Computational and Mathematical Methods in Medicine

Advances in Endodontics and Artificial Intelligence in Dentistry

Lead Guest Editor: Prashant Babaji
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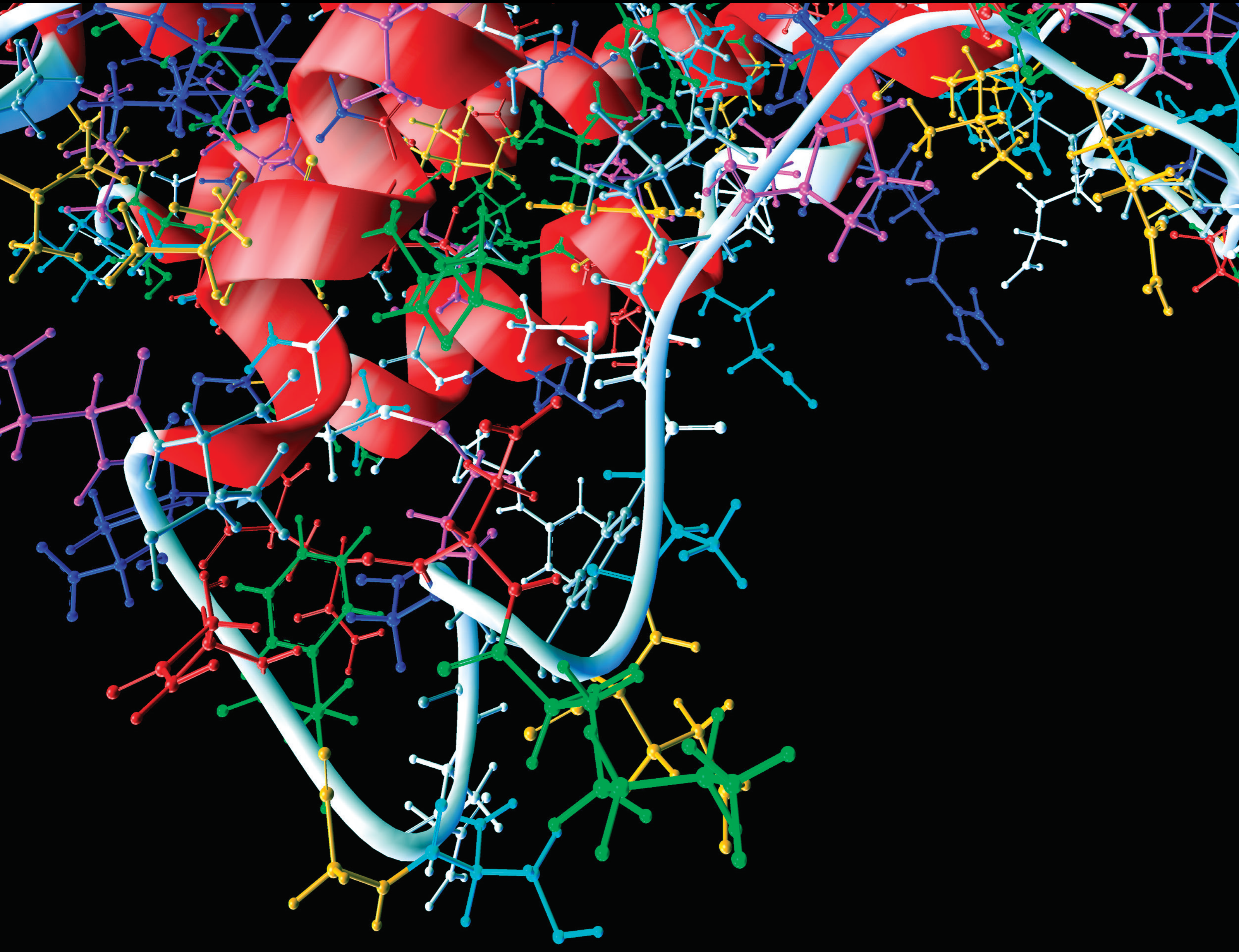

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Contents

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Review Article

Evaluation of the Diagnostic and Prognostic Accuracy of Artificial Intelligence in Endodontic Dentistry: A Comprehensive Review of Literature

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Aim. This comprehensive review is aimed at evaluating the diagnostic and prognostic accuracy of artificial intelligence in endodontic dentistry. *Introduction*. Artificial intelligence (AI) is a relatively new technology that has widespread use in dentistry. The AI technologies have primarily been used in dentistry to diagnose dental diseases, plan treatment, make clinical decisions, and predict the prognosis. AI models like convolutional neural networks (CNN) and artificial neural networks (ANN) have been used in endodontics to study root canal system anatomy, determine working length measurements, detect periapical lesions and root fractures, predict the success of retreatment procedures, and predict the viability of dental pulp stem cells. *Methodology*. The literature was searched in electronic databases such as Google Scholar, Medline, PubMed, Embase, Web of Science, and Scopus, published over the last four decades (January 1980 to September 15, 2021) by using keywords such as artificial intelligence, machine learning, deep learning, application, endodontics, and dentistry. *Results*. The preliminary search yielded 2560 articles relevant enough to the paper's purpose. A total of 88 articles met the eligibility criteria. The majority of research on AI application in endodontics has concentrated on tracing apical foramen, verifying the working length, projection of periapical pathologies, root morphologies, and retreatment predictions and discovering the vertical root fractures. *Conclusion*. In endodontics, AI displayed accuracy in terms of diagnostic and prognostic evaluations. The use of AI can help enhance the treatment plan, which in turn can lead to an increase in the success rate of endodontic treatment outcomes. The AI is used extensively in endodontics and could help in clinical applications, such as detecting root fractures, periapical pathologies, determining working length, tracing apical foramen, the morphology of root, and disease prediction.

1. Introduction

The capacity of an integrated platform to obtain, process, and implement skills and knowledge acquired through education or experience that are usually linked to human intelligence has been defined as artificial intelligence (AI) [1]. AI is a broad idiom that signifies the use of machines and technology to perform tasks similar to those performed by humans. According to Barr and Feigenbaum, AI is a branch of computer science involved with developing innovative application software that exhibits the characteristics users associate with intellectual ability in individual behaviour, such as language comprehension, acquiring knowledge, rationale, problem-solving, and several others [2]. The word AI is generally related to robotics. It explains using technology to create software or a device that quickly imitates human intellectual ability and performs specific tasks [3]. AI has been shown to make it more efficient, accurateness, and specificity in a timely and cost-effective manner, similar to medical professionals [4]. In 1955, a mathematician named John McCarthy proposed the word artificial intelligence, and he is widely regarded as the father of artificial intelligence. He coined the term to describe the ability of machines to perform tasks that can be classified as "intelligent" [5].

AI is a relatively new technology that has found widespread use in dentistry. AI is primarily made up of an architectural neural network comparable to the brain of humans and imitates human thinking [6]. This structure of neural architecture comprises neurons with robust interconnected systems that primarily function as information systems to determine the problems [7]. The use of neural networks in dentistry has advanced dramatically as science and technology have progressed. The AI technologies have primarily been used in dentistry to diagnose dental diseases, plan treatment, make clinical decisions, and predict the prognosis [8]. There are 2 types of AI in the healthcare sector (Figure 1).

AI includes subcategories like machine learning (ML) and related fields like deep learning (DL), advanced analytics, computational linguistics, automation, intelligent agents, and probabilistic reasoning. Machine learning enhances computer-controlled learning without requiring explicit programming. Its main goal is to make automated knowledge acquisition possible without requiring human intervention. AI technologies forecast future occurrences with the current sequence of examples [9]. Figures 2 shows a schematic representation of the AI model.

The purpose of endodontic therapy is to bestow high-quality care to preserve the tooth's function and avoid further complications. In recent years, the diagnosis of root canal pathology, equipment design features, components, and treatment options have advanced dramatically, intending to provide successful endodontic care [8]. The models of AI like convolutional neural networks (CNN) and artificial neural networks (ANN) are being used in the field of endodontics to study the system of root canal anatomy, determine working length measurements, detect periapical lesions and root fractures, predict the success of retreatment procedures, and predict the survival of stem cells in dental pulp [10]. In order to achieve the best results, accuracy in diagnosis and therapeutic judgement is essential. Due to advances in science and technology, many diagnosing devices and therapeutic options have opened up new vistas in diagnostic testing, clinical judgement, and making preparations for the best treatment for root canal system diseases [11]. The AI systems can revolutionize medicine and dentistry by identifying solutions to various clinical problems and making clinicians' jobs easier. Endodontic research has grown in lockstep with other dental specialties [10]. When AI is combined with endodontics, the root canals could be biomechanically prepared with accuracy [12]. The latest advancements in digital applications have also promoted the creation of clinical techniques such as AI-based diagnosis and assisted access cavity preparations to gain easy accessibility to root canals even in obliterated roots [13]. Multiple studies also showed the use of this newly developed concept for endodontic disease diagnosis and treatment planning [8]. From photographic color tooth pictures, Berdouses et al. [14] developed a computer-aided automated approach (ACDS) for the identification of occlusal caries lesions of posterior permanent teeth in accordance with the International Caries Detection and Assessment System (ICDAS II). In order to recognize the distal root shape of the mandibular first molar on panoramic dental radiographs, Hiraiwa et al. [15] used deep learning systems (AlexNet and GoogleNet). Both deep learning algorithms performed diagnostic tasks marginally better than radiologists with extensive training. Based on a random walk segmentation of a graph, a noninvasive differential diagnosis technique for periapical lesions and to pinpoint the precise position of periapical lesions and quantify their volume in CBCT images, a deep CNN-based AI diagnosis model was developed [16]. By extracting relevant features from the matrix, a Random Forest (RF) method is used to classify the picture after segmentation, which results in the formation of a grey level cooccurrence matrix of the image. With an applicable method that can discern gender from maxillary teeth plaster images, automatic gender determination has a success rate of 90% [17]. The facial deformation of a patient after receiving a complete denture prosthesis was predicted using a CAD/CAM (Computer-Aided Design/Computer-Aided Manufacturing) system, which also provided limitations for the digital placement of the complete denture's artificial teeth [18]. Miki et al. [19] investigated a deep convolutional neural network-based automated system for classifying tooth types on dental cone-beam CT images and as a component of an automated dental chart filing system. In addition, Raith et al. [20]

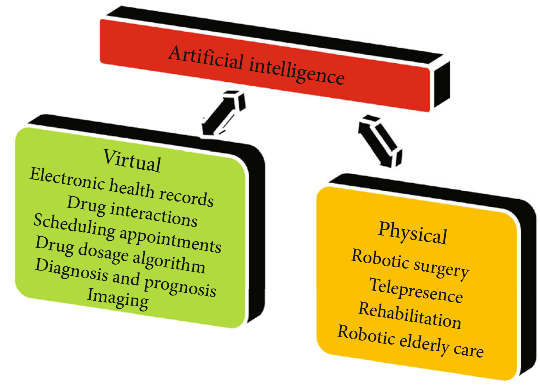

Figure 1: Types of artificial intelligence.

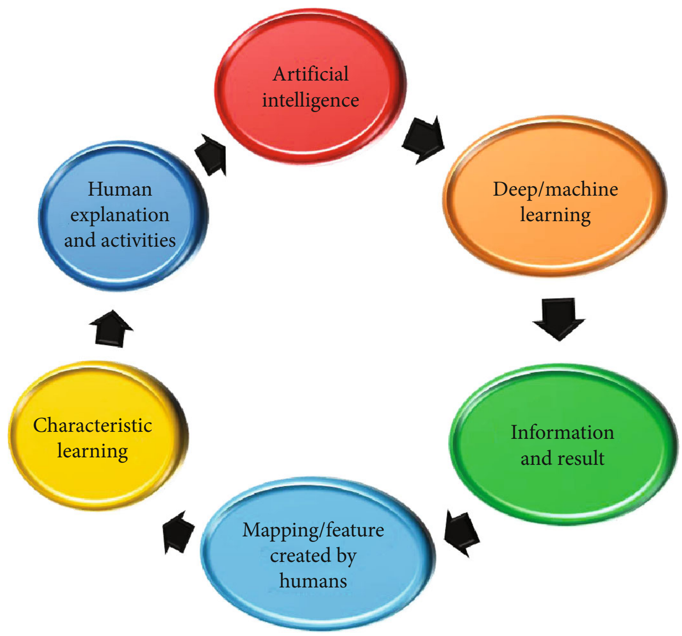

Figure 2: Schematic representation of artificial intelligence model.

introduced an automated computational technique for classifying teeth using artificial neural networks. A superresolution generative adversarial network (SRGAN) was suggested by Moran et al. [21] as a way to generate high-resolution periapical images with a 4-order-of-magnitude improvement. The accuracy of the AI-based diagnosis was identified to be 94.96%, and the level of difficulty for these cases could be decided with high precision in endodontic aspects [22]. The prevalence and usefulness of AI in many activities and applications in dentistry, especially endodontics, have greatly expanded in recent years. AI has the potential to perform diagnostic and prognostic predictions with decision-making ability in the healthcare. The endodontist's knowledge needs to be updated in terms of AI application. This comprehensive review is aimed at evaluating the diagnostic and prognostic accuracy of artificial intelligence in endodontic dentistry.

2. Methodology

The literature for this review article was recognized and listed by conducting a thorough search in electronic databases such as Google Scholar, Medline, PubMed, Embase, Web of Science, and Scopus, published over the last four decades (January 1980 to September 15, 2021) by using keywords such as artificial intelligence, machine learning, deep learning, application, endodontics, and dentistry. We were able to find full-length articles. To go through the journals, we used both hand and electronic searching. The information needed for this review was chosen in two stages. The first stage of the articles was chosen based on their titles and abstracts relevant to our research topic. The preliminary search yielded 2560 articles relevant enough to the paper's purpose. 560 articles were removed due to duplication. As a result, we were able to find 2000 articles for the second stage of the selection process.

The research conducted on AI and its application in endodontics was included in the current review. Further, there must be some predictability or measurable outcomes to be quantified. The articles not related to AI in endodontics, unpublished articles (preprints) available online, articles with only abstract not having the complete text, and articles are written other than the English language were excluded. A total of 88 articles met the eligibility criteria (Figure 3, PRISMA). Before being given to the panel members for critical analysis, the authors' identities and the details of the article were kept hidden. The panel was made up of two members, MIK and AHA. Every article was thoroughly read. The period in which these articles were published was used to track the evolution of AI trends in dentistry and endodontics over time.

3. Results

The quantitative data from 66 research articles were analyzed in this comprehensive review. The majority of the studies were conducted in the last two decades. According to the trends, the research on AI in dentistry is gradually increasing. The studies included in the comprehensive review focused primarily on applications of AI in endodontics. The majority of research on AI application in endodontics has concentrated on tracing apical foramen, verifying the working length, projection of periapical pathologies, root morphologies, retreatment predictions, and discovering the vertical root fractures (Figure 4).

4. Discussion

The DL with CNN has become the most common AI component used in endodontic diagnostics due to its ability to perform automated lesion segmentation [23]. AI allows

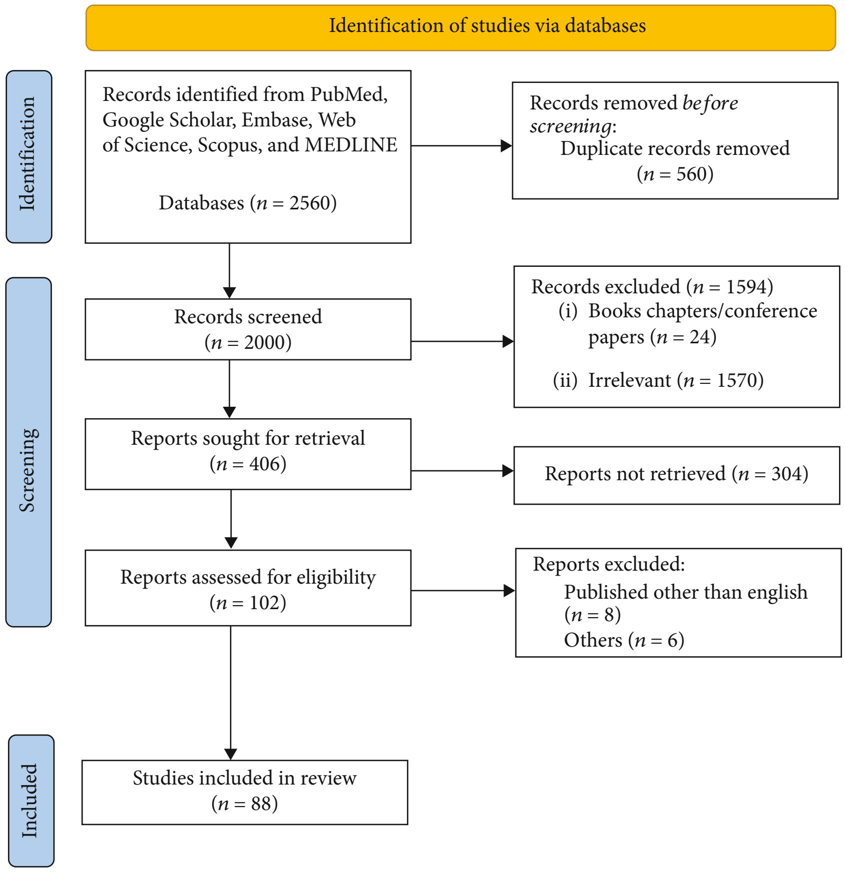

FIGURE 3: PRISMA flowchart showing the selection process of articles retrieved from different web sources.

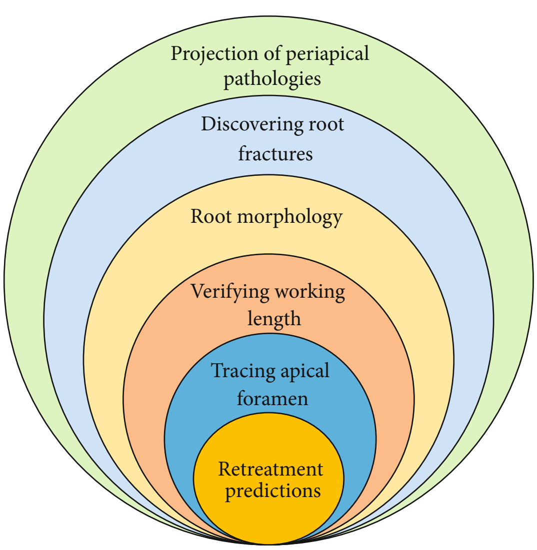

FIGURE 4: Uses of artificial intelligences in endodontics.

multiple and heterogeneous information domains, such as dental history, clinical data, and sociodemographic, to be integrated [9]. AI facilitates scientific investigations by incorporating in silico experimental research options into traditional research setups, supplementing other scientific degrees and existing modelling techniques [24].

4.1. Projection of Periapical Pathologies. Apical periodontitis is the most common endodontic disease, accounting for about 75% of jaw lesions that are radiolucent [25]. It is ubiquitous, affecting 33-62% of the population between 20 and 60 years [26]. Panoramic and intraoral periapical radiographs have been the most prevalent 2-D diagnostic aids used during daily clinical settings to recognize apical periodontitis. Radiolucencies are commonly seen in periapical lesions on radiographs. On the other hand, periapical radiographs do not provide reliable information since the actual 3-D anatomy is transformed into a 2-D image [27]. The different types of diagnostic techniques used in endodontics are [13] as follows:

(1) Radiography (digital)
(2) Cone beam computed tomography (CBCT)
(3) Computer-aided diagnosis (CAD)
(4) 3D printing
(5) Guided endodontics

CBCT imaging, a three-dimensional (3D) imaging technology, is now commonly used in practice by endodontists (about 80%) to diagnose and manage root canal pathologies. When compared to 2D periapical radiography, CBCT scanning has improved periapical pathology detection accuracy

Table 1: Endodontic diagnosis based on AI application.

Author and year	Diagnostic technique	AI method	Accuracy	Reference
Mahmoud et al., 2015	Periapical radiographs	ANN	77.2%	[50]
Hatvani et al., 2018	Dental CT images	CNN	92%	[51]
Ekert et al., 2019	Panoramic radiographs	CNN	85%	[30]
Hiraiwa et al., 2019	CBCT & panoramic radiographs	Deep learning algorithm	86.9%	[15]
Bouchahma et al., 2019	Periapical radiographs	Deep learning algorithm	87%	[52]
Endres et al., 2020	Panoramic radiographs	Deep learning algorithm	72%	[29]
Setzer et al., 2020	CBCT	Deep learning algorithm	93%	[53]
Orhan et al., 2020	CBCT	CNN	92.8%	[54]
Zheng et al., 2020	CBCT	Deep learning algorithm	High	[55]
Pauwels et al., 2021	Periapical radiographs	CNN	83%	[56]

[28]. The use of AI technologies to diagnose a periapical pathology from X-rays and CBCT diagnostic tests could aid clinicians in achieving identification precision that is comparable to, if not better than, specialists with good experience [29]. It may also decrease the dentist's diagnostic time and effort by reducing evaluation time by allowing semiautomated documentation [30]. Multiple studies have been done to achieve an accurate diagnosis (Table 1).

4.2. Discovering Root Fractures. Vertical root fractures (VRFs) are rare in root canal-treated teeth. VRFs are often insidious since they reveal only minor symptoms and, in many cases, no symptoms at all [31]. VRF is observed to result in 3.7–30.8 percent of root canal-treated teeth, with the mandibular premolars and molars being the most commonly affected [32]. VRF teeth are among the most difficult to treat appropriately, and then, almost all VRF teeth are extracted or treated with hemisection or root separation methods [33]. Early treatment encompassing the resection of infected roots, on the other hand, can result in substantially long survival times for the residual roots, with survival rates of 94% and 64%, respectively, after five and ten years [32]. Initial diagnosis of a VRF will aid to avoid comprehensive tissue injury. The diagnosis of VRF is based on clinical signs and symptoms and radiographic evidence of a fracture line. Moving from conventional radiography to digital imaging and digital image advancement has been attempted to improve the detection ability of radiographic techniques [34]. The diagnosis of a VRF, which could be challenging to detect, is aided by X-ray and CBCT image analysis. Unnecessary surgical procedures or tooth extraction may be required due to a lack of a proper diagnosis. The clinical presentation and the lack of sensitivity of diagnostic imaging in detecting VRFs frequently present a clinician with a diagnosing dilemma [10]. Compared to conventional radiographs, CBCT imaging was good at identifying VRFs in unfilled teeth, while radiographs were slightly better in root-filled teeth. There has been an invitation to explore innovative methods for improving the diagnosis of VRFs due to the incapability of typical techniques to precisely identify VRFs [35]. The AI applications like ML, CNN, and PNN (probabilistic neural network) are used to detect the VRFs [10]. Multiple studies have been reported, which are explained in Table 2.

4.3. Root Morphology. A dentist must have a comprehensive understanding of root canal morphology to provide successful root canal therapy. An untreated canal that was possibly missed could result in microbial colonization and, as a result, root canal treatment failure. Given these factors, a dentist wants to possess an absolute understanding of root morphologies and an effective diagnostic tool for identifying them [8]. For a nonsurgical endodontic treatment to be successful, the ability to identify the system of root canal variations is critical. Traditionally, periapical X-rays and CBCT image analysis were used to diagnose this [10]. CBCT for dental use, such as root and canal morphology variants, can now be accurately evaluated in clinics [15]. Even though conventional radiography is still widely used and plays an essential role in root canal pathology, diagnosis, and treatment planning, CBCT provides the highest quality 3D images. As a result, conventional radiograph limitations such as distortion and superimposition of bony and dental structures are no longer an issue [36, 37]. The performance of the DL system of AI in determining the root canal morphology was excellent [15]. The DL system could be helpful in diagnostics, and it classifies images that could aid in understanding images by inexperienced doctors [38, 39]. The ability of the DL algorithm developed by AI and data interpretation to assess the root canal morphologies and its 3-D alterations after instrumentation was demonstrated [40] (Table 3).

4.4. Verification of Working Length and Tracing the Apical Foremen. The accuracy of determining the working length is crucial to the success of endodontic treatment [41]. The dental practitioners can master the working length assessment using several different guidelines and techniques, with routine success when different techniques are used [42]. The endodontic treatment necessitates the precise determination of root canal length and the apical foramen. The hand sensation method, radiological determination, and usage of an electronic apex locator are the three methods for measuring root canal length [43]. CBCT and electronic apex locators have recently been used as modern tools for detecting the apical foramen [8, 44]. The electronic apex locator, most frequently used in clinics to measure root canal length, was developed over time using multiple techniques [45]. The

Table 2: Detection of vertical root fractures by AI.

Author and year	Diagnostic technique	AI method	Accuracy	Reference
Hassan et al., 2009	CBCT & Periapical radiographs	DICOM 3 Visualization Software	86%	[57]
Varshosaz et al., 2010	CBCT & Periapical Radiographs	ROMEXIS Software	91%	[58]
Metska et al., 2012	CBCT	ACCUITOMO 3D, NEWTOM 3G	93%	[59]
Kositbowornchai et al., 2013	Digital radiographs	PNN	95.7%	[34]
Gunduz et al., 2013	CBCT	ACCUITOMO 3D, VISTASCAN PSP, CCD SENSOR, CONVENTIONAL FILM	Significantly better	[60]
Melo et al., 2013	CBCT	DICOM, DOLPHIN, KDIS3D	73%	[61]
Johari et al., 2017	Periapical radiographs	PNN	96.6%	[62]
Fukuda et al., 2020	Panoramic radiographs	CNN-based detect net with DIGIT version 5	93%	[32]
Vicory et al., 2021	CBCT	ML	Superior	[63]
Xu et al., 2021	CBCT	Pyramids Attention Convolutional Neural Network (FPA-CNN)	Challenging	[64]

Table 3: Detection of root canal morphology by AI.

Author and year	Diagnostic technique	AI method	Accuracy	Reference
Hatvani et al., 2018	Dental CT	CNN	Superior	[51]
Hiraiwa et al., 2019	CBCT & panoramic radiography	DL (standard DIGIT algorithm)	86.9%	[15]
Lahoud et al., 2021	CBCT	AI-driven algorithm	High	[65]
Leite et al., 2021	Panoramic radiography	CNN	High	[66]
Başaran et al., 2021	Panoramic radiography	AI-model CranioCatch (deep CNN method)	Promising	[67]
Sherwood et al., 2021	CBCT	DL	Better	[68]
Jeon et al., 2021	Panoramic radiography	CNN-based DL	95.1%	[69]
Zhang et al., 2021	CBCT	DL	High	[70]
Khan et al., 2021	Periapical radiography	DL-based computer vision technique	Better	[71]
Liu et al., 2021	CBCT	CNN	93.3%	[72]

Table 4: Application of artificial intelligence for locating the apical foramen and determining the working of the root canal.

Author and year	Diagnostic technique	AI method	Accuracy	Reference
Saghiri et al., 2012	In situ radiographs using Rinn XCP	ANN	93%	[43]
Saghiri et al., 2012	Periapical radiographs	ANN	96%	[73]
Qiao et al., 2020	Circuit system	Neural network model	95%	[45]

root canal treatment prognosis can only be guaranteed when the instrumentation ends at the apical constriction of the root [46]. The ANN diagnosis method helps to improve the diagnosis and results in a better radiographic determination of working length. Further, in a wide range of clinical circumstances, ANNs are used as a judgement system [47]. Few studies have been done by applying artificial intelligence to locate the apical foramen and determine the root canal's working (Table 4).

4.5. Retreatment Predictions. In dentistry, the endodontic treatment is successful 90% of the time, with a failure rate of 10%. As a result, a dentist would value the ability to use the AI method to analyze and detect cases falling within this 10% and decide whether extraction or retreatment is preferable [48]. The case-based reasoning (CBR) paradigm was described by Campo et al. [48] to predict nonsurgical endodontic retreatment outcomes and the benefits and risks. In summary, the system determined whether retreatment was necessary. The system incorporates information from regions such as achievement, recollection, and analytical probabilities. The system's power is that it could be able to forecast the outcome of retreatment with reasonable accuracy. The system would only have been as good as the information obtained from the data, which was a limitation.

CBR is the procedure of coming up with answers to problems derived from earlier encounters with similar issues. By recovering similar instances, essential knowledge and information can be incorporated. The problem of variations and the availability of different methods may lead to system heterogeneity [49]. Future research must consider the variability of a human approach, and sample sizes may need to be increased to achieve higher responsiveness, selectivity, and precision [10].

4.6. Future Directions. Artificial intelligence has grown in importance as a central concept as we see significant advances in technology and science. Dentists' assessments of patient data are subjective, and research findings have shown that diagnoses are not always consistent among practitioners. Smart, new dental technologies offer a way to improve consistency significantly and, as a result, patient health. Dental research should grow the relationship between oral and general health in the future to concentrate on individualized treatment with patient-centred outcomes. Robotic assistance in dentistry has become possible thanks to technological advancements. "Augmented intelligence" has also been embraced a little too soon in the present scenario. However, the benefits of digital applications will complement human talents and capabilities to provide the best and more cost-effective healthcare to patients. Augmented intelligence based on big data can significantly reduce the number of misdiagnoses and provide more insightful information quickly, accurately, and efficiently. AI can schedule a patient list that includes the patient's ongoing requirements and health information. AI may predict patient-specific drug complications if patient records are made available. AI could help with diagnosis and staging, as well as predict outcomes. This could include things like outcome forecasting or prognostic risk determination.

5. Conclusions

In endodontics, AI displayed accuracy in terms of diagnostic and prognostic evaluations. The use of AI can help enhance the treatment plan, which in turn can lead to an increase in the success rate of endodontic treatment outcomes. In recent years, AI has transformed dentistry. It is rapidly progressing, with potential applications spanning various domains such as diagnosis, prognosis, and treatment prediction. The AI is used extensively in endodontics and could help in clinical applications, such as detecting root fractures, periapical pathologies, determining working length, tracing apical foramen, the morphology of root, and disease prediction. However, before integrating AI models into routine clinical work, it is still important to do additional research to test their dependability, relevance, and expenditure.

Data Availability

This article includes all types of information used to endorse the review findings.

Conflicts of Interest

With the publishing of this paper, the authors confirm no conflicting interests.

Authors' Contributions

Mohmed Isaqali Karobari and Abdul Habeeb Adil contributed equally to this work.

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Research Article

Optimization Analysis of Two-Factor Continuous Variable between Thread Depth and Pitch of Microimplant under Toque Force

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Microimplant, an anchorage device, is widely applied in clinical orthodontic treatment. Since tooth torque is required to be controlled during orthodontic tooth movement, a novel microimplant needs to be developed to apply better torque force during orthodontic. In this study, the optimal value ranges of thread depth and pitch under toque force were studied for choosing microimplant with relevant value ranges in clinical design from biomechanical perspective. Finite element analysis (FEA) and optimization design technology were used for accessing the optimal value ranges of thread depth and pitch under toque force. Thread depth (D) (0.1 mm to 0.4 mm) and pitch (P) (0.4 mm to 1 mm) were used as continuous variables, with the other parameters as constant, and the optimal value ranges were obtained by analyzing the tangent slope and sensitivity of the response curve. When a torque force of 6 Nmm was applied on the microimplant, the maximum equivalent stress (Max EQV) of cortical bone and maximum displacements (Max DM) of microimplant were analysis indexes. When $0.55\ \text{mm} \le P \le 1$ mm, the Max EQV of cortical bone was relatively smaller with less variation range. When $0.1\ \text{mm} \le D \le 0.35$ mm, the Max DM of microimplant was relatively smaller with less variation range. So in conclusion, the initial stability of microimplants with pitch $0.55\ \text{mm} \le P \le 1$ mm and thread depth $0.1\ \text{mm} \le D \le 0.35$ mm was better with the torque force applied.

1. Introduction

Using microimplant as an anchorage in orthodontic treatment has been widely accepted globally among orthodontists [1, 2]. Previous research studies showed that in most of the orthodontic anchorages, the success rate of microimplant anchorage was found to be between 74% and 93%, which was lower than that of regular dental implants reported [2–4]. Microimplant, as a temporary anchorage auxiliary device used widely in orthodontic treatment, exhibited stability from the mechanical embedment of the microimplant and cortical bone [5–7] rather than from the dental implant osseointegration. Therefore, microimplant can be used as orthodontic anchorage right after implantation, due to its efficiency. The stability of the immediate loading after implantation is termed as initial stability, which plays a crucial role for the successful anchorage in orthodontic treatment, as most of the microimplants tend to fail in this period [8].

Many orthodontists reported that the initial stability of implant after implantation can be influenced by many factors, such as the microimplant's shape, diameter, head length, the thread's size, height, and pitch, which are all known to create the stress of the surrounding cortical bone [9–11].

FEA (finite element analysis) is a highly efficient calculating method, mainly used in analyzing static, dynamic objects and physical systems, which can also be used in the study of internal micromotion of objects. Mathur et al. reported the outcome of the implant and its surrounding bone structure's orthodontic load simulated by 3D FEA [12]. Based on 3D FEA, the stress generated was analyzed and the changes in the implant's surrounding bone under orthodontic load could be identified. Similarly, FEA was applied in learning the design parameters of microimplant, such as diameter, length, shape, and size [10, 13–17]. Shen et al. [11] applied a 2 N of mesial-distal horizontal direction load, which was parallel to the maxillary buccal surface, to simulate the horizontal retraction of the anterior teeth in clinical practice. Based on FEA, it was observed that the stress in maxillary and the stability of the microimplant were easily affected by the thread pitch and height, and an increase of 1.20 mm on the thread height proved best at the maxillary posterior zone. Another study showed that the thread size of the microimplant holds zero effects on the stress distribution of the surrounding cortical bone and then its initial stability, based on the application of 2 N linear horizontal force on microimplant using 3D FEM [9].

However, these research studies mainly focused on the linear forces including horizontal traction and vertical force applied on microimplants. In orthodontic treatments, the 3D movements of teeth could not be seen without the torque control of teeth, such as upright of the lingual or buccal inclined molars and buccal or lingual controlling movement of the anterior tooth root [18]. A traditional method for the torque control expects many other teeth containing brackets and steel wire as an anchorage. As reaction force is generated on the anchorage teeth, it makes the treatment more complicated and increases the possibility of adverse reactions like alveolar bone fenestrations and root exposures [19, 20]. Torque control of the tooth determines the controlling root movement of the orthodontics, which can directly affect the outcome of the orthodontic treatment. In order to simplify the root torque control in orthodontic treatment and avoid the adverse reaction, using a microimplant as a torque control anchorage will provide a better outcome [21]. Therefore, a microimplant design specially for torque force controlling anchorage is highly essential. However, the influence of the loading torque on the initial stability of the microimplant is not clearly understood. Using thread depth and pitch as continuous variables, this study probes into the effects of these two variables on bone stress and initial stability of the microimplant, to obtain the optimal value ranges of the two variables under torque force.

Based on the aspects of biomechanics, this study probes further into the thread design requirements for the novel micro-implant and provides a theoretical basis for selecting micro-implants with suitable parameters, which can also meet the clinical requirements of torque force. By improving the microimplant's thread design, its initial stability under the torque force can be easily optimized. Based on our previous research, we have proposed the application of this new type of micro-implant and the design requirements on length, diameter, and thread shape [15, 22–26]. Here, a further study was done on the thread depth and pitch design requirements of the new microimplant for the torque force during the dental treatment, which could promote the initial stability of the microimplant under the torque force.

2. Materials and Method

2.1. Experimental Model. In the establishment of a 3D finite element model, the basic structural parameters of the microimplant are as follows: length 9 mm, diameter 2 mm, pitch 0.6 mm, and thread depth 0.3 mm. Part drawing stretching command in Pro/E 2.0 was used to draw the cortical bone and cancellous bone. The size of the bone structurally is defined as height 14 mm, length 10 mm, and width 7 mm, where the upper part was the cortical bone with thickness 1 mm, while the lower part was a cancellous bone layer. The basic shape of the thread in the microimplant was the buttress thread with apex angle of 15°. The depth (D) and pitch (P) were set as continuous variables: the value range of D was 0.1 mm to 0.4 mm and that of P was 0.4 mm to 1 mm. The microimplant was implanted from the cortical bone into the cancellous bone, in the direction of 90° to the cortical bone surface. The microimplant and the cortical bone were embedded with each other mechanically, and the microimplant was frictionally contacted with bones with a friction coefficient of 0.3 [22]. The above-mentioned model and the microimplant data were imported into the FEA software ANSYS Workbench 13.0 and processed (Figure 1).

2.2. Boundary Constraints and Loading Conditions. The boundary constraints indicate that the degrees of freedom of all the nodes in bone's mesial-distal surfaces equates to 0. A torque force of 6 Nmm was applied in the transverse groove at the head of the microimplant in our finite element model, based on Hohmann et al.'s study as they indicated that the torque load greater than 6 Nmm will lead to molar root resorption [23] (Figure 1(b)).

2.3. Parameters of the Mechanics of Materials. As per the setting conditions of our previous experiments, bones are the class III bone from Lekholm and Zarb classification, and all the materials were homogeneous, isotropic, and linear elastic materials [24–29]. The biomechanical parameters of the material, including Young's modulus and Poisson's ratio of cortical bone, cancellous bone, and miniscrew, are presented in Table 1. They were set in previous studies, and they are the reference for our study [24–26, 28–30].

2.4. Experimental Hypotheses and Definition of the Interface Contact

2.4.1. Hypothesis of Isotropy. The elasticities of an object will be similar in all directions, and the elastic constant will not change with direction.

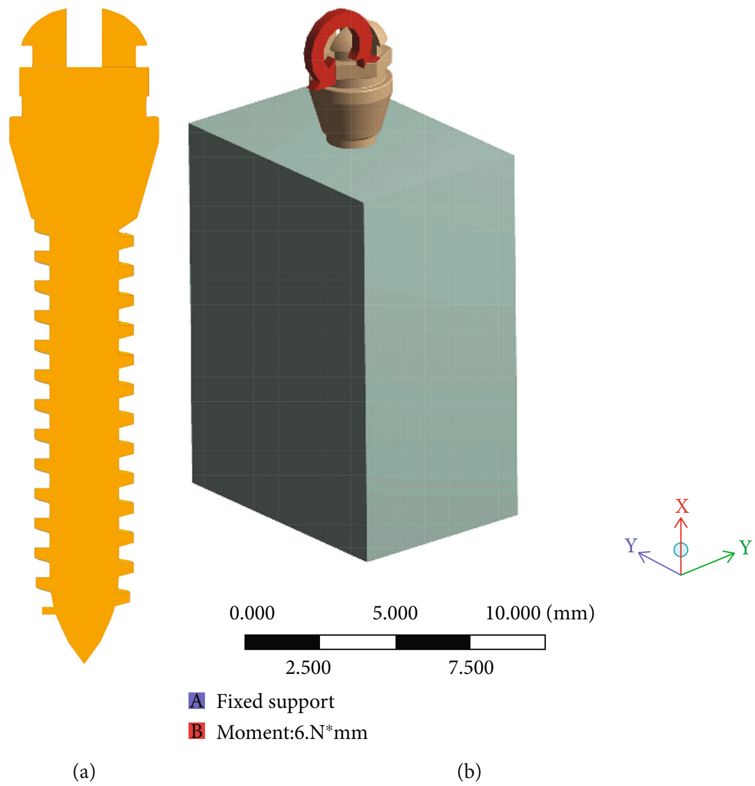


FIGURE 1: Construction of the model: (a) the model of micro-implant; (b) a torque load of 6 Nmm was applied to micro-implant head.

TABLE 1: The biomechanical parameters of the material.

	Young's modulus (MPa)	Poisson's ratio
Cortical bone	13,700	0.33
Cancellous bone	1,600	0.3
Micro-implant	110,000	0.35

2.4.2. Hypothesis of Homogeneous Continuity. The object will be in a continuous status, and the whole space of the object will be filled with the media that makes up the object without any space. And the mechanical properties of the object will be similar everywhere. The material that makes up the object fills up the space of the whole object without leaving any space.

2.4.3. Hypothesis of Linear Elasticity. The object will be perfectly elastic. By removing the external force causing deformation, the object still could completely restore to its original shape without any residual deformation. Deformation level will be proportional to stress. Elastic constant does not change with deformation and stress.

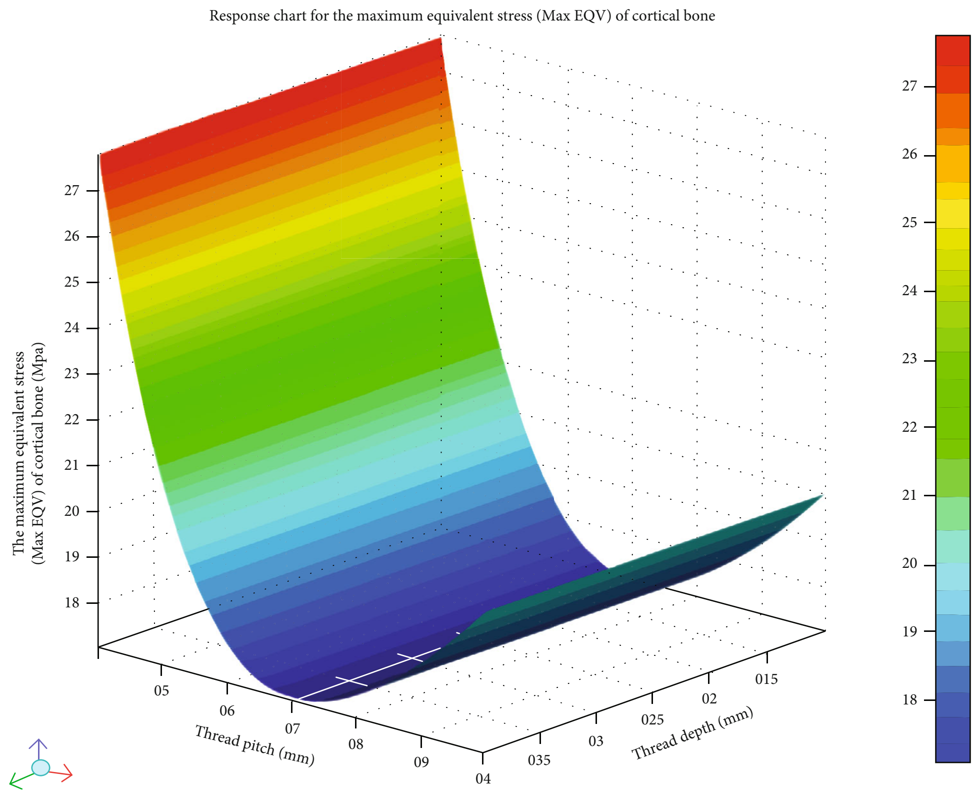
2.4.4. Hypothesis of Small Deformation. Slight deformation will occur after the object is loaded, which is called elastic deformation. Removal of the load can restore its original shape.

2.5. Analysis Indices. Max EQV was used in cortical bone and Max DM in microimplant as the analysis indices. Thread depth (D) and pitch (P) were used for the sensitivity analysis of Max DM and Max EQV. The Max EQV in cortical bone was used to represent the deformation resistance of the bone under torque load. The smaller the Max EQV index, the smaller the stress that the surrounding tissue received; then, the possibility of cortical bone being damaged tends to be lesser [26]. Max DM indicates the micromovement of the microimplant under stress, representing the mobility of the microimplant. The smaller the Max DM index, the lesser the mobility of the microimplant [29].

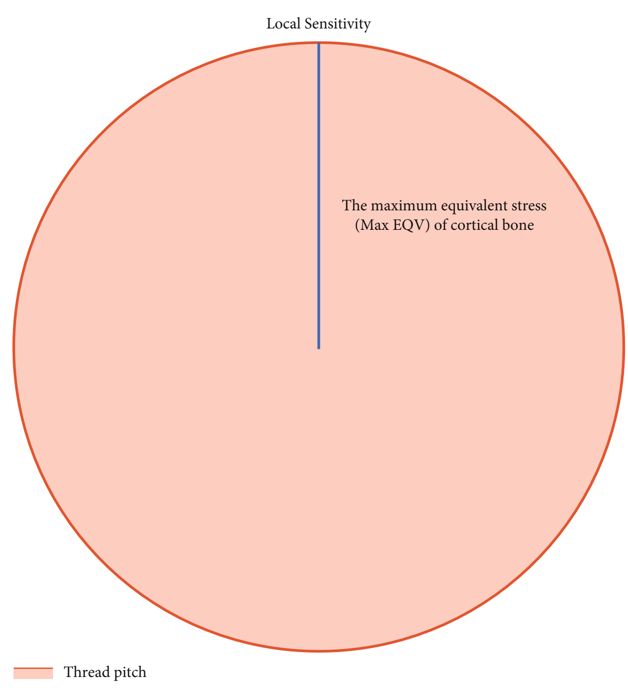
3. Results

The effects of different parameters of D and P on the Max EQV in cortical bone and Max DM in microimplant can be observed in the response surface cloud chart and sensitivity analysis pie chart (Figures 2 and 3, respectively), among which, decline range ((Maximum peak − Minimum peak)/Maximum peak × 100%) and increasing range ((Maximum peak − Minimum peak)/Minimum peak × 100%) were expressed. With P increasing within the range (P: 0.4 mm-1.0 mm), Max DM showed a slight uptrend and Max EQV fell by 38.61%. When D increased within the range (D: 0.1 mm-0.4 mm), the values of Max EQV were similar and Max DM increased up to 164.5%.

Our research focused on the variations of two-factor continuous variables D and P. When one of them was at intermediate values, the response curve to the objective function of the other one is shown in Figure 4. As the thread pitch increased, Max EQV fell by 62.88%. Max DM

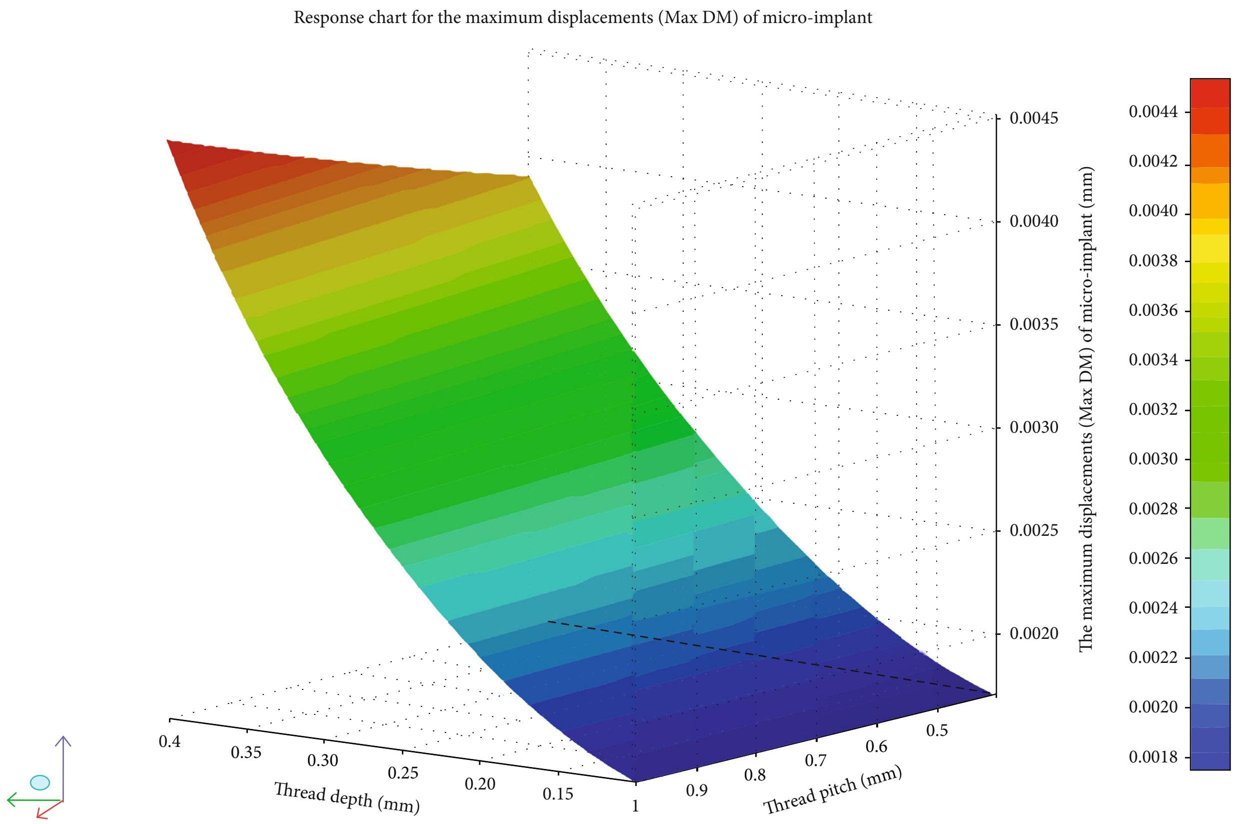


(a)

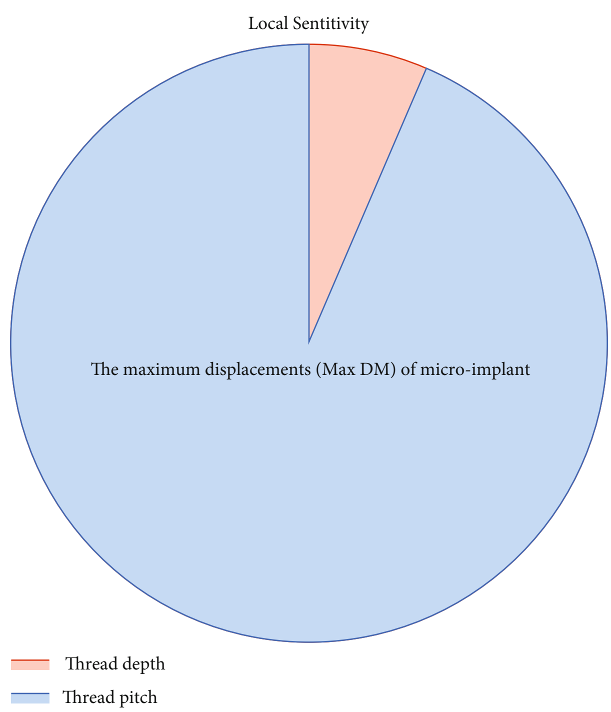


(b)

FIGURE 2: The effects of the continuous changes of D and P on the Max EQV in cortical bone can be seen in the response surface cloud chart and sensitivity analysis pie chart. (a) With the increase in P within the range (P: 0.4 mm-1.0 mm), the Max EQV in cortical bone declined by 38.61%; it decreased initially followed by a small increase, but the level in which it was decreased tends to be larger than the increasing range. As D increased within the range (D : 0.1 mm-0.4 mm), no variation in the values of the Max EQV. (b) The sensitivity analysis of Max EQV in cortical bone. Pitch was sensitive to the Max EQV compared to the depth.



(a)



(b)

Figure 3: The effects of the continuous changes of D and P on Max DM in microimplant can be observed in the response surface cloud chart and sensitivity analysis pie chart. (a) With the increase in P within the range (P: 0.4 mm-1.0 mm), a minimal increase was observed in Max DM. With the increase in D within the range (D: 0.1 mm-0.4 mm), Max DM increased up to 164.5%. (b) The sensitivity analysis of Max DM in microimplant. Depth was sensitive to the Max DM compared to pitch.

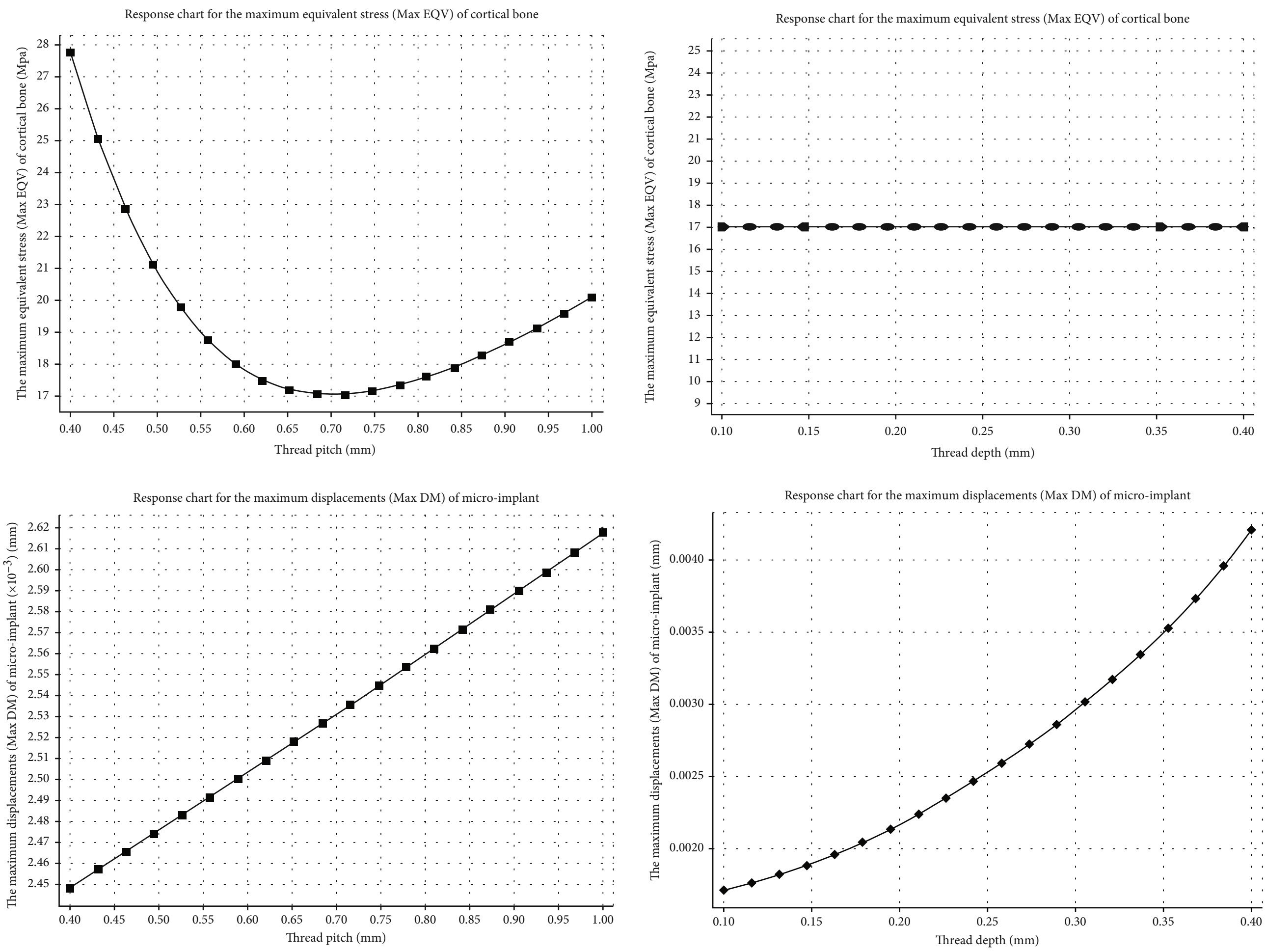


Figure 4: When one factor was set at intermediate value in the range, the effects of another factor on the Max EQV in cortical bone and Max DM in microimplant were evaluated in the response curve.

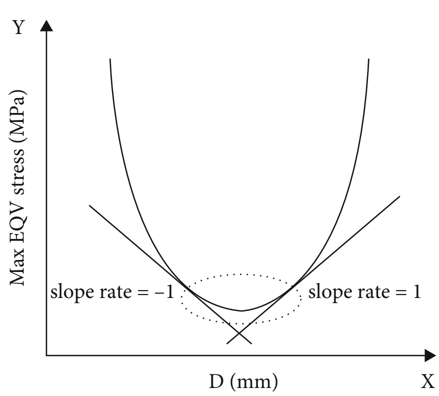


Figure 5: The optimum selection of the curve can be observed in this chart of slight changing and minimal value of the curve.

increased slightly (6.91%). The increase in thread depth influenced the Max DM with rapid increase (144.45%).

The determination method of the optimal value ranges of the response curve indicates that when a straight line was tangent to a curve, the slope of the straight line reflects the changing rate of the curve (Figure 5). When the slope was between -1 and 1, it showed the objective function changes by the variables in a mild manner. Similarly, if the value of the objective function was relatively small while the slope was within the range, the optimal variable parameters should be selected from this range [30]. When 0.55 mm $\leq P \leq 1$ mm, the Max EQV of cortical bone was relatively smaller. When 0.1 mm $\leq D \leq 0.35$ mm, the Max DM of microimplant was relatively smaller.

4. Discussion

4.1. Optimization Design and Analysis. A multiobjective optimization analysis (DesignXplorer) module is an optimization design module integrated in ANSYS Workbench for a collaborative design optimization environment [23]. It achieves the optimization scheme by advanced sampling technology. The principle of using the Monte Carlo method was collecting design parameter samples followed by calculating the response results of each sample, and by using a quadratic interpolation function, the response surface cloud chart was constructed, as well as the response curve of the design space. In this study, we sampled the required parameters of the model by ANSYS Workbench13.0 and established the response surface and response curve. The parameters were imported into Unigraphics through the two-way seamless connection between ANSYS Workbench and Unigraphics. After obtaining the entity model, it was imported back to ANSYS Workbench through the connection. By finite element calculation, the parameters were identified after comprehensive sampling and analyzed the Max EQV and Max DM, respectively. The response surface represents the 3D response chart cooperatively affected by the two factors on the evaluation index. And the response curve represents the 2D response chart when one factor was the intermediate value, while the other one works on the evaluation index of the model. Sensitive analysis was used to measure the effects of each factor on the result of the system or model to judge which factors might affect more.

Many scholars have reported the research on the mutual influences of different configuration factors between implant and microimplant by continuous bivariate analysis. Kong et al. [30] evaluated the mutual influence of the implant's length and diameter and their optimal value ranges using bivariate analysis. Reynders et al. [8] also applied bivariate analysis to identify the optimal value ranges of thread height and pitch. Their research was different from our study as they focused on horizontal linear force, while our objective was on torque force. We have earlier reported the research on using bivariate analysis for the optimization design of a microimplant with the length and diameter changing continuously under different forces, and it provided a theoretical basis for the selection of microimplants with optimal sizes in clinical treatments [33]. The thread depth and pitch work cooperate effectively on the initial stability of the microimplant. They are interconnected on the initial stability of the microimplant. In our study, D and P act as two-factor continuous variables, and we proposed a bivariate analysis which was closer to the real situations than a single-factor discrete variable in clinical treatments. And the research results provided more direct and accurate data for the design parameters of the microimplant. The application of the proposed microimplant has already been reported in our previous research [15], such as the design requirements of length and diameter [23]. This paper studied further on the thread design requirements to meet the requirements of torque force in orthodontic treatment. Optimizing the design of the thread could increase the initial stability of the microimplant under torque force. The purpose of the optimization and analysis of D and P was to identify the most optimal D and P.

4.2. Optimization Analysis of Thread Depth and Pitch. The initial stability of microimplant is the core factor for the stable and reliable orthodontic treatment. Several scholars have learnt the effects of its shape and thread design on the initial stability of the microimplant from different aspects using different methods, with a lot of research studies on the reasonable value ranges of thread depth and width [31–33].

An earlier study analyzed the effects of the pitch on the initial stability of the microimplant by measuring the highest insertion torque and pull-out strength of the microimplant and identified that by minimizing the thread pitch, a decrease in pull-out strength was observed. A study based on the pull-out test on four groups of self-drilling microimplants with different geometric design features proposed that the geometric design features does not hold any noticeable effects on the initial stability of microimplants [35]. That is to say, with higher thread pitch, side, thread angle, and top angle, the initial stability of microimplants was higher.

A 3D FEM revealed that by keeping the external diameter of the microimplant unchanged, increasing the thread size (depth and width), and decreasing the internal diameter, there was increase in stress on the cortical bone. When the external diameter was 1.4 mm, the minimum stress on the cortical bone of microimplants with no thread was generated. When the depth was 0.3 mm, the maximum stress was generated. When the thread depth decreased from 0.33 mm to 0.1 mm, the maximum stress on the cortical bone decreased by 61% [9].

Based on 3D FEM and pull-out test, Chang et al. [10] studied the effects of the thread depth on the initial stability of the microimplant under a lateral load of 3 N horizontal force on it when its external diameter was 2 mm, and it was observed that when the ratio of internal and external diameters was 0.68, it generated the maximum pull-out resistance with higher initial stability.

On analyzing the effects of the thread pitch on the microimplant's initial stability based on measuring the maximum screw insertion torque and the pull-out strength, it showed that the optimal pitch tends to be between 0.75 and 0.80 mm [34]. Microimplant with too large or small pitch values was unfavorable for its initial stability. Applying 3D FEM and pull-out test, Sana et al. [36] evaluated the stabilities of three different microimplants based on Thread Shape Factor (TSF) and calculated the average thread depth, pitch, and their relationship and identified that microimplants with relatively bigger diameter, smaller pitch, and shorter taper did have better geometric features and initial stability.

As per the above-mentioned research reports, forces applied were all linear including horizontal traction, retraction, and vertical and lateral forces. But in orthodontic treatment, the movement of teeth cannot be done without torque control. Therefore, it is essential to find out a microimplant suitable for orthodontic treatment under torque force, which could form a good orthodontic anchorage system to avoid reaction forces on other teeth as anchorage, simplify the treatment process with more direct and efficient control on the teeth's torque force, and reduce adverse reactions.

Our study observed the variations of the Max EQV in cortical bone and Max DM in microimplant (Figures 2 and 3) after 6 Nmm torque force applied on the microimplant. With P increasing within the range (P: 0.4 mm-1.0 mm), the Max EQV in cortical bone showed a thorough downtrend, and Max DM showed a slight uptrend. The values of Max EQV decreased initially and then increased, but the range of decrease was highly significant compared to that of increase. The Max EQV fell by 38.61%. When D increased within the range (D: 0.1 mm-0.4 mm), the values of Max EQV were similar and the displacement peak of the microimplant was in an uptrend with an increase up to 164.5%. The data certified that the effects of the thread pitch and depth on cortical bone and microimplant micromovement were different. From the sensitivity analysis pie chart, the effects of thread pitch were much greater than those of depth with regard to Max EQV (Figure 2). So, when we want to decrease the cortical bone stress, attention needs to be paid on the thread pitch rather than on depth. As to the microimplant's displacement, the thread depth tends to be more influential than the thread pitch. Therefore, more attention should be paid on the thread depth design rather than on the thread pitch to decrease the microimplant's micromotion.

When one factor was set at intermediate value in the range, we discussed the effects of the other factor on the Max EQV in cortical bone and Max DM in microimplant. We found that the increase in the thread pitch led to a decrease trend on Max EQV. As the thread pitch increased, Max EQV in cortical bone decreased firstly and then increased. The decrease range was larger than the increase range, and as a whole, the Max EQV showed a downtrend trend in an asymmetric parabola. The Max EQV fell by 62.88%. Meanwhile, with the thread pitch increased, the max displacement of the microimplant increased slightly (6.91%) in a straight line. On the other hand, the increase in thread depth had no impact on the Max EQV in cortical bone, while it did influence the Max DM in microimplant in an asymmetric parabola with rapid increase (144.45%).

Through the analysis of the tangent slope of the response curve, it showed that when $0.55\,\text{mm} \le P \le 1\,\text{mm}$, the values of Max EQV in cortical bone were small with limited changes; when $0.1\,\text{mm} \le D \le 0.35\,\text{mm}$, the values of Max DM in microimplant were small with limited changes. In total, when the thread pitch of microimplant varies from 0.55 mm to 1 mm and the depth varies from 0.1 mm to 0.35 mm, the optimal initial stability of microimplant could be achieved.

5. Conclusions

Setting thread diameter and pitch as the two-factor continuous variables, we drew the response cloud charts and response curves, respectively, using ANSYS Workbench 13.0. The two-factor analysis performances were better and identical to real clinical treatment than the single-factor discrete variable analysis, by providing a more direct and accurate certification for the design parameters of the microimplant.

With the increase in thread pitch, the values of Max EQV in cortical bone decreased initially, followed by a small increase, showing an overall sharp downtrend, while the values of Max DM in microimplant were in a slight upward trend. On the other hand, as thread depth increased, the values of Max EQV in cortical bone remained unchanged, while the values of Max DM in microimplants increased sharply.

Therefore, to reduce the cortical bone stress, the thread pitch is a key important factor. Meanwhile, to reduce the microimplant movement, the thread depth plays a vital role.

In summary, at $0.55\,\text{mm} \le P \le 1\,\text{mm}$ and $0.1\,\text{mm} \le D \le 0.35\,\text{mm}$, the microimplants achieving optimal initial stability tends to be higher.

Abbreviations

FEA:	Finite element analyses
Max EQV:	The maximum equivalent stress
Max DM:	Maximum displacement of micro-implant
EQV:	Equivalent stress
DM:	Displacement.

Data Availability

All the materials and data have been presented in the main paper.

Conflicts of Interest

The authors declared that they have no competing interests, and none of the authors has financial interests that are directly or indirectly related to the work submitted for publication.

Authors' Contributions

We declare that all the listed authors have participated actively in the study and meet the requirements of the authorship. Shaohai Chang was responsible for the conception. Yushan Ye, Jiuyang Jiao, Jinsong Li, and Shaohai Chang designed the study. Wei Wang and Yamei Wang were responsible for the acquisition and analysis. Qinghe Yao and Jieying He interpreted the data. Yushan Ye and Jiuyang Jiao drafted the manuscript. Song Fan and Jinsong Li critically revised the manuscript for important intellectual content. All authors approved the final version of the manuscript. Yushan Ye, Jiuyang Jiao, and Song Fan contributed equally to this work. Yushan Ye, Jiuyang Jiao, and Song Fan are joint first authors.

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