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Correlation between cuspal inclination and tooth cracked syndrome: a three-dimensional reconstruction measurement and finite element analysis

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Abstract – *Background/Aim*: This paper explored the correlation between cuspal inclination and tooth cracked syndrome by measuring and reconstructing the cuspal inclinations of cracked maxillary first molars through three-dimensional (3D) finite element analysis (FEA). *Material and methods*: The cuspal inclinations of 11 maxillary left first molars with cracked tooth syndrome and 22 intact controls were measured by 3D reconstruction. The mean values of each group were used to construct two 3D finite element models of maxillary first molar for comparing stress distribution under the loads of 200N at 0°, 45°, and 90°, respectively, to the tooth axis. *Results*: There was statistically significant difference in the cuspal inclination between the incompletely fractured group and the intact control group ($P < 0.001$), which was 5.5–6.7 degrees steeper. The model from the mean cuspal inclinations of the incompletely fractured molars showed the maximum tensile stress of 5.83, 10.87, and 25.32 MPa, respectively, in comparison with 5.40, 8.49, and 22.76 MPa for the model of the control group. Besides, the tensile stress was mainly at the center groove and cervical region of the molar model. *Conclusions*: Steeper cuspal inclinations resulted in an increment in tensile stress that was mainly at the center groove and cervical region of the molar model under equivalent loads. Higher unfavorable tensile stress was generated with the increasing horizontal component load on the cuspal incline. This indicates an effective reduction of cuspal inclination to the compromised teeth for dentists.

Introduction

The term of cracked tooth syndrome (CTS) was first coined by Cameron (1) in 1964. It has been defined as an incomplete fracture of the dentine in a vital posterior tooth that involves the dentine and occasionally extends into the pulp and must be distinguished from a split tooth (1–6). The condition was associated with the teeth of older age groups, mainly in patients aged between 40 and 60 years (7). Its prevalence was similar in men and women.

It is well known that cracked teeth occur most frequently in the mandibular molars with large or poor restorations (1–9). However, cracks in teeth with no restoration appear more frequently in dental clinics these days, and the location of cracked teeth in the mouth seems to vary. Recent researches have shown that the prevalence of cracked tooth was the highest in the intact teeth with no restoration, in maxillary first molars (10, 11). As has been reported by Roh and Lee (10), cracked teeth were found more frequently in the maxillary molars (33.8% in first molar, 23.4% in second molar) than in the mandibular molars (20.1% in first molar, 16.2% in second molar) of 154 cracked teeth. Qing et al. (11) reported that intact maxillary first molars (45.7%) were the most commonly affected teeth by CTS of 258 cracked teeth without restorations.

It is difficult for dentists to identify CTS from other dental diseases with similar symptoms, as the CTS bears with complex and multifactorial pathogenesis as well as the atypical symptoms of those affected teeth (4–6). The prognosis of those cracked teeth is pessimistic. Most affected teeth crack and split successively for the lack of sufficient attention, timely diagnosis, and effective treatment. As a result, awareness of the existence and etiology of CTS is an essential component of its prevention.

Cracks in intact teeth are still considered to an unusual and embarrassing situation, which are caused by occlusal traumas such as a steep cusp inclination and too heavy bite forces (10). The role of occlusion in the development of CTS has been addressed in several articles (5, 8, 12). Teeth with excursive interferences, which created shear stress during function and parafunction, were 2.3 times more likely than teeth without excursive interferences to experience cracking (8). Occlusal forces misdirected over the surface of the tooth combined with chewing may produce stresses severe enough to violate the elastic limits of teeth, and eventually resulted in the establishment and propagation of cracks.

For the cracked posterior teeth, restored or intact, steep cuspal anatomy acts as one of the main risk indicators (6, 11, 12). Few studies are available to build up the correlation between cuspal anatomy and the occurrence of CTS. Khers et al. (13) examined functional and non-functional cusps of the maxillary and mandibular posterior teeth by measuring the angle of cuspal inclinations based on the photographs of tooth sections in each five posterior teeth. They illustrated cuspal inclinations as the angles between the cuspal incline and the line paralleled to the long axis of the teeth and suggested that cuspal anatomy played a critical role in fracture potential and in the incidence of both incomplete and complete cuspal fracture. The modern computer tomography (CT) has been used for the construction of three-dimensional (3D) physical models by scanning physical model and digitizing its two-dimensional (2D) images in DICOM format. This makes it feasible to measure the parameters such as cuspal inclinations of the molars when they are in the human oral cavity by reconstructing 3D molar models. This study depends on the spiral CT and its 3D reconstruction tools for modeling the exterior and dentinoenamel junction (DEJ) geometric shapes of human tooth maxillary first molars. The multi-planar reformat tools of spiral CT reset the measuring plane of 3D tooth model. Cuspal inclination will be measured at identifiable anatomic landmarks for each molar in DICOM format.

Finite element model (FEM) analysis has been used for many years in dental research (14–19). This method of analysis has been proven valuable by improving the professional understanding of various aspects of 3D objects (enamel, dentin, and so on) in oral biomechanics. As a powerful computational tool for solving stress-strain problems, it has the ability to handle inhomogeneous biomaterials and complex shapes. This method makes it feasible to reconstruct tooth cuspal anatomy of 3D models for stress analysis according to the mean cuspal inclinations of the cracked maxillary first molars and intact control ones.

The objective of this study is to explore the correlation between cuspal inclination and tooth cracked syndrome by measuring and reconstructing the cuspal inclinations of cracked maxillary first molars for 3D finite element analysis (FEA), compared with intact controls. The hypothesis tested is that the inclination of cusps on human intact teeth affects their propensity to 'tooth cracked syndrome' and fracture.

Materials and methods

Specimen preparation

Eleven maxillary left first molars suffering from CTS belonged to 11 outpatients (6 men and 5 women) between the ages of 40 and 58, with an average age of 47.18. They all complained for the pain in the maxillary left first molar on occlusion. But each had 28 natural intact teeth with no restorations or large areas of caries. Tooth mobility and inclination were within normal limits. There were no severe periodontal or endodontic problems. No iatrogenic factors such as endodontic procedures, inlays, or occlusal adjustments were available for the 11 incompletely fractured molars. Percussion on these 11 molars in different directions evoked pain, significantly when pressure was applied to certain cusps surface. Further diagnosis of CTS was confirmed by 'bite tests' through a wooden stick and 'staining test'. Patients complained of pain when the biting pressure was released. Cracks were stained by 3% iodine in staining test.

Twenty-two intact maxillary left first molars were from 22 volunteers (10 men and 12 women) as controls. The ages of the volunteers were between 41 and 58, with an average age of 48.75. Each volunteer had 28 natural intact teeth with no restorations or large areas of caries. Tooth inclination was within normal range. Those pristine teeth had vital pulp and healthy periodontal tissue. They had never suffered from CTS or other iatrogenic factors.

Those 33 persons were impressed readily by alginate impression materials (CAVEX HOLLAND BV, Haarlem, Holland). The impressions were modeled into 33 dentures by super-hard plaster (Shanghai Dental Materials Factory, Shanghai, China). All models were seated in plastic model trays as study casts. The occlusal plane of denture model was parallel to the horizontal plane as well as the undersurface of the cast. The die of each maxillary left first molar was cut from its cast denture. After being rooted in a paralleled line with suitable intervals, they were scanned at a thickness of 0.5 mm by the spiral CT scan (Somatom Simens Volume Zoom, Simens, Germany). CT images representing 0.5-mm buccolingular slices of all dies were immediately 3D reconstructed by the spiral CT system tools. In 3D visual image, the measuring plane of each stone die was reset by the multi-planar reformat tools, which is perpendicular to the buccolingular scanning plane. In this way, it is convenient to measure the cuspal inclination of each molar cusp.

Cuspal inclination measuring

The cuspal inclination of molar cusp is angulated between a line drawn from the cuspal tip to central development groove and a line perpendicular to the long axis of the tooth crown, which also passes through the central groove (Fig. 1). The mean cuspal inclinations for 11 incompletely fractured maxillary left first molars and 22 intact ones were listed in Table 1. Data are expressed in the form of means ± standard deviation. Parametric data were compared using the group *t*-test for independent samples.

Modeling and stress analysis by 3D finite element method

The proposed modeling method, as shown in Fig. 2, includes three steps, which will be introduced as following.

Tooth modeling

The construction of the FEM model began with the design of a geometric model of the tooth, which was based on the dimensions of a human maxillary left first molar sample (Fig. 3a). The height of the tooth (distance from the apex of the palatal root to mesiopalatal cuspal tip) was 23.62 mm, and the mesiodistal and buccopalatal widths of the crown were 10.46 and 11.50 mm, respectively. The root lengths (vertical distance from alveolar crest to apex) were 15.63 mm for palatal and 13.62 mm for mesiobuccal (MB) and distobuccal (DB) roots. The tooth sample was then scanned along its long axis at a thickness of 0.5 mm by the spiral CT scan. There were totally 48 digital sections for the tooth samples. The coordinates of tooth contours including its exterior shape, dentinoenamel junction, and pulp cavity in each section were recorded and digitalized. Those coordinates were imported into the software ANSYS 8.0 (ANSYS Inc., Canonsburg, PA, USA) as key points to create the tooth solid model (Fig. 3b,c). To explore the correlation between molar's cuspal inclination and the CTS in maxillary first molars, the model tooth's cusps were shaped according to the mean cuspal inclinations listed in Table 1. The cuspal inclinations of Molar 1 were one-to-one corresponding to the mean cuspal inclinations of the incompletely fractured maxillary first molars. The cuspal inclinations of Molar 2 were one-to-one corresponding to the mean cuspal inclinations of the intact controls. The finite element mesh of Molar 1 and Molar 2 was created manually in ANSYS 8.0. The periodontal ligament (PDL) was simulated as a 0.2-mm-thick layer around the roots. Each 3D finite element model comprised a maxillary left first molar, PDL, and alveolar bone: Molar 1 consisting of 6050 nodes and 55 828 elements; Molar 2 consisting of 5984 nodes and 55 470 elements (Fig. 3d–g). The mechanical properties of the PDL, tooth, and alveolar bone were obtained from previous studies (Table 2) (20, 21).

Fig. 1. Measurement for buccal and palatal cuspal inclinations: This DICOM image of a maxillary first molar is reset by the multi-planar reformat tools of the spiral CT for cuspal inclination measuring. The cuspal inclination is measured between a line drawn from the cuspal tip to central development groove (beige) and a line (yellow) perpendicular to the long axis (green) of the tooth crown, which is also passing through the central groove. 'Buccal' was a substitute for buccal cuspal inclination as well as 'palatal'.

Stress analysis

The magnitude of the chewing force was selected as 200N (22). To simulate lateral mastication, the center of occlusal surface of two buccal cusps acted as the loading points, 100N for each loading point. The sum of the nodal force on the occlusal surface was 200N after displacement constraints were applied to the model. The load was applied from three directions: at 0° to the tooth axis (vertically), at 45° to the tooth axis (angularly), and at 90° to the tooth axis (horizontally). In this study, achieving tensile cracks between the cusps of tooth model under various force directions was one of the objectives, so the tensile stress was the most suitable quantity to analyze.

Results

As shown in Table 1, there was statistically significant difference in the cuspal inclination between 11 incompletely fractured maxillary left first molars and 22 intact maxillary left first molars (significance $P < 0.001$). The cracked maxillary first molars had steeper cuspal inclinations than the intact and healthy controls, with the mean differences ranging from 5.5 to 6.7 degrees.

In response to loads of 200N at 0°, 45°, and 90° to the tooth axis, the FEA model with the mean cuspal inclinations of the incompletely fractured molars (Molar 1) showed the maximum tensile stress of 5.83, 10.87, and 25.32 MPa, respectively. The FEA model with the mean cuspal inclinations of the intact molars (Molar 2) showed the maximum tensile stress of 5.40, 8.49, and 22.76 MPa, respectively. The tensile stress was mainly at the center groove and cervical region of the molar model.

Tensile stress distributions in Molar 1 and Molar 2 were shown from Figs 4a to 5c, in which the tendencies

Table 1. Mean values and standard deviations for cuspal inclinations of 11 incompletely fractured maxillary left first molars and 22 intact ones in degrees.

	Mesiobuccal cusp	Mesiopalatal cusp	Distobuccal cusp	Distopalatal cusp
Incompletely fractured (n = 11)	44.2(4.1)	37.1(4.7)	39.2(3.9)	31.3(4.4)
Intact (n = 22)	37.7(3.2)	30.4(3.4)	32.5(4.4)	25.8(3.0)
Mean difference	6.5	6.7	6.7	5.5

Significance $P < 0.001$.

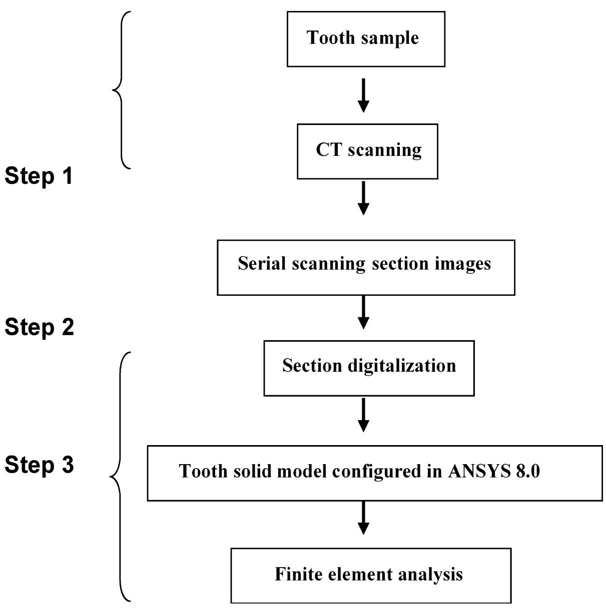

Fig. 2. The proposed modeling method.

of color plots demonstrated the extension of the area under tension with the increasing horizontal force. With different maximum tensile stresses under equivalent loads, the two FEA models had the similar distribution of tensile stresses. The Molar 1 experienced a concentration of tensile stresses (maximum of 5.83 MPa) in areas around the loading points on the palatal surface of its buccal cusps, when loads of 200N were applied vertically (at 0° to the tooth axis). When the loading direction was 45 degrees to the tooth axis, there was a concentration of tensile stress observed in the mesiodistal groove (maximum of 10.87 MPa) and palato-cervical (6.39–8.95 MPa) area on the tooth surface. The maximum tensile stress became higher under such loading than that under vertical loads of 200N. When the load was applied horizontally (at 90° to the tooth axis), the maximum tensile stresses in the mesiodistal groove below the loading points increased to 25.32 MPa (especially in the medial groove). And there also was a concentration of tensile stress observed in the palato-cervical area of the mesiopalatal cusp (9.76–14.9 MPa). The Molar 2 also experienced similar tensile stress distribution as Molar 1 under loads of 200N at 0°, 45°, and 90° to the tooth axis. Furthermore, Molar 1 experienced larger tensile stresses than Molar 2, especially under the horizontal loads. Maximum tensile stresses were demonstrated in Fig. 6, which concentrated in the areas around the loading points on the surface of the molars.

In Fig. 6, the maximum tensile stress increased with the increment of the total horizontal component load of 200N at 0°\45°\90° to the tooth axis in both Molar 1 and Molar 2 FEA model. Under the load of 200N at 0° to the tooth axis with the total horizontal component load of 0 N, the maximum tensile stress was 5.83 MPa (Molar 1) and 5.40 MPa (Molar 2). Under the load of 200N at 45° to the tooth axis with the total horizontal component load of 141.4 N, the maximum tensile stress was 10.87 MPa (Molar 1) and 8.49 MPa (Molar 2). Under the load of 200N at 90° to the tooth axis with the total horizontal component load of 200N, the tensile stress reached a maximum of 25.32 MPa (Molar 1) and 22.76 MPa (Molar 2).

Discussion

The results supported the research hypothesis that the inclination of cusps on human intact teeth affects their propensity to 'tooth cracked syndrome' and fracture. For the compromised teeth with CTS, steeper cuspal inclination, which led to an increment in tensile stress at the center groove and cervical region, predisposes to fracture formation.

Tooth anatomy could be partially responsible for its susceptibility to fracture (12, 13, 23). In 1990s, for the first time, Khers et al. (13) measured the cusps' angular inclinations on the photographs of histological sections in each five posterior teeth samples, which had been extracted. They concluded from their measurements that angulation of cuspal inclines played a critical role in fracture potential and in the incidence of both incomplete and complete cuspal fracture. They measured angular inclination of the functional and non-functional cusps between a line drawn from the cusp tip to central developmental groove and a line parallel to the long axis of the teeth. As the long axis of the tooth is an ideal axis through the center of the entire tooth, it is difficult to determine the accurate location of long axis manually when the tooth was in oral cavity. So our experiment measured the cuspal inclinations of molar cusps in three-dimensional images of tooth model plaster dies in spiral CT applications by locating the long axis (green) of the tooth clinical crown, which also passes through the central groove (Fig. 1). This improved method simplifies the measurement of cuspal inclinations. In addition, there is no extraction of molar samples for sectioning.

Perhaps the best way to prevent tooth fractures is to understand the factors that predispose a tooth to crack.

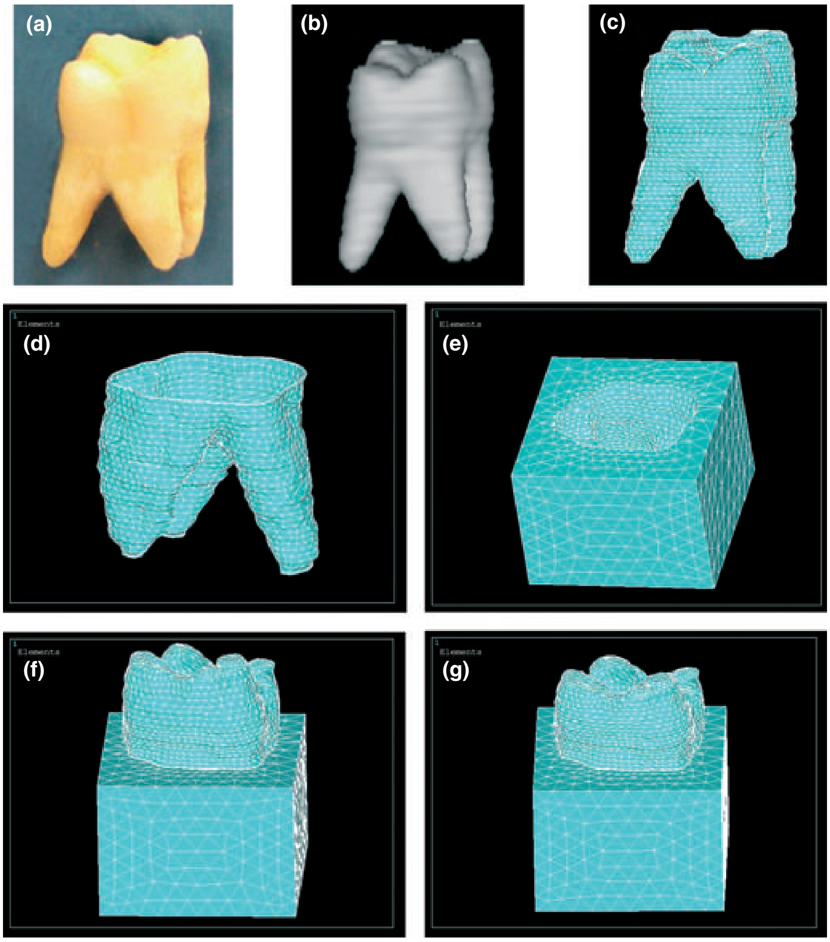

Fig. 3. Tooth modeling of a human maxillary left first molar. (a) a 2D photograph, (b) a 3D geometric model in CT, (c) a 3D-FEM model in ANSYS, (d) a FEM model of the periodontal ligament (PDL), (e) a FEM model of alveolar bone, (f) a FEM model of Molar 1 (a), and (g) a FEM model of Molar 2.

Table 2. Mechanical properties of dental and periodontal tissues

Material	Material Young's modulus (MPa)	Poisson's ratio
Enamel	83 000	0.33
Dentin	18 600	0.31
Pulp	2	0.45
PDL	68.9	0.45
Alveolar bone	1370	0.3

The pathogenesis of CTS was complex and multifactorial for those teeth with or without restorations, with two primary factors predisposing teeth to cracks: natural predisposing features (steep cuspal anatomy, bruxism, clenching, extensive attrition, and abrasion) and iatrogenic causes (use of rotary instruments, cavity preparation, and the width and depth of the cavity) (5, 6). Usually, steep cusp and fossa occlusal anatomy is cited as a predisposing factor for tooth fracture, while parafunctional habits and other incidents have been included as contributing factors (3, 23–25). As iatrogenic causes, restorative procedures may lead to altered strength, fatigue fracture, and CTS by removal of tooth substance. Restorations put teeth at a 29 times greater risk for cracks (8). Fracture and CTS were more common with amalgam restorations for fatigue fracture than composite restorations after 12 years clinical service (26).

As the non-functional cusps of the maxillary molars, buccal cusps demonstrated only inner incline contact type. In this way, the risk of lateral component force directed against the inner cuspal incline would be magnified. Most important of all, unfavorable tensile stress increased with the cuspal inclination. This was demonstrated in our experiments, which tried to measure cuspal inclination of cracked maxillary first molars and intact controls and compared distributed stress by reconstructing it in 3D FEMs. Within the limitations of this study, the results suggested that the cracked maxillary first molars had steeper cuspal inclinations than the intact controls, and there were more unfavorable tensile stress concentrated in the central groove of the 'cracked' 3D-FEA model molar (Molar 1) than the 'intact' control (Molar 2) under equivalent loads. There was also a concentration of tensile stress observed in the palato-cervical area of the mesiopalatal cusp in FEA molar model. Magne and Belser (27) concluded that convex surfaces with thick enamel raise less concentrated stresses than concave areas, which tend to concentrate stresses. The enamel ridge of posterior intact teeth, such as strong marginal ridge and oblique ridge, reduces the stress locally, proved to be essential mechanisms to protect crown biomechanics.

Defects in the enamel structure are presented as sources of weakness. Lawn et al. (28) depicted that tufts may act as preferential sites for crack initiation

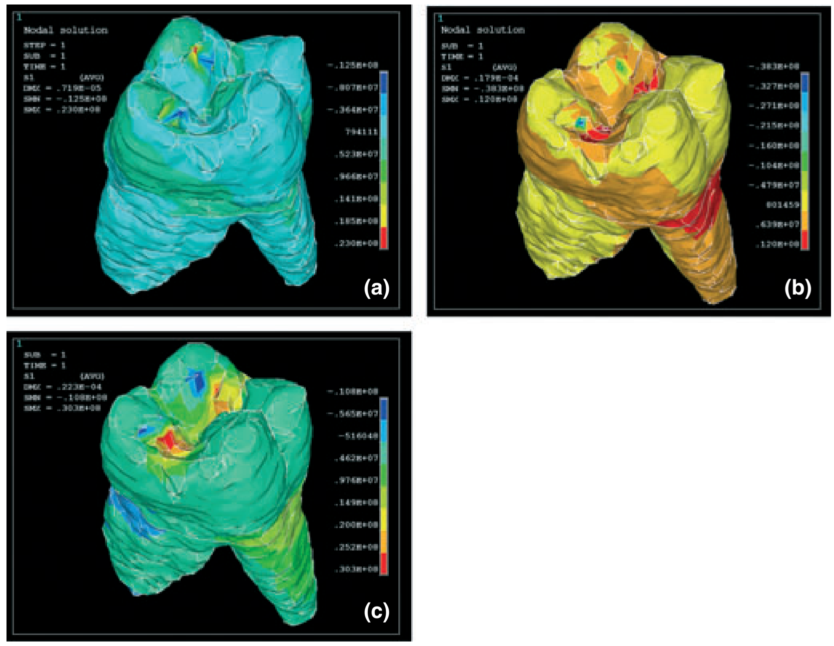

Fig. 4. The tensile stress distribution in finite element analysis model of Molar 1 under loads of 200N at 0° (a), 45° (b), and 90° (c) to the tooth axis.

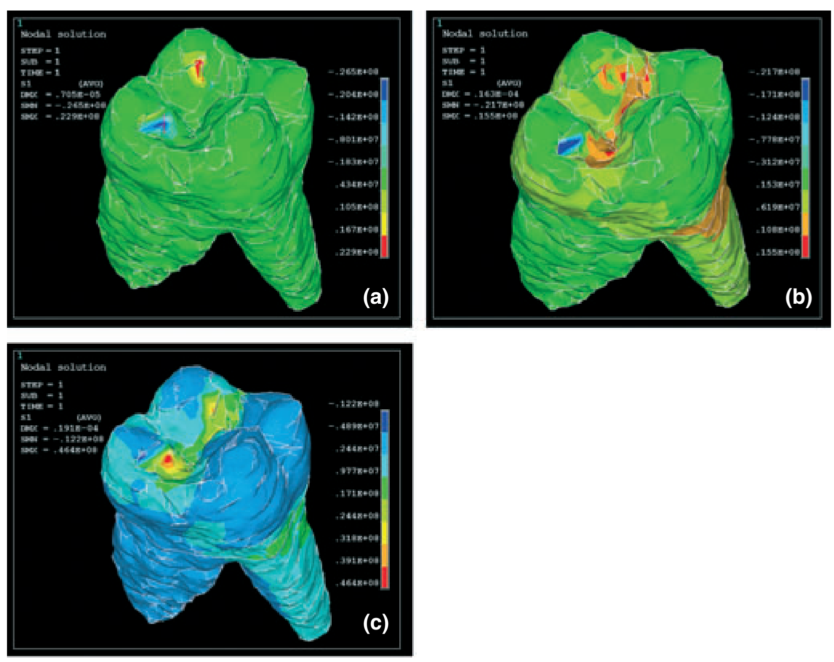

Fig. 5. The tensile stress distribution in finite element analysis model of Molar 2 under loads of 200N at 0° (a), 45° (b), and 90° (c) to the tooth axis.

within the enamel coat in microstructure. Cracks in human teeth extend from the developmental flaws of the inner enamel toward the enamel outer surface and develop as the force rises. In clinical detection, the central groove is considered as the most frequent site of CTS (usually in mesiodistal crack) at the macroscopic level. As a developmental groove with weakness in tooth structure, the undermined central groove then is gradually sheared off under such tensile stress concentration.

Additionally, a 'steep cusp/deep groove' interrelationship between maxillary molars and their antagonists will result in 'wedging effect' (12), which has been attributed to a primary factor in tooth or cuspal fractures. As wedging forces are applied on both buccal and palatal cuspal inclines, the resulted crack may run in a mesiodistal direction over one or both marginal ridges and propagate toward the pulp or buccolingually between the cusps with no complete separation of segments and terminate in the cervical region. If the cusps of the intact molars are steeper, or the internal inclines converging to the center grooves of those teeth have bigger angular inclination, the detrimental effect of wedging forces will be magnified. After a longer period of time, the relatively consistent magnitude of this unfavorable force will split the tooth completely into

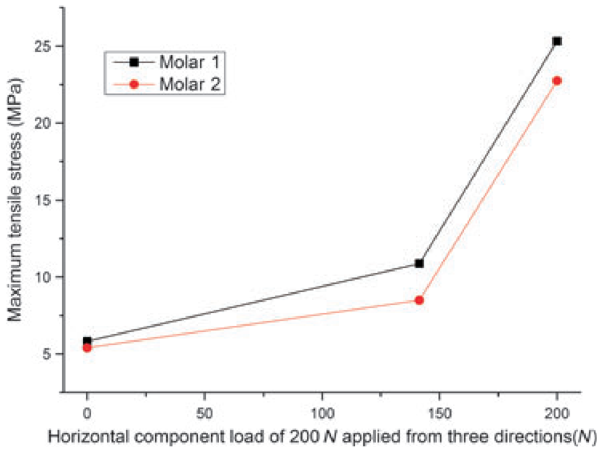

Fig. 6. Tensile stress plots comparing stresses on finite element analysis models of Molar 1 and Molar 2 under loads of 200N at 0°, 45°, and 90° to the tooth axis (*Z* axis).

two separate segments or make cusps fracture completely.

There was a remarkable increment of the maximum tensile stress with the increase of the total horizontal component load demonstrated in this study. The maximum tensile stress reached a peak value when the loads applied horizontally. As Imanishi et al. (16) concluded, the bite forces applied from the horizontal direction were a critical factor to the fracture of tooth crown, although there was little likelihood of such a strong masticatory force being applied horizontally during usual mastication with the exception of some patients with bruxism or clenching.

On the other hand, the inclination of the molars compared with the opposing teeth is important. Occlusal contact area and contact points can be altered by tooth inclination, when a tooth occludes with its antagonist. Cavel et al. (23) reported that the slight buccoversion of maxillary molars placed non-functional buccal cusps in a position that increases the susceptibility to be cracked. Therefore, in our study, all the subjects with normal tooth inclination were stressed.

Dentists are ready to use occlusal adjustment to reduce the stress on the suffering tooth by reducing cuspal inclination and height once a cracked tooth is diagnosed. Ratcliff et al. (8) suggest that equilibrating the occlusion and eliminating interferences wherever appropriate during excursive movements may effectively eliminate etiologic factors that contribute to the propagation of cracks. Braly and Maxwell (24) recommended reducing cuspal heights to remove traumatic occlusal contacts and eliminate eccentric contacts. Agar and Weller (25) suggested that three steps of occlusal adjustment were applied to contour the cusps by reducing the height and lowering the cuspal inclination. However, how to control the extent of occlusal adjustment is still in question. In this study, the mean difference of cuspal inclination between the cracked maxillary first molars and normal controls may be contributive to this, which can be taken as a parameter for the measurable reduction of the cuspal inclination.

The extent to which FEA results are clinically relevant depends on various factors, including the accuracy of a model, the application of proper materials data, genuine boundary conditions, and loading of a model studied in relation to the real tooth. The present study represents an initial stage of research to simulate how steep cuspal anatomy on human intact teeth increases the risk for CTS under simplified loading by 3D-FEM analysis. As tooth material especially enamel is largely anisotropic and inhomogeneous in its microstructural complexion, and many risk indicators for CTS including steep cuspal anatomy, further studies should concentrate on anisotropy of tissues, changing parameters of cuspal anatomy, etiological factors, and mastication based on a more accurate 3D-FEA tooth model. For the cracked posterior teeth, restored or intact, occlusal adjustment is the most conservative yet appropriate way, and still an effective prevention from CTS by cusp reduction and reconfiguration.

Conclusion

Within the limitations of this study, the mean cuspal inclinations of the cracked maxillary first molars were steeper than the intact maxillary first molars, with the difference ranging from 5.5 to 6.7 degrees. And the 3D-FEA simulation indicates that those molars with steep cuspal anatomy result in an increment in unfavorable stress and their occurrence of the CTS would be magnified, which enlighten an effective reduction of cuspal inclination to the compromised teeth for dentists.

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