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Effects of different patterns of movement for correcting a deep curve of Spee with clear aligners on the anterior teeth: a finite element analysis

Lin Zhu¹, Lin Liu^{2*}, Wei Wang³ and Wen Wen Deng²

Abstract

Objective To analyse the anterior teeth effects of clear aligners on five different patterns of mandibular molar movement and to define the most effective configuration to be implemented with clear aligners through finite element analysis.

Methods A three-dimensional mandibular model with a deep overbite in the mandible was constructed using cone beam computerized tomography (CBCT) data. The model included the mandibular dentition, mandibular periodontal ligaments, attachments, and aligners. Five models were created: (1) configuration A: second molar distalization (0.25 mm); (2) configuration B: second molar distalization (0.25 mm), first molar extrusion (0.15 mm); (3) configuration C: second molar distalization (0.25 mm), first and second premolar extrusion (0.15 mm); (4) configuration D: second molar distalization (0.25 mm), first molar and first/second premolar extrusion (0.15 mm); and (5) configuration E: second molar distalization (0.25 mm), first molar and first/second premolar extrusion (0.15 mm), first molar and first/second premolar expansion (0.15 mm).

Results In all configurations, the anterior teeth exhibited labial tipping and the mandibular central incisor of configuration E showed the highest labial tipping. Configuration E demonstrated a relatively minor impact on mandibular molars distalization compared with configuration A. Configuration A showed the highest distal displacement value, and configuration E produced the lowest displacement value. Configuration E caused the highest periodontal ligament (PDL) pressure of the central and lateral incisors. The differences in the canines between configurations C and D, were not significant, and the stress distribution differed among the five groups.

Conclusions All patterns utilizing clear aligners facilitated mandibular molar distalization. Extruding the premolars and second molar distalization at the same time had little impact on second molar distalization; When expansion and extrusion were simultaneously performed during the distalization of mandibular molars, our prime consideration was the alveolar bone on the labial side of the anterior teeth to prevent the occurrence of gingival recession, dehiscence, and fenestration. Due to the lack of consideration for periodontal tissues in this study, clinical protocols should be designed based on the periodontal status of the mandibular anterior teeth.

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Keywords Clear aligners, Deep curve of Spee, Different pattern of mandibular tooth movement, Effects of anterior teeth, FEM analysis

Introduction

The demand for clear aligners has increased significantly over the last decade, primarily due to their aesthetic appeal, comfort, and superior facilitation of oral hygiene compared to traditional appliances [1–3]. Clear aligners offer a desirable alternative to traditional braces, particularly for adults who prioritize the aesthetic aspects of orthodontic treatment [4, 5].

Clear aligners have been found to be highly efficient in various orthodontic treatments, including molar distalization, space closure, and anterior tooth alignment [6–8]. Previous studies have reported that the distalization movement of upper molars with clear aligners has a high predictability (approximately 80%) [8, 9]. For decades, maxillary dentition has been widely used as a classic biomechanical research model [10–14]. In 2009, Kravitz et al. [6] conducted a prospective clinical study to address the issue of the efficacy of clear aligners. They showed that molar extrusion and mandibular incisor intrusion with clear aligners are difficult to control. Thus, clear aligners have low efficiency in deep overbite correction. To date, mandibular models have rarely been evaluated, especially the models with deep curve of Spee.

Nonsurgical deep bite correction techniques include molar extrusion, incisor intrusion, or a combination of both [15]. Extrusion of posterior teeth might be viewed as a good option in low-angle growing patients. With clear aligners, the mandibular incisors can be intruded earlier in the treatment process, allowing for more efficient and timely correction of the deep bite [16].

Extrusion is the least accurate tooth movement achieved with clear aligners. Following the distalization of the mandibular molars, there is slight labial tipping, intrusion, and protrusion of the mandibular incisors [9, 17]. Traditional orthodontic treatments often require aligning and levelling the dental arch to level the curve of Spee before placing reverse-curve arch wires [18]. Many studies have reported that movement of mandibular anterior intrusion and molar extrusion has low efficiency [6, 19, 20], especially the hypodivergent face.

Here we aimed to explore the effects of different movement patterns of mandibular molars using a three-dimensional (3D) finite element model of invisible aligners without brackets on the anterior teeth and to provide a reference for the selection of clinical treatment methods.

Materials and methods

Modelling reconstruction from CBCT

The 3D geometrical model was constructed using cone-beam computerized tomography (CBCT) data from a patient with a deep overbite. The study protocol was approved by the Ethics Committee of the DaLian Stomatological Hospital (DLKQLL202302). The subject provided written informed consent. All methods were performed in accordance with the relevant guidelines and regulations.

The authors confirmed that the patient provided informed consent for data collection. The CBCT images (slice thickness 0.2 mm and pixel size 0.200 mm) were input into Mimics 20.0 software (Materialise NV, Belgium) as digital imaging and communications in medicine (DICOM) files for 3D model reconstruction. For further noise reduction and smoothing, a standard tessellation language (STL) file was input into Geomagic Studio 2014 software (3D System, USA) and NX 1911 software (Siemens, Germany).

Finite element modelling

Specialized FE software, ANSYS Workbench 2019 (ANSYS, USA), was used to create the models. In the models, isotropic, homogeneous, continuous elastic materials were defined and used; only the right side of the mandibular dentition was modelled because of the models' bilateral symmetry (Fig. 1).

To achieve greater simulation accuracy, the interface between the aligner with the tooth crown surface and the attachments was set to be in frictional contact with a friction coefficient of 0.2 [21, 22]. Additionally, friction with a coefficient of 0.18 was established at the contact interfaces between the tooth crown surface [22].

The junctions between other modelled components, such as periodontal ligament (PDL)-bone and tooth-PDL, were set to be rigidly connected. The PDL was modelled as a linear elastic material of 0.25 mm thickness [11]. The Young's modulus and Poisson's ratio were 0.69 MPa and 0.49, respectively. As shown in Table 1, the material properties of the components were set as those reported in previous studies [23–25].

The aligner was developed by making an external offset with a thickness of 0.5 mm according to the result of repeated measurements [23].

The numbers of nodes and elements for all the components are summarized in Table 2.

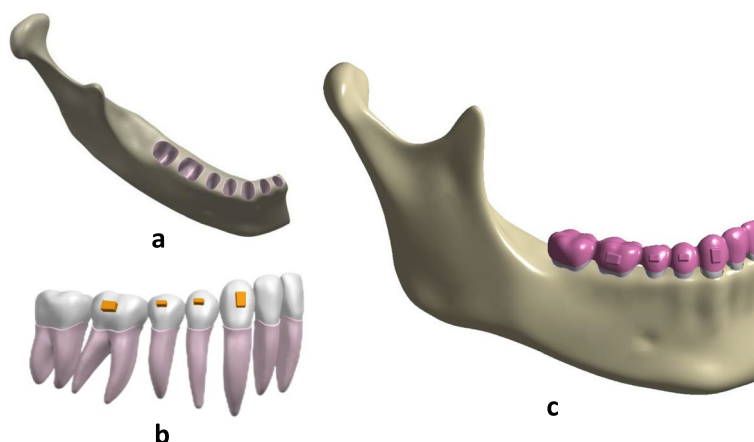


Fig. 1 Finite models. **a** Mandibular. **b** periodontal ligament, dentition, and attachments. **c** Model of the mandibular, periodontal ligament, dentition, attachments and clear aligner

Table 1 Material properties

Component	Young's Modulus (MPa)	Poisson's Ratio
Cortical bone	13,700	0.26
Spongy bone	1370	0.3
Teeth	19,600	0.3
Periodontium	0.69	0.49
Aligner	528	0.36
Attachment	12,500	0.36

Table 2 Number of nodes and elements of the components of the finite element model

Component	Elements	Nodes
Cortical bone	21,036	41,723
Spongy bone	30,378	50,058
Aligner	17,659	34,514
Bone	51,414	80,515

Establishment of a coordinate system

This research involved the utilization of two coordinate systems (Fig. 2). First, the global coordinate system was established from CBCT data.

In the global coordinate system, the X-axis represents the direction of the coronal plane, with the positive direction pointing towards the mesial surface of the tooth; the Y-axis represents the sagittal plane, with the positive direction pointing towards the lingual surface; and the Z-axis represents the vertical plane, with the positive direction being towards the tooth crown surface.

Local coordinates for every tooth were also defined for calculating 3D movements. The local coordinates were separately located at the body centre of the clinical

crown. The x-, y-, and z-axes represent the labial lingual, mesiodistal, and tooth long-axis directions, respectively.

Experimental design

In this study, our aim was to investigate the most effective method of invisible orthodontic treatment by extruding the posterior teeth and subsequently distalizing the second molar. The configuration parameters of the five movement protocols are summarized in Table 3.

Results

The results of the displacement pattern of the 2nd molar in each direction for the 5 molar displacement protocols are shown in Fig. 3.

In Configuration A, the maximum deformation observed was 0.092578 mm, followed by configurations C (0.090879 mm), B (0.088289 mm), D (0.085437 mm), and E (0.315 mm). All the root apices moved in the mesial direction, resulting in uncontrolled lingual distal tipping movement (Fig. 3).

Figure 4 shows the vector analysis of the overall displacement pattern of the dentition for the 5 molar distalization protocols.

The direction of movement for the second molar was mainly along the x-axis (Fig. 4). The maximum tooth displacement was obtained with the distalization configuration (configuration A), which showed 0.093723 mm of translation compared to 0.085493 mm obtained with the expansion configuration (configuration E). The second molar showed a distal inclination tendency. The mandibular anterior teeth exhibited mesial and labial proclination with a rotation centre at the intersection of the apical and middle thirds of the roots in all of the models. Uncontrolled tipping movement was observed for the entire dentition (Fig. 4).

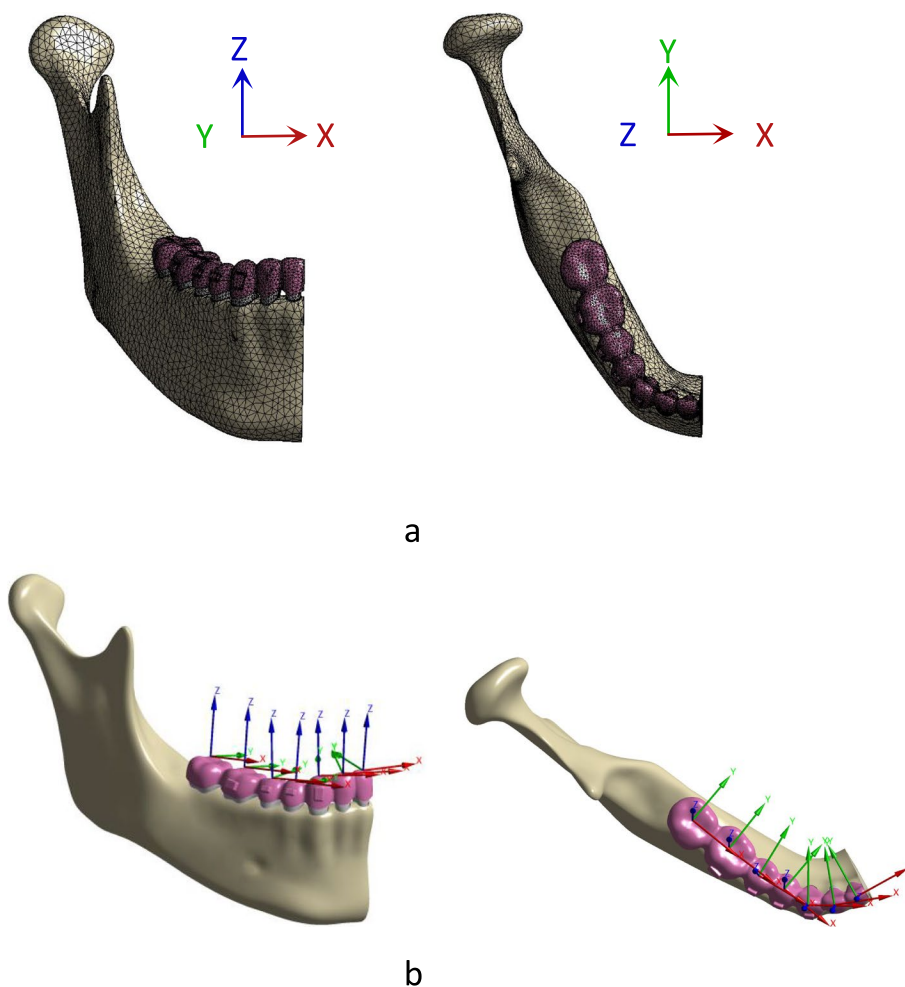


Fig. 2 Coordinate systems. **a** Global coordinates. **b** Local coordinates. The x-, y-, and z-axes represent the labial lingual, mesiodistal, and tooth long-axis directions, respectively

Table 3 Five movement protocols

	Configuration A	Configuration B	Configuration C	Configuration D	Configuration E
Distalization (0.25 mm)	7	7	7	7	7
Extrusion (0.15 mm)	–	6	4,5	4,5,6	4,5,6
Expansion (0.15 mm)	–	–	–	–	4,5,6

7=second molar; 6=first molar; 5=second premolar; 4=first premolar

Figures 5 and 6 show the equivalent (von Mises) stress distribution of the PDL of the central incisor, lateral incisor, and canine.

For central incisors, the stress was distributed at the cervical third on the lingual surface. In the case of lateral incisors, the stress was distributed at the cervical area on the labial and distal surfaces. However, the stress distribution for canines varied across the five groups (Fig. 5).

In configurations A and B, the stress was distributed at the cervical third and apex. In configurations C and D, the stress was distributed at the cervical area on the labial and distal surfaces, respectively, and at the apex. In configuration E, the stress was distributed in the cervical area on the labial and lingual surfaces (Fig. 5).

In the dentition of anterior teeth, the equivalent stress on the PDL of configurations A, B, C, and D was located

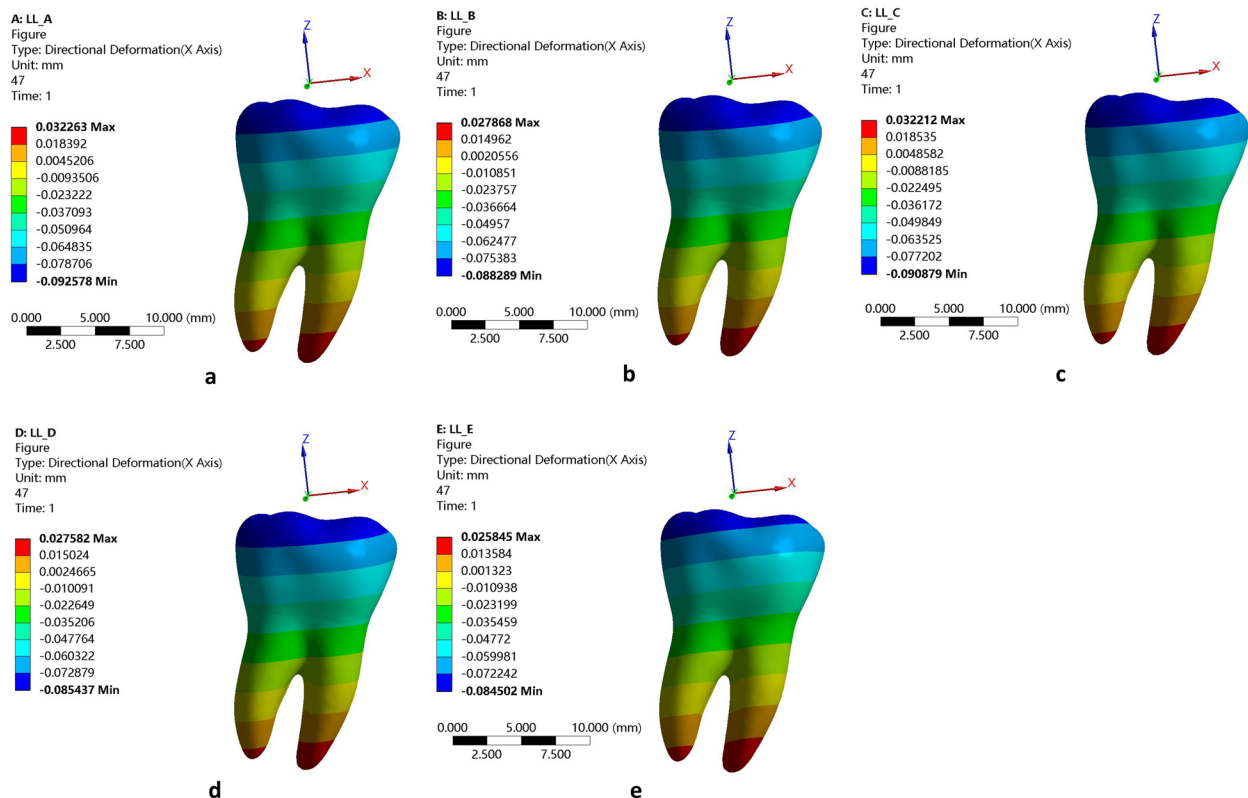


Fig. 3 Displacement pattern of the second molar in each direction for the 5 molar displacement protocols. **a** Configuration A, **(b)** Configuration B, **(c)** Configuration C, **(d)** Configuration D and **(e)** Configuration E. The color intensity correlates with the magnitude of tooth movement, with cooler hues indicating smaller movement trends and warmer hues indicating greater movement trends. Positive and negative values denote specific directions

at the distal and labial cervical area of the canine, and to a lesser extent, the root apex of the canine. In configuration E, the equivalent stress on the PDL was located at the labial cervical area of the canine (Fig. 6).

The maximum labial displacement of the central incisor crown was observed in configuration E, and the maximum labial displacement of the lateral incisor and canine was found in configurations C and D, respectively (Fig. 7).

Discussion

Deep bite malocclusions are a relatively common type of malocclusion found in adolescents and adults, and their severity can be influenced by a combination of dental and skeletal conditions [26]. Skeletal deep bite malocclusion is predominantly characterized by a horizontal growth pattern of the mandible, resulting in a lower anterior face height and a deep curve of Spee [27, 28]. In these cases, extrusion of posterior tooth resulted in an increase in the posterior vertical dimension. On the other hand, dental deep bite malocclusions are caused by excessive development of the alveolar bone in the anterior teeth region

or insufficient development of the alveolar bone in the posterior teeth region. Some studies have indicated that both maxillary and mandibular anterior intrusion were inaccurate [20, 29], Shahabuddin found approximately 1 mm of intrusion of mandibular incisors with 42.5% accuracy [20]; in other words, correcting deep overbite and deep curve of Spee by only intruding the mandibular anterior teeth is not an efficient method, The main mechanisms of deep bite correction were proclination of incisors, intrusion of incisors, and extrusion of mandibular posterior teeth. Depending on whether deep bite malocclusions have a skeletal or dental aetiology, corrective techniques that involve maxillary and mandibular incisor intrusion, proclination, posterior tooth extrusion, and increasing lower anterior facial height through surgical means have been proven effective [15, 30]. It may increase efficacy to intrude the incisor and extrude the posterior at the same time while treating skeletal class II with a low-angle of the deep curve of Spee.

Correcting the deep curve of Spee via extrusion of mandibular posterior teeth has poor efficiency, but Khosravi et al. [31] reported that an approximately 1.5 mm

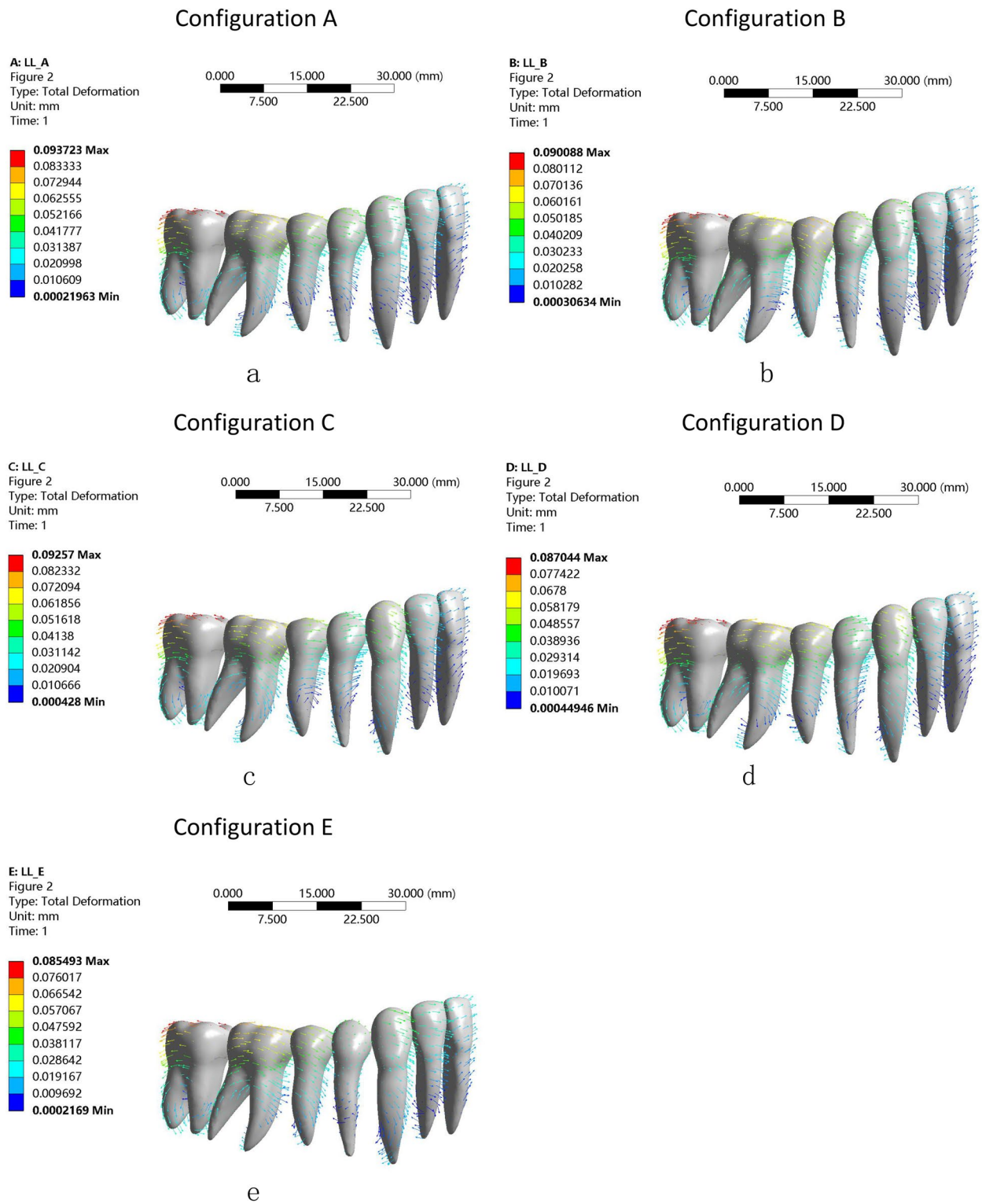


Fig. 4 Trends in total displacement (mm) of the dentition for each configuration. Arrows indicate the direction of tooth movement; (a) Configuration A, (b) Configuration B, (c) Configuration C, (d) Configuration D and (e) Configuration E. the color intensity reflects the magnitude of tooth movement, with cooler hues indicating smaller movement trends and warmer hues indicating greater movement trends

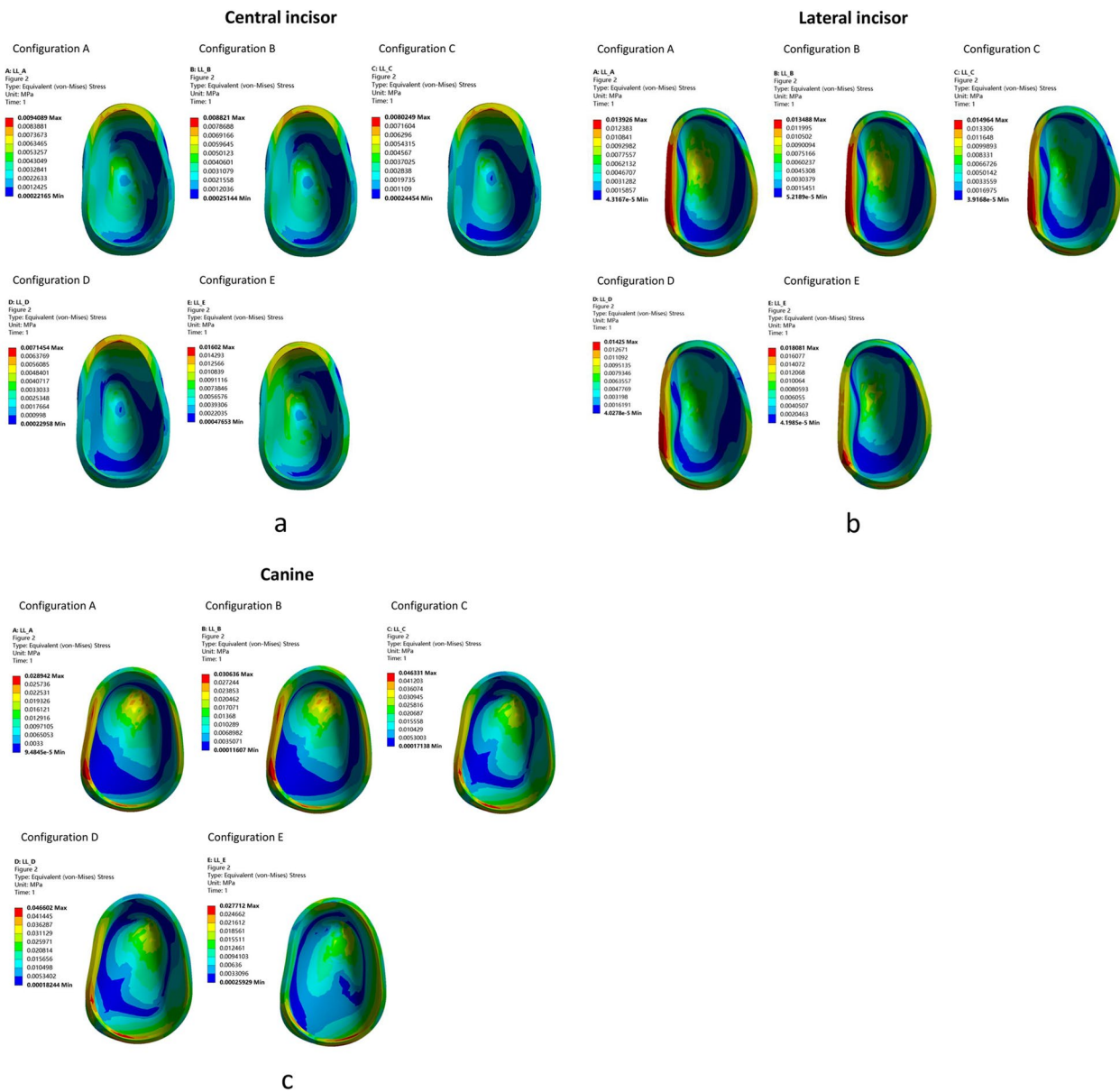


Fig. 5 Equivalent (von Mises) stress distribution of the PDL of the anterior teeth. **a** Central incisor, **(b)** Lateral incisor, and **(c)** Canine

overbite improvement could be achieved when Invisalign appliances were used by patients with a deep overbite. Additionally, clear aligners could improve vertical dimensional malocclusions, such as dental deep bites, within a mild to moderate range.

Our results for the displacement pattern of the second molar demonstrate that extruding the premolars during molar distalization has little impact on molar distalization (Fig. 3). According to the initial displacement results shown in Fig. 3, the greatest maximum tooth displacement (0.092578mm) was obtained by configuration A (distalization of the second molar), while the

lowest (0.084502mm) was obtained by configuration E (distalization, extrusion and expansion), representing a 0.008076mm difference. The tooth displacement of configuration C (extrusion of 4 and 5 simultaneously) was 0.090879mm, differing from that of configuration A by 0.001699mm. However, it's important to note that the maximum tooth displacement alone does not provide comprehensive information for analyzing the efficacy of tooth movement as it does not offer insights into the movement direction.

As shown in Fig. 3, it was observed that the second molar in the mesial-distal (x-axis) direction underwent

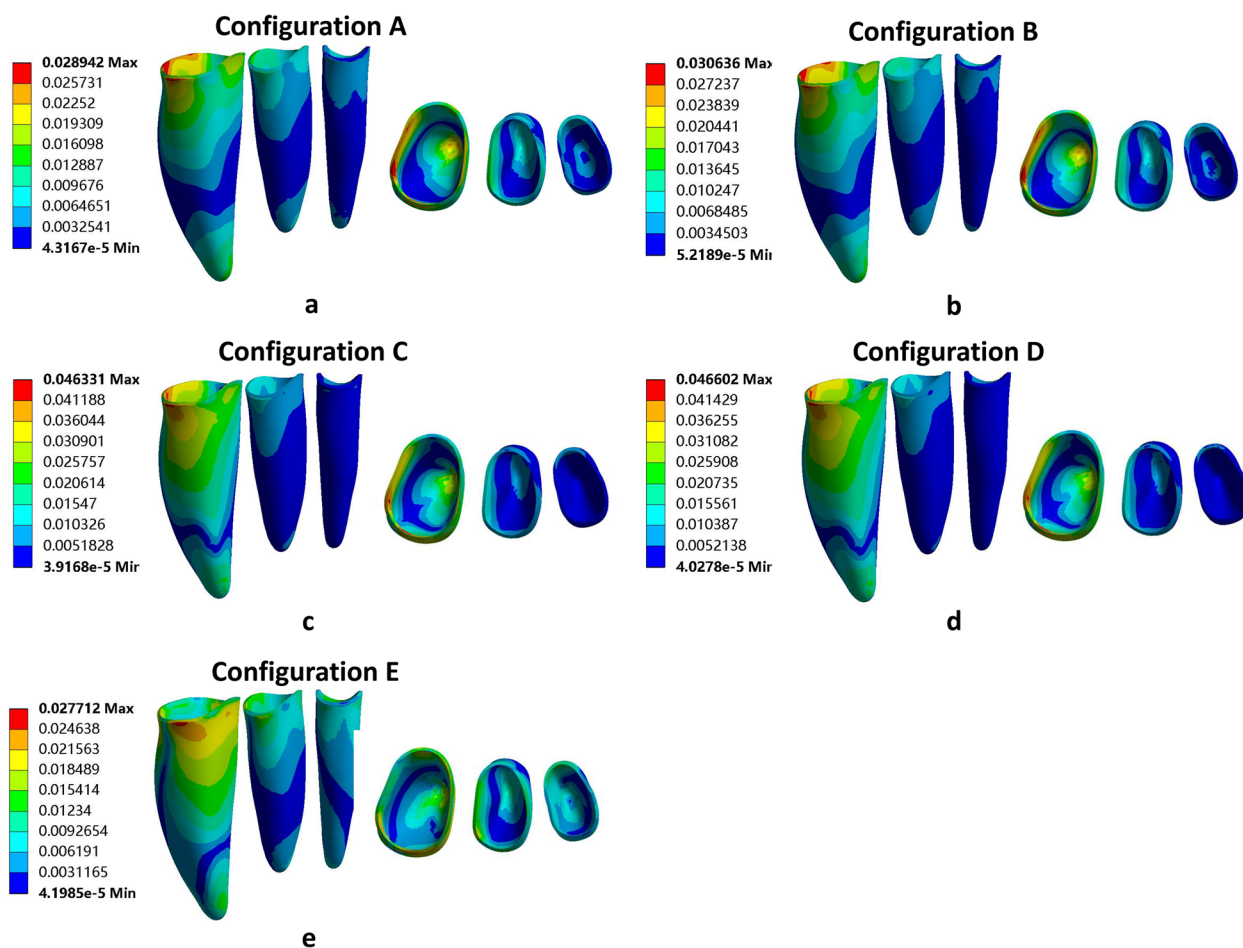


Fig. 6 Equivalent stress distribution of the PDL of the anterior teeth (1-3). **a** Configuration A, **(b)** Configuration B, **(c)** Configuration C, **(d)** Configuration D and **(e)** Configuration E

the maximum distal displacement at every point in the distalization protocol (configuration A). Each configuration exhibited a certain degree of rotation in the second molars during distalization. The results shown in Figs. 3 and 4 are essentially consistent. The difference between configuration A (distalization group) and configuration C (extrusion of 4 and 5 simultaneously) was not significant, indicating that the simultaneous distalization of the second molar and extrusion of premolars has a relatively minor impact on distalization. With the extrusion of the posterior teeth, the expansion of the arch had little effect on distalization (Figs. 3 and 4). Therefore, in clinical practice, it is possible to simultaneously extrude the premolar teeth while distalizing the molars to improve the efficiency of tooth movement.

The anchorage loss of the anterior tooth in orthodontic treatment can lead to labial inclination of the incisors, thereby affecting the efficiency of molar distalization [32, 33]. According to the principle of force interaction, clear aligners are subjected to opposite

forces on the anterior teeth during molar distalization [12, 14]. To increase anterior tooth anchorage, clear aligners perform sequential molar distalization, utilizing the remaining teeth as a group anchor to counteract the reactive forces generated during the distalization process [34]. Furthermore studies [35, 36] suggest that elastic traction and mini-implants can be beneficial in enhancing anterior tooth anchorage control during molar distalization with clear aligners. Our studies indicated that distalization and expansion may not increase anchorage loss of anterior teeth (Figs. 4, 7). In patients who require levelling of the Spee curve, when sequencing the distalization of the second molar, the teeth anterior to the first molar could maintain immobility in the sagittal direction and can be used as an anchor to enhance the clinical efficacy of tooth movement. The premolars and the first molar can be simultaneously extruded in the vertical direction to improve efficiency.

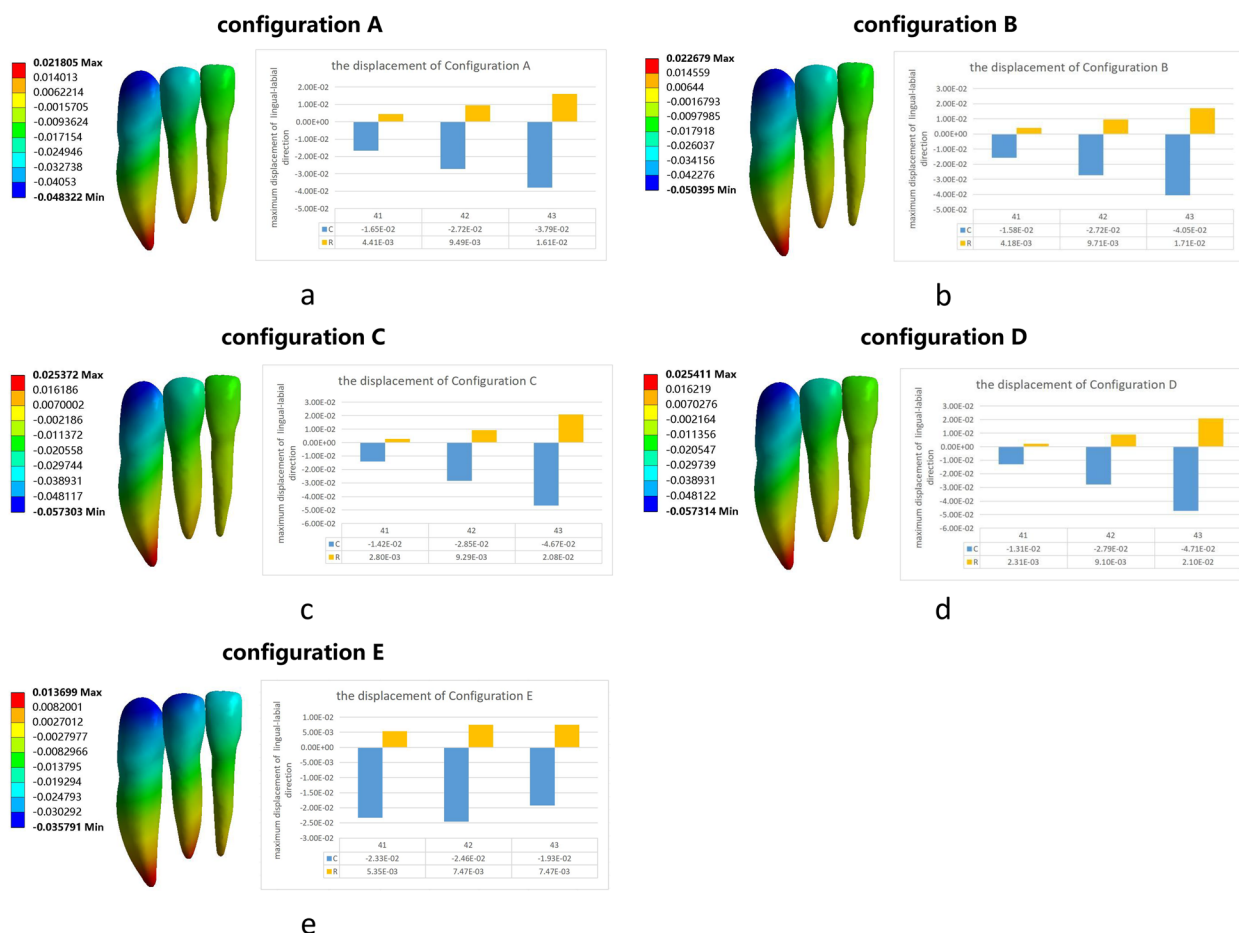


Fig. 7 Anterior displacement in the lingual-labial direction. **a** Configuration A, **(b)** Configuration B, **(c)** Configuration C, **(d)** Configuration D and **(e)** Configuration E

Alveolar bone resorption, a potential side effect of orthodontic treatment, arises from excessive concentrated stress [37, 38]. After orthodontic treatment, patients with significant alveolar ridge resorption may have a higher incidence of gingival recession [39, 40]. Some studies have demonstrated a higher incidence of gingival recession with labial-tipping movements [41].

Based on our experiments, clear aligners produced high levels of concentrated stress mainly on the cervical area, indicating that the buccal alveoli fossa might bear higher stress and is prone to the risk of buccal alveoli fossa resorption and gingival recession (Fig. 5). In our study, the equivalent stress on the periodontal membrane of the canines in configurations C and D was twice that of configuration A (Figs. 5 and 6). However, the equivalent stress distribution in the PDL of configurations C and D was more scattered than that of the other configurations (Fig. 6). In configuration E (distalization, extrusion and expansion), the central incisors were subjected to significantly greater stress than

in the other configurations, and the lateral incisors were also found to be stressed to a greater extent. Comparing the results for configurations D and E, there is a greater force on the incisors during distal movement and expansion of the arch (Fig. 6). For patients with a thin alveolar bone in their anterior teeth, it is important to prevent buccal bone resorption and gingival recession during the process. In configuration E, there was a concentration of stress on the buccal cervical area of the canines (Fig. 6). During expansion, it is necessary to monitor the condition of the buccal alveolar bone. In the anterior dentition, the maximum stress was concentrated on the cervical area of the canines in all configurations. This indicates that during orthodontic treatment, attention should be given to the cervical area of the canines. As a result, the anchorage loss of anterior teeth in orthodontics can lead to increased labial tipping and protrusion of the maxillary incisors [32, 33], which can affect the efficiency of molar distalization. Whether the patient has good periodontal health

or is suffering from periodontal disease, it is important to protect the canines when retracting the upper anterior teeth, ultimately avoiding excessive forces on the canines that can lead to gingival recession, alveolar bone resorption, dehiscence, and fenestration.

This study has several limitations. First, it is limited by the current finite element analysis technology. Tooth movement is influenced by many factors, especially the condition of periodontal tissue. The health of the periodontal tissue directly impacts the design method and magnitude of molar movement. When the lower anterior alveolar bone is reduced, distalization of mandibular molars may affect the mechanism of lower anterior teeth. Second, this study includes a single model rather than a sample of models with varied severities. During the process of distalization of the mandibular molars, different curves of Spee may have different modalities. In the future, more animal and clinical experiments should be carried out to acquire evidence at a higher level.

Conclusions

In conclusion, this study showed the following: (1) All different patterns for correcting the curve of Spee with clear aligners results anchorage loss of the anterior teeth. During this process, the anterior teeth exhibited labial inclination with a rotation centre at the intersection of the apical and middle thirds of the roots. (2) Simultaneously extruding the premolars during molar distalization has little impact on molar distalization (3) When expansion and extrusion occur simultaneously during the distalization of teeth, attention must be given to the alveolar bone on the labial side of anterior teeth, especially the canines, to prevent the occurrence of gingival recession, dehiscence, and fenestration.

Abbreviations

FE	Finite element
FEA	Finite element analysis
PDL	Periodontal ligament
CBCT	Cone beam computed tomography

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Not applicable.

Authors' contributions

LZ analyzed and interpreted the data obtained, and was a major contributor in writing the manuscript; LL interpreted the data obtained and were a supervisor in writing the paper; WW: built and solved the Finite element model; WWD revised the manuscript; All authors have read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the DaLian Stomatological Hospital (DLKQLL202302). Written informed consent was obtained from the subject. All methods were performed in accordance with the relevant guidelines and regulations.

Consent for publication

Not applicable.

Competing interests

WW was employed by Urumqi DW Innovation InfoTech Co., Ltd. The remaining authors declare that they have no competing interests.

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