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Original Article

Effect of occlusal slope related to uneven attrition on root stress distribution and potential fracture

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Biomechanics;
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Abstract *Background/purpose:* Severely uneven occlusal attrition is thought to play an important role in the occurrence of spontaneous vertical root fracture (VRF), a frequent problem among Chinese people. This study evaluated the influence of occlusal slope related to uneven attrition on the root stress condition.
Materials and methods: A finite element model of the mandibular first molar was established. Two different occlusal slope patterns were simulated in 5 models: (A) sound tooth, (B) 0.5—1.5 mm and (C) 2—3 mm attrition increased buccally, and (D) 0.5—1.5 mm and (E) 2—3 mm attrition increased distally. A static load of 200 N was applied vertically or angled at 45° to the longitudinal axis. The von Mises stress was evaluated.
Results: Under vertical loading, more stress was transferred from the cervical to the middle root with attrition, especially the mesial root, while stress declined with attrition under oblique loading. Stress was mainly distributed in the buccal surface and mesial root with vertical loading, or in the lingual surface and distal root with oblique loading. The maximum von Mises with oblique loading was significantly higher than with vertical loading.
Conclusion: Uneven occlusal attrition made the middle of the mesial root bear more stress, increasing fracture risk under vertical load. This finding suggests that timely restoration of the sloped occlusal morphology in teeth with severe attrition should be recommended to prevent VRFs. Lateral loading was not a risk factor of typical vertical root fractures, but the high stress could cause distal root cervical fracture.

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Introduction

Attrition refers to the wear of dental hard tissues through tooth-to-tooth contact, without the intervention of foreign materials, and it is the most common type of wear.[1,2] It is a natural and inevitable process that occurs continuously and runs throughout life. Moderate occlusal attrition contributes to the extensive contact between opposing dentition. However, exceptional attrition can lead to morphological changes of the occlusal surface, reduced crown height, and exposed dentin, causing functional difficulties and pathological problems.[3] Attrition is age related, and the attrition score was reported to be highest at 51–60 years of age.[4–6] Moreover, with the aging of the population and improving dental health, there has been a greater prevalence of tooth attrition in elderly people. Tooth attrition has now become a significant dental problem.[4]

Spontaneous vertical root fracture (VRF) means VRFs in non-endodontically treated teeth, and accounts for 40% of VRFs.[7] VRFs were reported to have a high frequency in Chinese people, particularly because of their specific dietary pattern.[8,9] Clinical studies have found that spontaneous VRFs always occur in severely attrited first molars, and mainly in patients over age 40.[8–10] Thus age-related tooth attrition could play an important role in the occurrence of spontaneous VRFs.

Tooth attrition, with occlusal surface changes and tooth shortening, might affect the stress distribution and potential for fracture in teeth.[11,12] The lingual cusps of the maxillary molars and the buccal cusps of the mandibular molars become more heavily attrited, which creates an occlusal attrition pattern sloping lingually on the maxillary molars and sloped buccally on the mandibular molars.[13] Moreover, severe occlusal attrition in spontaneous VRF-affected teeth often presents with specific characteristics, such as a high, steep, non-functional cusp, a low, flat, functional cusp, and a distal marginal ridge.[14] As a result of the slope in the occlusal plane, the bite force might be transmitted to the root deviating from the normal axis, and ultimately might lead to stress redistribution at the root surface. This uneven tooth attrition was suspected to be an important factor for spontaneous VRFs.[14] However, this relationship has not been confirmed. To date, studies of tooth attrition have focused mainly on morphology and epidemiology.[5,13,15]

Tooth attrition is a slow, long-term, dynamic process, and is difficult to simulate by in vitro laboratory testing. Three dimensional (3D) tooth models provide an accurate method for measuring tooth attrition.[16,17] Finite element analysis (FEA) is a digital analytical method that can accurately model complex geometries, simulate mechanical events, and analyze stress–strain patterns upon loading.[18] It has been applied to the analysis of stress distributions of attrited tooth models, although the model was taken as a hemispherical shell (enamel) on a compliant interior (dentin), and thus was not accurate.[11] To our knowledge, no scientific investigations have studied the effect of occlusally uneven attrition on the mechanical behavior of the root surface.

Therefore, the present study used 3D FEA to evaluate the root stress condition of teeth with changes in the occlusal plane related to uneven attrition. We hypothesized that occlusal slope would cause stress redistribution on the root, and might be an important factor for spontaneous VRFs.

Materials and methods

Finite element model

An intact, cavity-free mandibular first molar with almost no attrition was selected by following a protocol approved by the Ethics Committee of the West China Hospital of Stomatology (No. WCHSIRB-D-2013-063). The collection of teeth did not change the course of the patient's treatment plan. Informed consent was acquired before teeth were collected. Care was taken to ensure that the tooth had double roots and three canals, and it was scanned using 16-slice spiral computed tomography (Sensation 16, 120 kV, 100 mA; Siemens, Erlangen, Germany) in increments of 0.6 mm. The scanned slices were imported into Materialise Mimics 8.1 software (Materialise, Leuven, Belgium), which allows extended visualization and segmentation. The 3D architecture (enamel, dentin, and pulp) was automatically created in the form of masks by growing a threshold region on the entire stack of scans. The objects were converted into stereolithography files (STL) using a Mimics STL+ module and imported into Magics of Materialise to produce a watertight model. The model was refined using Geomagic Studio 12.0 (Geomagic, Inc., Research Triangle Park, NC, USA) and CATIA v5R21 software.

The structure of the optimal tooth was labeled group A (Fig. 1). Teeth with uneven attrition were constructed, leading the occlusal plane to slope buccally or distally. The occlusal surface of the model was cut down deeper and deeper gradually both in the lingual-buccal and mesial-distal directions from 0.5 to 1.5 mm (groups B and D, respectively) or from 2 to 3 mm (groups C and E, respectively) (Fig. 1 and Table 1). In this model, the dentin was not exposed by 0.5–1.5 mm attrition, while 2–3 mm of attrition exposed the dentin without exposing the pulp chamber. The alveolar bone and periodontal ligament were modeled. According to the mean values found in the literature, the thickness of the periodontal ligament and cortical bone were assumed to be 0.2 mm and 2.5 mm, respectively.[18]

Graphics were created in IGES format. The solid model was transferred into a FEM program, Ansys 12.0 (Swanson Analysis, Houston, PA, USA), where the volumes were

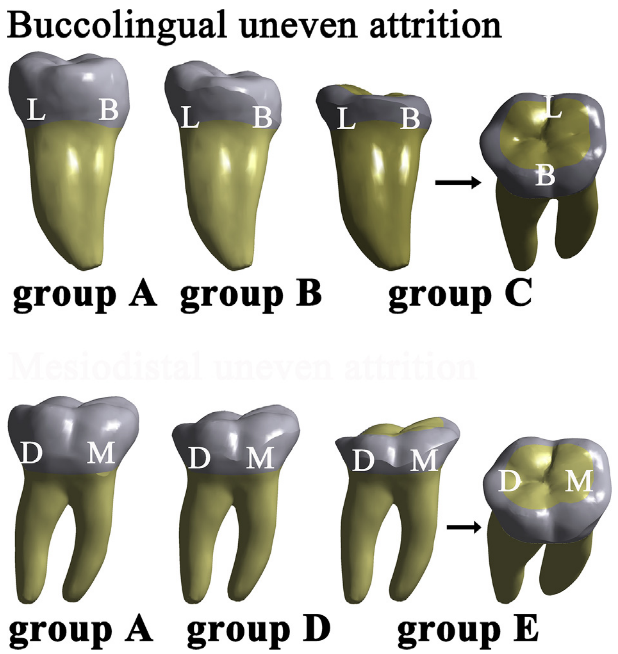

Figure 1 Finite element models of the two different uneven occlusal attrition patterns: bucco-lingual and mesio-distal attrition. (group A: Sound tooth, group B: 0.5–1.5 mm attrition increased buccally, group C: 2–3 mm attrition increased buccally, group D: 0.5–1.5 mm attrition increased distally, group E: 2–3 mm attrition increased distally. B: Buccal, L:Lingual, D: distal, M: mesial).

redefined and meshed with four node tetrahedral elements. The number of units and nodes of each model are shown in Table 1.

Materials and load conditions

All materials were considered to be homogenous, linearly elastic, and isotropic. Their mechanical properties are summarized in Table 2.[19–24] As a boundary condition, no displacement was allowed for the nodes around and along the bottom end lines of the bone models. A static load of 200 N was applied at the occlusal central fossa and the buccal surface of the buccal cusp. As shown in Fig. 2, two

Table 1 Description of model groups used in finite element analysis, summarizing the number of mesh elements and nodes used in the models.

Model group	Description	Elements	Nodes
group A	Sound tooth	65,518	103,700
group B	0.5–1.5 mm attrition increased buccally	65,609	104,040
group C	2–3 mm attrition increased buccally	70,842	112,541
group D	0.5–1.5 mm attrition increased distally	71,040	112,408
group E	2–3 mm attrition increased distally	71,207	113,092

Table 2 Summary of tooth material mechanical properties.[19–24]

Material	Elastic modulus (Gpa)	Poisson's coefficient
Enamel	82.5	0.33
Pulp	2×10^{-3}	0.45
Dentin	18.6	0.31
Periodontal ligament	68.9×10^{-3}	0.45
Cortical bone	13.7	0.30
Sponge bone	1.37	0.30

loading conditions were performed in the models: (1) vertical loading, and (2) oblique loading from the buccal direction, angled at 45° to the longitudinal axis. The stress distribution was analyzed according to the von Mises (equivalent stresses) energetic criterion by measuring nodes, where:

$$\sigma = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Here, σ_1, σ_2, and σ_3 are known as the principal stresses, and σ is the von Mises stress. The principal stresses are, in fact, normal stresses acting on principal planes in which the shearing stresses are zero. The von Mises criterion, which results in a tensile-type normal stress, was selected, as brittle tooth failure occurs primarily as a result of tensile-type normal stresses.[18,25]

Results

Under vertical loading

Stress distribution of the root surface

As shown in Fig. 3a, stress was mainly concentrated on the buccal and lingual surfaces, while the proximal surface stress was relatively small. There were five stress

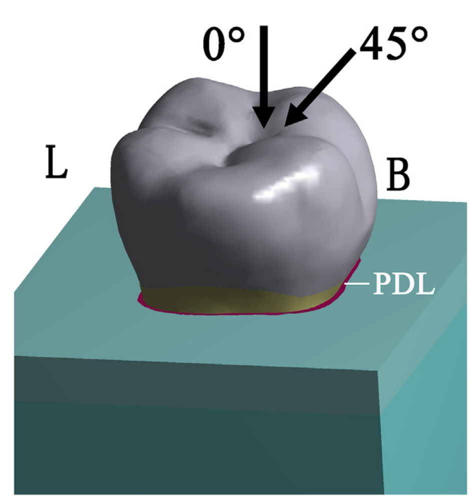

Figure 2 Two loading conditions were performed in the models: (1) vertical load, (2) oblique load, angled at 45° to the longitudinal axis. (B: Buccal, L: Lingual, PDL: Periodontal ligament).

concentration zones: the upper/middle part of the buccal surface in the mesial (BM) and distal (BD) roots, and the lingual surface of the distal root (LD). The stress in the apical root was relatively small. With increasing occlusal attrition, the areas of high stress increased for the middle root.

Maximum von Mises values of the stress concentration zones

The two attrition patterns had a similar effect on the maximum von Mises value. For the buccal surface, with attrition, the maximum von Mises values in the upper part of the root became smaller, while the value for the middle root increased. Compared with group A, the maximum values of group C were reduced by 9.19% and 9.11% in the upper part of the root for the mesial and distal roots, respectively, while the values in the middle root were increased by 17.88% (mesial root) and 8.57% (distal root). Similarly, the maximum von Mises values of group E were reduced by10.76% (BM) and 6.07% (BD) in the upper part, while those in the middle root were increased by 16.09% (BM) and 6.73% (BD) respectively. This finding means that the stress was transferred from the upper to the middle root gradually with attrition, which was more obvious in the mesial root (Fig. 3b,c). In addition, it can be seen that the maximum von Mises value in the mesial root was slightly higher than in the distal root.

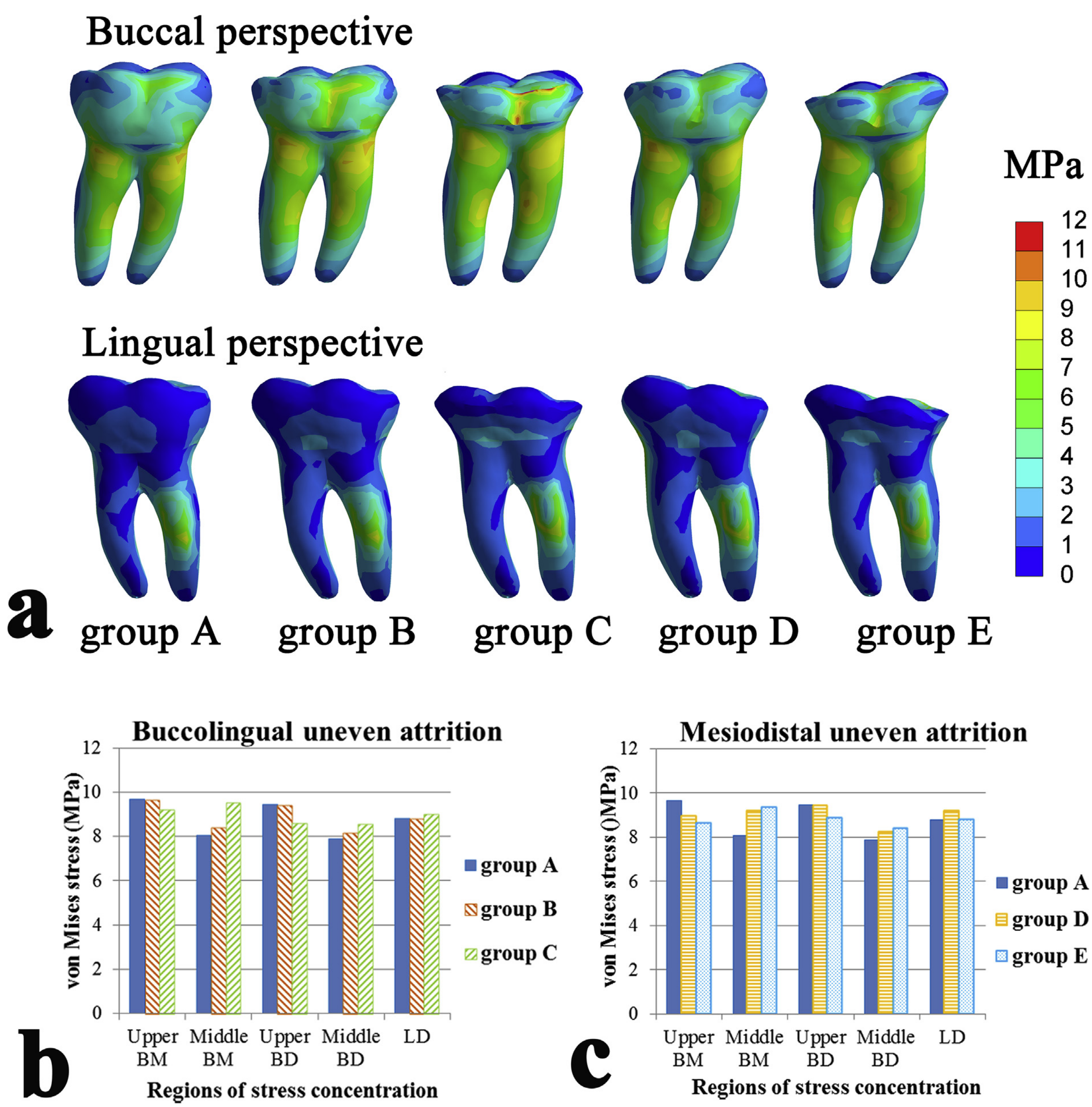

Figure 3 Under vertical loading. (a) Stress distribution of the root surfaces (view from the buccal and lingual perspectives). Maximum von Mises stress of the five stress concentration zones (b) bucco-lingual and (c) mesio-distal occlusal uneven attrition. (BM: Buccal surface of the mesial root, BD: Buccal surface of the distal root, LD: Lingual surface of the distal root).

Under oblique loading

Stress distribution of the root surface

Similar to vertical loading, under oblique loading, the stress was mainly distributed in the buccal and lingual root surface and concentrated in the upper-middle part. Unlike with vertical loading, four stress concentration zones were seen: the buccal surface of the mesial (BM) and distal (BD) roots, and the lingual surface of the mesial (LM) and distal (LD) roots (Fig. 4a). Moreover, occlusal attrition decreased the areas of high stress zones.

Maximum von Mises values of the stress concentration zones

Seen from Fig. 4b, the maximum von Mises stress with oblique loading (37.57 MPa in the LD) was significantly higher than with vertical loading (9.67 MPa in the upper BM). In contrast with vertical loading, with oblique loading, the lingual root surface bears more stress than does the buccal surface, especially on the LD, while the maximum values in the mesial root were lower than in the distal root.

With attrition, the maximum von Mises stress on the root surface declined gradually. Compared with group A, group C had stress reduced by 64.61%, 51.29%, 33.84%, and 34.80% in the BM, BD, LM, and LD, respectively, while for group E the stress reduced by 51.89%, 44.39%, 27.04%, and 30.18%.

Discussion

The complexity of tooth attrition leads to difficulties in studying attrition. Many tooth attrition assessment criteria have been developed for clinical and laboratory use worldwide, most of which are based on quantitative and qualitative analyses. A classic example is the Smith and Knight tooth attrition index,[26] which has been used frequently. However, this measurement is subjective and imprecise, as it relies on the observer's judgment. Quantitative methods tend to rely on objective physical measurements, such as angles between cusp tips, heights of crowns, and areas of facets.[27] However, neither assessment above took account of the occlusal slope in the lingual-buccal or mesial-distal direction, which results from

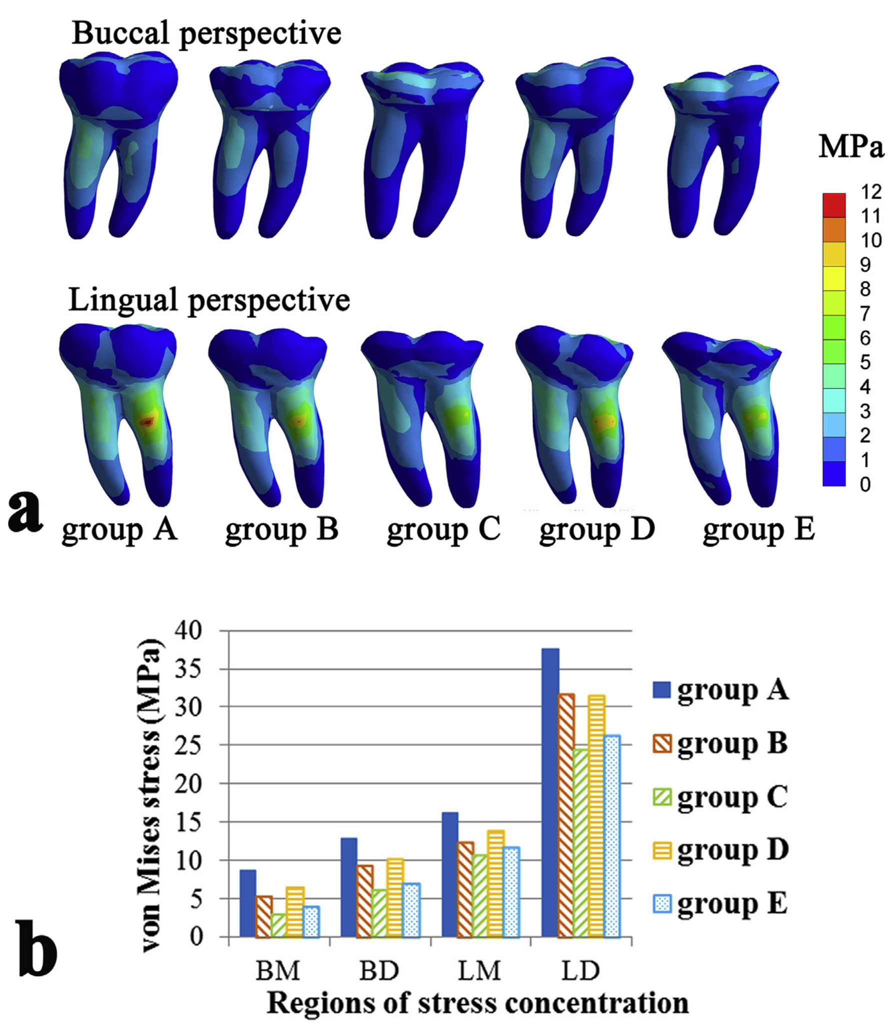

Figure 4 Under oblique loading. (a) Stress distribution of the root surfaces (view from the buccal and lingual perspectives). (b) Maximum von Mises stress of the four stress concentration zones under oblique loading. (BM: Buccal surface of the mesial root, BD: Buccal surface of the distal root, LM: Lingual surface of the mesial root, LD: Lingual surface of the distal root).

uneven attrition. To evaluate the effect of uneven occlusal attrition on mechanical behavior and root fracture, a FEA model of the mandibular first molar was established, in which the degree of attrition gradually increased buccally and distally.

Stress distribution analysis indicated that loads in both directions were distributed mainly in the buccal and lingual root surfaces. This distribution might be related to the ovoid shape of the root cross section, which was longer in the buccal-lingual direction.[28] Under long-term masticatory force, this local stress concentration was enlarged. Dental structure in this location was damaged and, even with the thicker dentin than in the mesio-distal direction, fractured first. This result was consistent with the buccal-lingual direction of VRF, a characteristic reported in many clinical and experimental studies.[7,10,28]

Under vertical loading conditions, occlusal attrition caused increased stress and a larger area of high stress zones in the middle root. This result might be because the crown absorbed fewer loads, leaving more stress to be transmitted downward. Because the dentin of the middle root is thinner and less resistant to breakage than the cervical root, the roots of severely attrited teeth are more susceptible to fracture. This susceptibility is in accordance with a clinical survey, which showed that spontaneous VRF-affected teeth always present with severely attrited occlusal surfaces.[10] In the clinic, timely restoration of the sloped occlusal morphology in teeth with severe attrition should be recommended to prevent VRFs. Furthermore, compared with the distal root, the maximum von Mises stress of the mesial root was higher, and the stress transmission downward was more obvious. As a result, VRFs are always found in the mesial root, as presented in previous reports.[7,10] The apical root portion presented relatively small stress. However, VRFs in non-endodontically treated teeth often initiate from the apical areas.[8,9] This effect may be due to the weakness of tooth tissue at the apical root, due to intrinsic material properties and dentin thickness.

However, under oblique loading, the effect of attrition on root stress was different. Both the maximum von Mises stress and area of high stress were reduced, which might be due to the leverage effect in the cervical root. As the crown shortened, the coronal moment arm decreased, and, thus, the moment decreased, resulting in smaller stress on the root. Therefore, with lateral occlusion, tooth attrition itself did not cause adverse effects on root stress. However, the significantly high maximum stress compared with vertical loading is very dangerous to the root, indicating that this loading mode may be a risk factor for root fracture. Significantly, the maximum stress in the distal root was higher than in the mesial root, especially on the upper part of the lingual surface. These findings suggest that lateral masticatory force might be more likely to cause root fracture, which occurred mainly in the cervical portion of the distal root, possibly causing horizontal or transverse root fracture, rather than VRFs.

Consistent with previous publications,[18] we found that root stress conditions were significantly different between the two loading modes. In addition to the maximum von Mises stress, they had different high stress zones. Under vertical loading, high stress zones were mainly in the buccal root surface. This might because the buccal cusps, the functional cusps, bore the most occlusal load in the mandibular molar. Masticatory force was transmitted mainly along the buccal side to the root. As for oblique loading, the force was transmitted from the buccal side of the crown to the lingual side of the root, resulting in high stress in the lingual root surface.

In this study, the attrited model kept the original morphology of the cusp and fossa, and thus did not take into account the effect of cusp height. Under normal conditions, the upper and lower posterior teeth were intercusping during occlusal contact. Masticatory force could be resolved by the cusp cant, leaving less stress transmitted along the tooth's long axis. In the case of severe attrition, when the tooth cusp and its effect are reduced, the stress condition of the root needs further study. Moreover, spontaneous VRFs might be "fatigue root fractures" that result from an excessive, repetitive, heavy masticatory stress applied to a tooth,[7] or accidental root damage that happens suddenly under an abnormally large bite force. These are limitations of the present study. More studies will be conducted to simulate fatigue load or large bite force in the oral cavity, as well as the anisotropic nature of dental tissues.

In summary, occlusal slope related to uneven attrition made the middle part of the mesial root bear increased stress on the buccal-lingual surface. Thus, it became easy to fracture the mesial root under a vertical load, which is consistent with clinical reports that spontaneous VRFs are more likely to occur in the mesial roots of severely attrited teeth. Loading conditions may have different effects on stress distributions. A lateral load is not likely to cause typical VRFs, but the high stress can easily cause cervical fracture of the distal root.

Declarations of interest

None.

Acknowledgments

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