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ORIGINAL ARTICLE

The remodeling of alveolar bone supporting the mandibular first molar with different levels of periodontal attachment

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Abstract The objective of this study was to investigate alveolar bone remodeling of the mandibular first molar with differing levels of periodontal attachment under mastication loading. Three-dimensional finite element models of the mandibular first molar with differing levels of periodontal attachment were established. The stress distributions and bone density changes were analyzed under mastication loading to simulate the remodeling process of mandibular bone based on the theory of strain energy density. The results showed that the alveolar buccal, lingual ridges and root apex areas experienced higher stresses. The stresses and densities of the alveolar bone increased proportionally to increased mastication loading. Decrease in alveolar bone density under extreme loading indicated bone resorption. The remodeling rate was continual with gradual loading. Periodontal ligament support marginally decreased with an increased remodeling rate under extreme loading. Changes in alveolar bone density can reflect the remodeling process of periodontal tissue under mastication loading. The relationship between the change in density and mastication loading during remodeling can provide useful indicators into clinical treatment and diagnosis of the periodontal disease.

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1 Introduction

Periodontitis, dental caries and physiological atrophy are contraindications into loss of alveolar bone, changes in bone density and reduction of periodontal attachment which may potentially result in tooth loss [19, 35, 39]. These diseases induce remodeling of alveolar bone in order to adapt to the changes in the biomechanical environment. These changes occur as the teeth and periodontal tissues cannot tolerate normal bite forces with reduced alveolar bone support due to periodontitis. Excessive bite forces can lead toward continuous resorption of alveolar bone and consequentially tooth extraction. However, if appropriate bite forces are maintained, the resorption can be reduced [17]. Therefore, it is very important to understand the remodeling of the periodontal tissues and evaluate its influencing factors in clinical practice.

Bone, as a living tissue, has an ability to remodel itself to adapt its biomechanical environment and function by changing both its material properties and geometry (bone apposition or resorption) until new functional equilibrium is achieved [27]. This phenomenon is called bone remodeling, which is associated mainly with density (internal) and/or geometric (external) changes [26]. Recently, there are many theories describing the bone remodeling process. For example, the process of bone remodeling is heavily influenced by mechanical loading conditions [12, 44]. If loading is excessive, bone's self-repair mechanisms cannot keep pace with the increasing damage, and resorption will result [26]. Generally, bone remodeling can be defined as a

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process where bone gradually alters its morphology in an attempt to adapt to any new external load [12]. Many investigators propose that numerical simulations and algorithms can be combined with finite element (FE) analysis to develop quantitative numerical models for the prediction of bone remodeling [3, 26, 33]. There have been some investigations into the biomechanics of alveolar bone remodeling. These investigations were mainly associated with finite element (FE) analysis combined with mathematical bone remodeling algorithms to predict bone remodeling induced by dental implants [13, 29]. Nevertheless, there have been relatively few reports on mathematical model for simulating the remodeling process induced within natural teeth. There is limited study into bone remodeling and its influencing factors induced by natural teeth with different periodontal tissue attachment levels.

This study incorporates three-dimensional (3D) FE models of the mandibular first molar with different levels of periodontal attachment. The stress distributions and bone density changes during the remodeling process of alveolar bone were investigated using FE software ABAQUS and the material subroutine (UMAT). Strain Energy Density (SED) algorithms were applied to predict alveolar bone remodeling induced around natural teeth with differing levels of periodontal attachment under mastication loading conditions. This study's outputs may be useful for diagnosis and treatment planning for periodontal disease.

2 Materials and methods

2.1 Finite element model generation

A 3D FE model was the basis for the remodeling analysis. Computer Tomography (CT) image-reconstruction technique was used in this study. Firstly, the X-ray images of mandible with the left first molar in gray scale were recorded by Cone beam CT (CBCT 3D, Sirona, Germany). Images of each layer were imported into the Mimics software (Mimics, V 10.01, Materialise, Belgium) and edited to create closed contours. These contours on different layers were matched to reconstruct the 3D surface model of the first molar within the mandible. The 3D surface model was imported into the Geo-magic Studio software (Geo-magic Studio, V11.0, Rain Drop, USA) to obtain the Non-Uniform Rational B-Splines (NURBS) of the model, this model was transformed into the solid model based on the NURBS. The whole model consisted of four parts: cortical bone (thickness of 2 mm), periodontal ligament (thickness of 0.2 mm), cancellous bone and mandibular first molar. Each part was imported into ABAQUS software (ABAQUS, V 6.10, Dassault SIMULIA, USA) and meshed using 4-node solid tetrahedral elements. In order to investigate the effect of alveolar bone loss on the remodeling, the level of periodontal attachment was defined to describe the condition of alveolar bone loss. Three models with different attachment levels were finally established in the analysis (Fig. 1).

Linear elastic, homogeneous, isotropic properties of teeth, alveolar bone and periodontal ligament were assumed in the remodeling analysis [6, 8, 40, 41]. The contact interfaces between teeth, PDL and bone were treated as tie-constraint (ABAQUS) that was used to determine one surface tied to another without sliding, in order to simulate the attachment of the teeth to alveolar bone through periodontal ligament. Boundary conditions were prescribed to the mandibular bone sectional edges which restricted the displacement along the Z axis (Fig. 2a). Vertical loading varied from 180 to 480 N was loaded along Z axis (Fig. 2b), which was considered to be within the normal range of occlusal mastication forces [1, 2, 25, 31]. Material properties for the FE model were obtained from literature (Table 1).

2.2 Bone remodeling algorithm and procedure

An effective mechanical stimulus for bone remodeling is SED, which has been employed in a number of dental implant-induced bone remodeling studies [9, 26, 30, 34, 42].

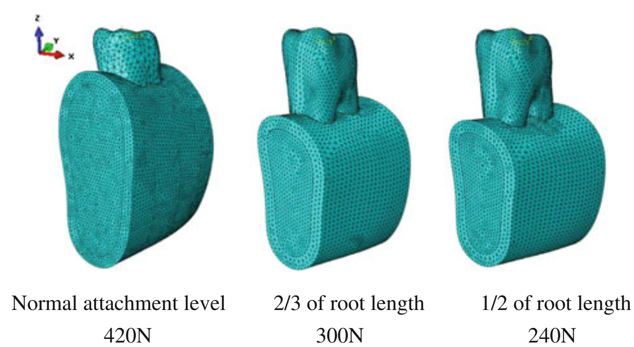

Fig. 1 FE models with different attachment levels

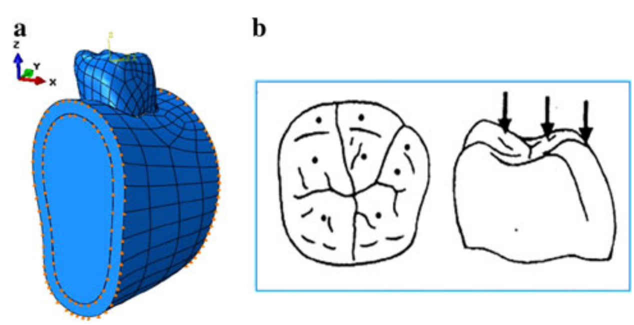

Fig. 2 Boundary condition and loading [20, 32]

Table 1 Material properties of teeth and periodontal tissue

Material	Young's modulus (GPa)	Poisson'Ratio	Density (g/cm^3)	References
Teeth	18.6	0.3	–	[28, 38]
PDL	0.0689	0.45	–	[28, 38]
Cortical bone	14.7	0.3	1.74	[22]
Trabecular bone	1.47	0.3	0.9	[21, 23]

The alveolar bone remodeling process is mainly formulated by the changes in density due to the mechanical stimulus [36]. Change in bone density is expressed as a function of the mechanical stimulus [6, 37, 42, 43]:

$$\frac{\partial \rho}{\partial t} = B(S - K) \tag{1}$$

where B is a constant, K is the threshold value for the stimulus. S represents the mechanical stimulus and is given as follows:

$$S = \frac{U}{\rho} \tag{2}$$

U is the SED, and ρ is the local bone density. The Young's modulus varies with the bone density changes during the process of remodeling, the relationship between bone density and Young's modulus can be expressed as follows:

$$E = C\rho^3 \tag{3}$$

Here C is a constant and has the value 3,790 MPa (g cm)$^{-3-2}$ [7]. Eq. (2) can be rewritten as follows:

$$\frac{U}{\rho} = \frac{\sigma^2}{2E\rho} = \frac{\sigma^2}{2C\rho^4} \tag{4}$$

From Eqs. (1) and (4), the relationship between stress and density of bone can be obtained.

Based on the SED theory of bone remodeling, a user subroutine was developed in FORTRAN language to perform the bone remodeling simulation [5]. The remodeling procedure applied the user subroutine to calculate the density of each element for alveolar bone. FE iterations of the entire model enabled continual updating of the material properties according to the changes in bone density (Fig. 3). The critical threshold for remodeling of alveolar bone was based on the following rules [13, 26, 34]:

$$\frac{\partial \rho}{\partial t} = B\left(\frac{U}{\rho} - K_{\min}\right) \quad \text{if } \frac{U}{\rho} \le K_{\min} \quad \text{Bone loss} \tag{5}$$

$$\frac{\partial \rho}{\partial t} = 0 \quad \text{if } K_{\min} \le \frac{U}{\rho} \le K_{\max} \quad \text{Equilibrium} \tag{6}$$

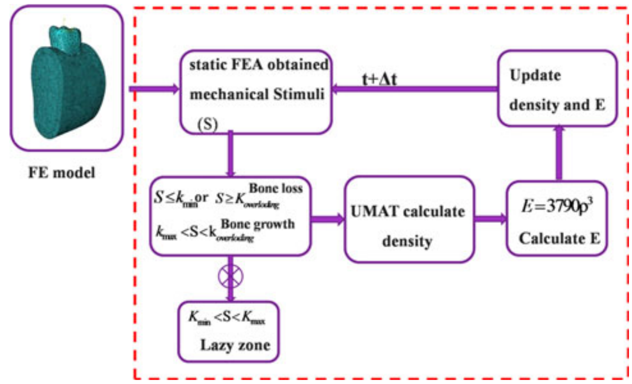

Fig. 3 Flow chart of bone remodeling analysis

$$\frac{\partial \rho}{\partial t} = B\left(\frac{U}{\rho} - K_{\max}\right) \quad \text{if } K_{\max} < \frac{U}{\rho} < K_{\text{overloading}} \quad \text{Bone growth} \tag{7}$$

$$\frac{\partial \rho}{\partial t} = B\left(K_{\text{overloading}} - \frac{U}{\rho}\right) \quad \text{if } \frac{U}{\rho} \ge K_{\text{overloading}} \quad \text{Bone loss} \tag{8}$$

where, $K_{\min}$, $K_{\max}$ and $K_{\text{overloading}}$ denote the reference SED. If the value of is less than $K_{\min}$ or more than $K_{\text{overloading}}$, then the rate $\partial\rho/\partial t$ will be negative, and bone density will gradually decrease with time, meaning bone loss (Eqs. 5, 8). If the value is greater than $K_{\min}$ and less than $K_{\max}$, the $\partial\rho/\partial t$ will be zero, meaning bone density in equilibrium (Eq. 6). If the value is greater than $K_{\max}$ and less than $K_{\text{overloading}}$, then the $\partial\rho/\partial t$ will be positive, and bone density will increase with time, meaning bone growth (Eq. 7) (Fig. 4).

In this study, each remodeling period was chosen to denote one month. In total, 24 iterations were performed for every finite element model, simulating the remodeling period of 2 years.

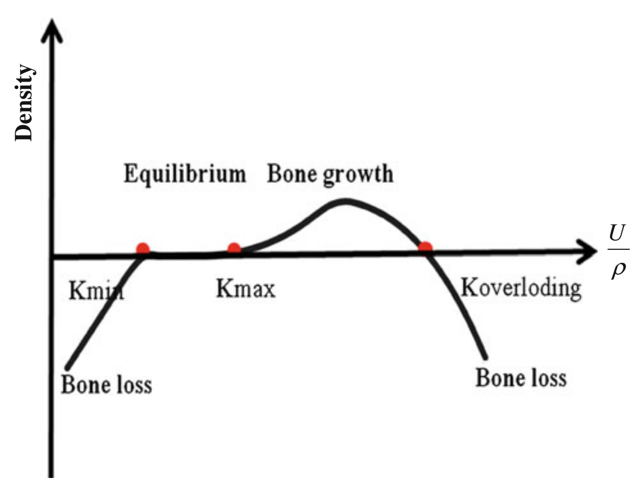

Fig. 4 The bone remodeling curve

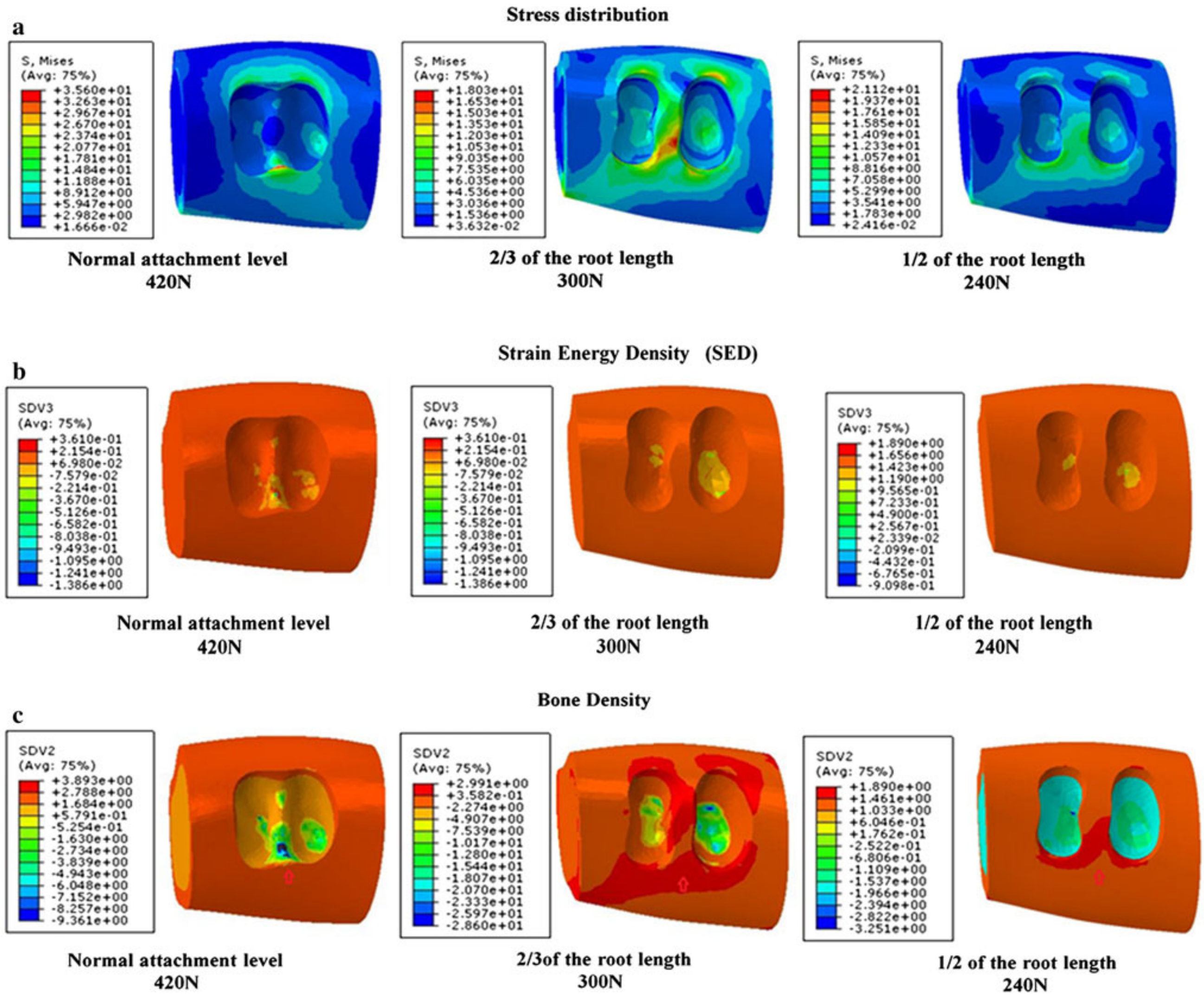

Fig. 5 Stress, SED and density contours of the alveolar bone with different attachment levels at month 24

3 Results

In order to quantify the relationship between the mastication loading and the bone density changes during the remodeling of alveolar bone, in this study, changes in stresses, SED and density of alveolar bone were investigated over a simulated 24 month period.

3.1 The influence of loading magnitude on bone density changes

High concentrations of stresses, SED and bone density changes (Fig. 5) were mainly situated in the alveolar lingual ridge, alveolar buccal ridge and root apex.

Figure 6 plotted the changes in alveolar bone density in the regions of high stresses with increasing bite force. It was shown that the density changes of mandibular bone first increased gradually with increasing bite force and then decreased when the load exceeded a certain value after an equilibrium period. This load was defined as extreme load.

3.2 The effect of attachment levels on bone density changes

The alveolar bone surrounding the mandibular first molar with different periodontal attachment levels showed a decrease in density under extreme loading that resulted in bone resorption. The extreme loads were different and decreased with reduced periodontal attachment level. When the level of periodontal attachment was at the cement-enamel junction (CEJ) in normal position, extreme load was 420 N. The remodeling places were in the alveolar lingual ridge region and root apex area. The density reduced from 1.74 to 1.68 g/cm^3 (cortical bone), 0.9 to 0.8468 g/cm^3 (cancellous bone) and 0.9 to 0 g/cm^3 (root apex), respectively (Fig. 6a). When the attachment level

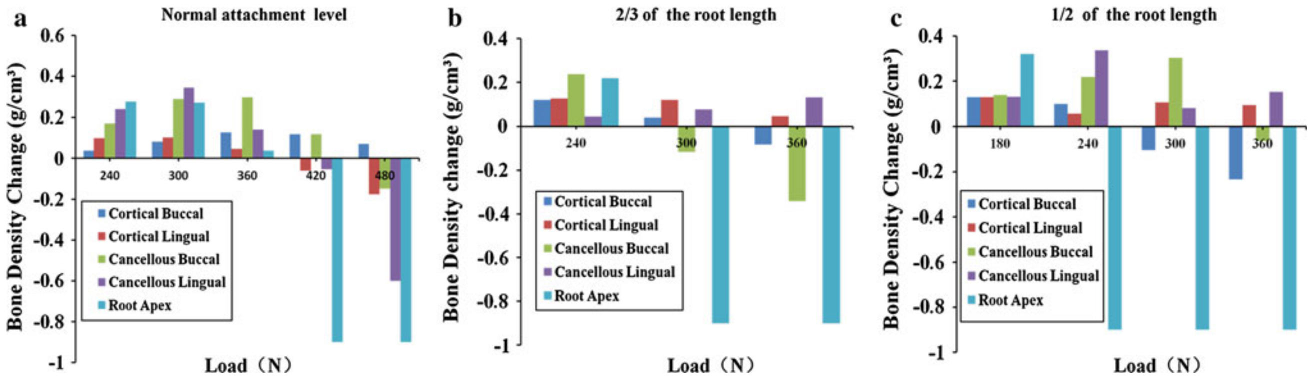

Fig. 6 Bone density change in the regions of high stress: **a** normal attachment level. **b** attachment level was 2/3 of the root length. **c** attachment level was 1/2 of the root length

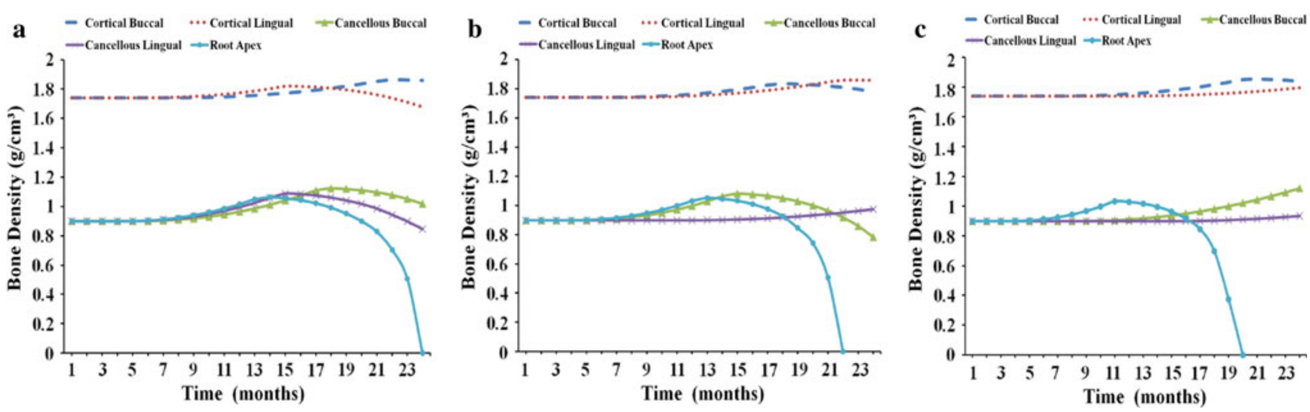

Fig. 7 Remodeling history of alveolar bone with different attachment levels under extreme load: **a** normal attachment level under 420 N extreme load. **b** attachment level was 2/3 of the root length under 300 N extreme load. **c** attachment level was 1/2 of the root length under 240 N extreme load

was at the 2/3 of the root length (Fig. 6b), extreme load decreased to 300 N. Similarly, the density of the cancellous bone reduced from 0.9 to 0.784 g/cmg/cm^3 in the alveolar buccal ridge region and the density from 0.9 to 0 g/cmg/cm^3 in root apex region. Until the attachment level to 1/2 of root length, extreme load was only 240 N, the density of root apex decreased to 0 g/cm^3 also (Fig. 6c).

3.3 The remodeling history of alveolar bone with different attachment levels

This research investigated the effect of loading time on the changes in alveolar bone density during remodeling with differing periodontal attachment levels under the corresponding extreme load.

Figure 7 showed the remodeling of alveolar bone under extreme loading over 24 months. The density increased gradually between months 9 and 15, after the equilibrium period of 8 months where the alveolar bone attachment level was normal. Density decreased in the following months until the density at root apex was 0 g/cm^3 at 24 months (Fig. 7a). Figure 7a–c showed that the time when the bone density appeared decreasing was advanced with increasing alveolar bone loss. This demonstrated the reduced capability of alveolar bone to support dentition and that the remodeling rate was faster, when the periodontal attachment level was reduced.

4 Discussion

In the present study, the alveolar bone remodeling model induced by the mandibular first molar was developed to investigate remodeling process. This numerical model distinguishes itself from other published models [10, 11] by incorporating the alveolar bone remodeling with different levels of periodontal attachment which is still not reported at resent. SED was used as the mechanical stimulus [9, 30, 34] in the bone remodeling algorithm to successfully establish the relationship between the change in density and mastication loading during remodeling which would provide useful indicators into clinical treatment and diagnosis of the periodontal disease.

The simulated results showed that the high stresses and SED (Fig. 5a, b) on the alveolar buccal, lingual ridges and root apex areas increased with the loss of periodontal attachment, especially when the height of alveolar bone was under 2/3 of the root length. After horizontal bone loss from periodontal disease, the PDL-supported root surface area can be dramatically reduced [18]. Excessive load on the teeth may lead to high mechanical stimulus at the interface, therefore, transferring stress to the bone, damages the original bone modeling/remodeling equilibrium [12, 29]. The present study, as well as previous investigation [29], demonstrates that the marginal bone loss around the teeth is produced mainly by excessive occlusal overload on the teeth in remodeling process. The bone remodeling takes place quickly in these regions (Fig. 5c). These results reflects the bone's rapid response to the altered mechanical environment. Although the maximum stress and the remodeling rate in this study is a little different from that in Clarice Field and Daniel Lin et al.'s paper [10, 11, 13], the results are similar in terms of the stress distributions and progress of bone resorption. From Fig. 7, the remodeling history could be seen that the mandible bone density began to decrease at the areas of high stress caused by extreme load after periods of equilibrium and increase during the remodeling. The density changes of alveolar bone were continual with gradual loading. Periodontal ligament support marginally decreased with an increased remodeling rate under extreme loading. This remodeling process is in general agreement with those observed experimentally [14, 16] and suggests that the periodontal ligament physiologically adapts to increased occlusal loading by resorption of the alveolar crestal bone resulting in increased tooth mobility. This is occlusal trauma and is reversible if the occlusal force is reduced properly to the molar with different attachment level in clinical treatment of periodontal disease.

The present study has some limitations. To simplify model, the enamel of mandibular first molar in the established models was omitted which could affect the stress value and distribution slightly. The material properties of periodontal ligament (PDL) and bone were assumed to be linear elastic, homogeneous, isotropic which would determine the accuracy of the mechanical responses obtained. For example, the initial cancellous and cortical bones were assumed to uniform with the lower bound densities of 0.9 and 1.74 g/cm^3, respectively [4, 37]. Further study is certainly needed to improve the geometric similarity and mechanical similarity of the finite element model. The loading is also need to be improved to simulate dynamic loading condition [15, 24]. In spite of these limitations, this paper presents a 3D mandibular bone remodeling induced by natural teeth with different height bone loss. Computational results can simulate the remodeling process of alveolar bone. The effect of overloading on the bone resorption has been clearly demonstrated. The findings of the present study are in a good agreement with the remodeling in the surrounding natural dentitions in the published literature [11, 13]. All these results are need to be confirmed by the clinical follow-up data, which would validate the established model.

In conclusion, the alveolar buccal, lingual ridges and root apex areas would undergo a progressive bone resorption, if the mandibular first molar with different levels of periodontal attachment was under extreme loading. Establishing relationships between mastication force and its resulting change in bone density can help dentists to adjust bite force properly in clinical patient-specific treatment.

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Conflict of interest None of the authors has any conflict of interest in this study.

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