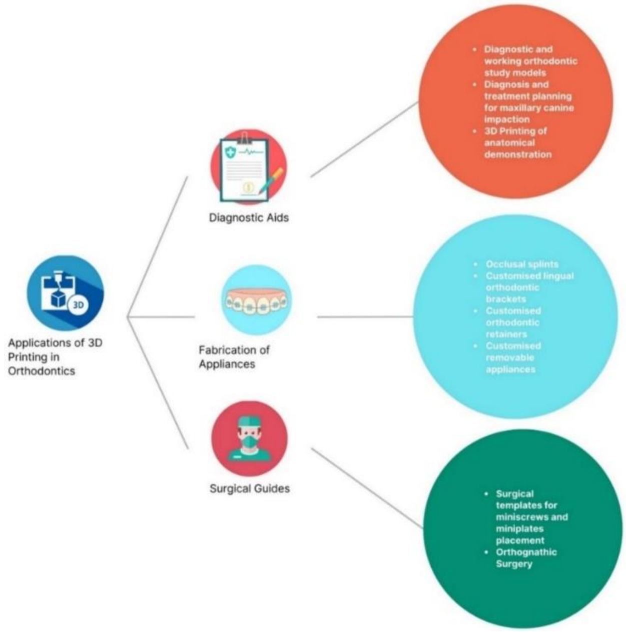

Figure 2. Applications of 3D printing technology in orthodontics.

Table 2. Literature showing the applications of 3D printing in orthodontics.

Year	Article	Applications	3D printing technology	Reference
2003	Customized brackets and arch wires for lingual orthodontic treatment	Custom-made lingual orthodontic brackets, wires	An optical 3D scanner was used	[63]
2006	Rapid prototyping as a tool for diagnosis and treatment planning for maxillary canine impaction	Maxillary canine impaction diagnosis and treatment planning	Computed tomography (CT) scanning with rapid prototyping software to construct 3D models was used	[64]
2008	Herbst appliance in lingual orthodontics	Custom-made lingual orthodontic brackets, wires	An optical 3D scanner with STL was used	[65]
2012	Bone anchor systems for orthodontic application: a systematic review	Surgical guides for the placement of orthodontic mini-screws and miniplates	Stereolithography with CAD/CAM drill guide was used	[66]
2013	A digital process for additive manufacturing of occlusal splints: a clinical pilot study	Occlusal splints	A laser-based AM technique was used	[67]
2014	Virtual techniques for designing and fabricating a retainer	Customized orthodontic retainers	DICOM images with selective laser sintering	[68]
2017	Developing customized dental miniscrew surgical template from thermoplastic polymer material using image superimposition, CAD system, and 3D Printing	Surgical guides for the placement of orthodontic mini-screws and miniplates	Stereolithography with CAD/CAM drill guide was used	[69]

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Year	Article	Applications	3D printing technology	Reference
2020	Accuracy of digital light processing printing of 3-dimensional dental models	Orthodontic study models	3D printing and liquid polyjet photopolymer were used	[70]
2020	Evaluation of the effectiveness of a tailored mobile application in increasing the duration of wear of thermoplastic retainers: a randomized controlled trial	Approaches to enhance removable retainer wear	A micro-electronic sensor was used to evaluate the wear of the clear plastic retainer	[55]
2021	Removable retention: enhancing adherence and the remit of shared decision-making	Removable orthodontic retainers	Shared decision-making and motivational interviewing were used for removable orthodontic retainers	[71]

Advantages of 3D printing include accuracy, high-quality production, full integration with a digital workflow (utilization of intraoral scanners and digital models), reduced manufacturing costs, ability to detect and repair scanned faults before model printing, smaller required manual workforce and cost savings on materials. The disadvantages include a large required initial capital investment for the purchase of the 3D printer and post-processing hardware, the need for staff training to master new skills, the need to process the scan file and manipulate the digital models before printing, the post-print washing and curing phases and the need for an update of health practices and the safety guidelines for the handling and storage of new materials [72].

Advances in 3D printing technology have been explored for automobiles, aviation, aerospace, science and medicine. Various materials, such as gypsum, metal alloys, glass, carbon fiber, resins, organic materials, living cells and tissues, can be used to print objects with 3D printers. Some of the materials mentioned above have widespread applications in dentistry and orthodontics.

Three-dimensional printing applications in orthodontics (Figure 2 and Table 2) include the fabrication of diagnostic and working orthodontic study models, surgical templates and guides for the placement of mini-implants, clear aligners and lingual appliances, as well as wire components for removable appliances and occlusal splints [73].

3.1. Orthodontic study models

Three-dimensional printing can fabricate orthodontic study models owing to its accuracy, visualization and accessibility [70,74]. It can convert a digital, virtual dental model of a patient's dentition into a physical model, skipping the conventional steps of impression-taking and model casting [75]. The 3D-printed models are useful for fabricating removable orthodontic appliances, expansion appliances, indirect bonding trays and thermoplastic aligners [76].

3.2. Removable orthodontic appliances

Several removable orthodontic appliances and other appliances such as the activator and sleep apnea devices are manufactured using 3D printing technology. With the advancement of 3D printing, the Hawley retainer can be fabricated using an intraoral scanner, eliminating the need for conventional impression-taking and pouring study models [71,77]. At present, 3D printing technology allows the manufacture of wire components, such as labial bows and clasps, as well as the incorporation of these parts into the base plate of the appliance. Another important use of 3D printing is the fabrication of custom-made soft silicone removable appliances [78]. Although the literature mentioned earlier and appliances are only case reports, they demonstrate the potential of 3D printing applications in orthodontics. The procedures described by the article authors must be evaluated, particularly regarding costs, workflow, accuracy and clinical efficiency.

3.3. Maxillary canine impaction diagnosis and treatment planning

Maxillary canine impaction is one of the most common dental anomalies in orthodontic patients. Identifying the correct location and angulation is crucial for the success of treatment. The 3D printing of an anatomical model created from computed tomography images of an impacted maxillary canine allows clinicians to thoroughly assess and visualize the anatomy, localization of the impacted tooth and surgical exposure procedure of the impacted tooth [64]

3.4. Custom-made lingual orthodontic brackets and wires

Lingual orthodontic brackets can be manufactured using 3D printing. The digital design enables customization of the in-out, angulation and bracket torque for an individual bracket prescription created for each patient. Wiechmann et al. [63] presented 3D printing to make wax designs of lingual brackets, permitting customization of the bracket design. Making thicker and amplified bracket bases on maxillary teeth, as well as starting with the molars and mandibular canines to make those brackets as groups, was part of the digital design of lingual orthodontic brackets. Exact prototyping of the planned machine is required and can be accomplished with 3D printing technology, allowing customized fixed functional treatment in conjunction with lingual orthodontic treatment [65].

3.5. Occlusal splints

Occlusal splints are used to treat temporomandibular disorders. The occlusal splints prepared from the 3D printing were more accurate as the best fit for the patients. In addition, the printing preparation is very reproducible and faster, and it significantly reduces fabrication time relative to that for the conventional fabrication method of splints [67]. One advantage of AM is that it allows one to print a large number of individual splints in a short period using modern digital technology, thereby eliminating manual working phases in a dental laboratory. This could reduce costs, technician working time and chair-side time in the coming years.

3.6. Surgical guides for the placement of orthodontic mini-screws and miniplates

Miniplates and orthodontic mini-screws are used in a variety of orthodontic treatment procedures, including those for the intrusion of molars, the correction of open bite, molar distalization and maxillary impaction or protraction [66]. Hence, accurate placement of these mini-screws and miniplates in patients is critical for the success of treatment. The material utilized to construct surgical guides should be firm and sufficient to stay stable during the mini-implant insertion procedure. Three-dimensional-printed surgical guides have become progressively popular because they offer orthodontists a safe and simple method of placing mini-implants [69,79]. They provide custom-made adaptation, accuracy and precision for the placement of the final position of the miniplate, as well as the utmost surface contact between the bone and the miniplate, stability and a lower risk of miniplate failure [80–82].

3.7. Customized orthodontic retainers

Three-dimensional printing opens a new avenue in orthodontics to fabricate custom-made removable retainers. The procedure incorporates cutting-edge technologies such as cone-beam computed tomography (CBCT), CAD and 3D printing. The first step is to use CBCT to scan the patient's dentition and create a 3D model of the patient's dentition. The retainer is virtually designed after importing the 3D model into dedicated software, and it is possible to print a clear plastic retainer directly by using an additive 3D printing process [68,83].

4. Conclusions

AI and 3D printing technology have revolutionized oral health care and the orthodontic practice by addressing the weaknesses of conventional diagnosis and treatment planning procedures. With AI-based algorithms, orthodontists can better diagnose and plan treatment, whereas 3D printing helps manufacture customized orthodontic appliances with precision.

AI and 3D printing can solve various clinical problems, improve diagnosis, clinical decision-making and prediction of failures, as well as reduce the chair side time, bypass various extra steps of conventional methods and provide quality treatment with accuracy and precision. There is fascinating literature evidence that AI and 3D printing broaden the scope of state-of-the-art technology in orthodontics and can play a crucial role in sufficiently aiding practicing clinicians in delivering health care in the 21st century.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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