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Development of FEA Procedures for Mechanical Behaviors of Maxilla, Teeth and Mandible

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KEYWORDS: Masticatory action, Finite element analysis, Maxilla, Mandible, Cortical bone, Cancellous bone

This paper aims at investigating mechanical behaviors of maxilla, teeth and mandible. There are three models considered; a model of one tooth with mandible subjected to coronal-apical, lingual-buccal and mesial-distal directional pressures, a model of an upper, a lower tooth with mandible and part of maxilla subjected to mandible displacements in coronal-apical, lingual-buccal and mesial-distal directions, and a model of three upper and two lower teeth with mandible and part of maxilla subjected to mandible displacements in coronal-apical direction. FE models of teeth, part of maxilla and mandible are generated based on CT images. Material properties for teeth, PDL, cortical bone, and cancellous bone are applied to the corresponding parts. From the analyses of one tooth model, von Mises stress distributions are obtained and compared with the previously reported data for validation of modeling approaches. Those are then applied to models with multiple teeth to examine effect of directions of mandible movement and interactions. Analytical results show that geometries of teeth and directions of masticatory movement can cause significant differences in stress distributions. It is suggested that importance of parameters to be considered in predicting mechanical behaviors under masticatory action, and provide useful information for developing prosthetic devices or diagnosis.

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1. Introduction

Recently, FEA (finite element analysis) technique has been widely applied in the biomedical field,[1-18] for understanding the human body from a mechanical view point. Difficulties in measuring the stresses and strains of teeth and skull in vivo experiments can be resolved by applying FEA technique to simulating behaviors of the human body. In particular, it is important to predict the mechanical behaviors of teeth and skull accurately by using FEA since they can be used to diagnose diseases or to design prosthetic devices.

There have been studies about the analytical approaches to predicting mechanical behaviors of the human skull. Kim et al.[19] and Merdji et al.[20] studied FEA technique in relation to the mechanical behaviors of mandible bone and single molar tooth, respectively. Kim et al.[19] proposed an efficient FE modeling technique for predicting the stress distributions on mandible under masticatory force. They generated FE model of mandible and teeth without maxilla based CT (computed tomography) images of the real human. The analytical results of strains on teeth were compared with experimental data, which showed that the proposed FE model was able to predict the mechanical behaviors of mandible and mandibular teeth during mastication with high accuracy without suffering from a long period of computation time due to the complex maxillary structure. Merdji et al.[20] carried out stress analysis of single molar tooth, and their FE modeling approach can be successfully used in biomechanical study for stress distributions in constituent parts associated with masticatory action. They also showed that distal-mesial directional loading caused higher von Mises stresses on tooth, periodontal ligament, and cortical bone compared to other directional loads, such as coronal-apical and lingual-buccal directional loads.

The FE modeling approaches were also used to investigate the mechanical behaviors of occlusal adjustment and contacts. Oliveira et al.[21] evaluated the effects of different occlusal contact patterns on tooth displacement in an adult dentition using a three-dimensional FE model of a human maxilla and mandible. Kasi et al.[22] investigated the influence of occlusal forces exerted during occlusal adjustment on the distribution of forces among teeth and implants in intercuspal clenching using FEA. Eraslan et al.[23] evaluated the effects of different restoration alternatives on stress distributions on endodontically treated teeth without lingual cusp. They found that different restoration techniques do not affect the stress distribution within tooth-restoration complex.

Regarding the various influencing parameters on the mechanical behaviors of skull and teeth, studies using FE models of animal skull have been reported. Marinescu et al.[24] improved existing modeling efforts by introducing new parameters: designing a less stiff edentulous model, imposing more realistic boundary conditions, and incorporating heterogeneity and transverse isotropy into the mandible of Macaca fascicularis models. Wang et al.[25] proved hypothesis that sutures have a significant impact on global skull mechanics. They also proved that the mechanical behavior and significance of sutures depended on their material properties and positions on the cranium, by generating macaque FE model with four different sets of suture material properties and three different loading conditions simulating incisor, premolar and molar biting.

Fittion et al.[26] systematically quantified the effect of masticatory muscle activations on a primate skull model and found out that with the exception of the zygomatic arch, reasonable loading range caused by muscles for a second molar bite had considerably less effect on cranial deformation and the resulting strain map than did varying molar bite point. Young et al.[27] simulated feeding behaviors by generating FE models of Diplodocus skull with three different loading conditions. The three behaviors are: muscle-driven static biting (occlusion), unilateral branch stripping, and bark stripping. They tested how occlusion and branch stripping comparatively influence the skull biomechanics. Although many studies simulating masticatory action using FEA have been performed, relatively few analytical studies have been reported about the stress distributions and propagations considering the directions of masticatory action in real situation. Also, limitation has been found such that simplified FE models were used without considering the interactive behaviors between maxilla, mandible and teeth part.

The purposes of this study were to suggest CAE (computer-added engineering) procedure of structural analysis to simulate masticatory actions and to predict stress distributions occurring on maxilla, teeth and mandible during mastication with the actual human computed tomography (CT) images. To achieve these goals, FE models of maxilla, teeth and mandible were generated based on the actual human CT images. A FE model of mandible with one molar tooth was used to validate the proposed CAE procedure by comparing it with previously reported data.[20, 28] Then, the validated procedure was used to generate FE models of skull having maxilla, teeth and mandible. By applying different directional loads to the FE models, the effects of masticatory directions on stress distributions were investigated. In addition, FE models having different number of teeth were generated to examine the relations between the number of teeth and stress distributions.

2. Analytical Modeling Method

2.1 3D FE models

2.1.1 Converting CT images

To generate 3D model, CT (Computed Tomography, SOMATOMTM SENSATION, Siemens AG, Germery, 120 kVp, 200 ms, 0.75 mm thickness) images were captured from a 38 year old male skull with normal occlusion status. Total of 964 dicom files obtained from CT were used to construct a 3D model by using commercial software, Scan IP (Simpleware Ltd, exeter, United Kingdom) as illustrated in Fig. 1.

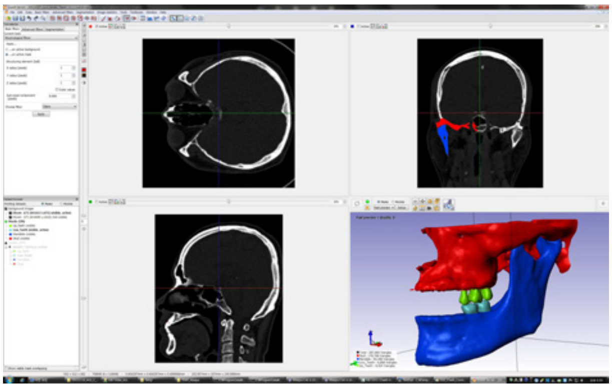
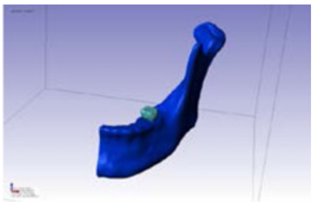
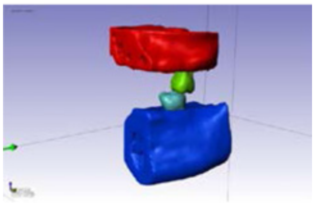


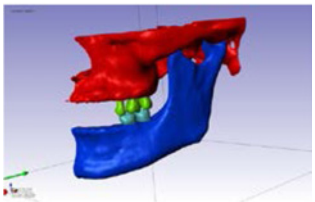
Fig. 1 Process for 3D model generated using CT images



(a) 1 tooth 3D model



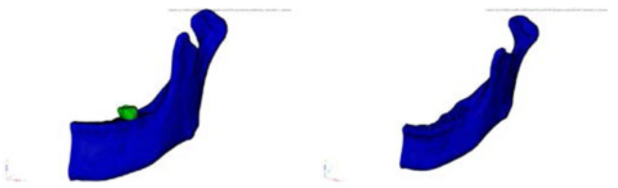
(b) 2 teeth 3D model



(c) 5 teeth 3D model

Fig. 2 3D models generated from CT images

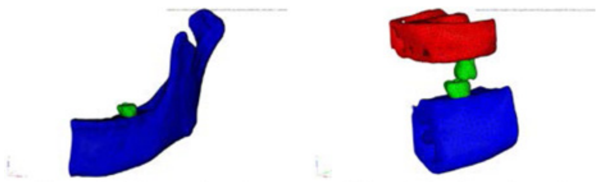
After removing some parts of maxilla and teeth and mandible for simplifications, three different solid models were generated as shown in Fig. 2; 1) a model with one tooth and mandible, 2) a model with an upper and a lower teeth, including mandible and maxilla, and 3) a model with three upper and two lower teeth, including mandible and maxilla. A model with one tooth was generated to compare the results to the previously reported data from Merdji et al..[20] Other two models were generated in order to see the effect of loading prescription and interactions between the upper and the lower teeth on stress distributions. While 3D models were generated, microscopic protrusions were removed in order to save unnecessary computational time. However, inhomogeneous densities of maxilla and mandible were included in the model by leaving empty spaces, as they might have an effect on stress distributions.



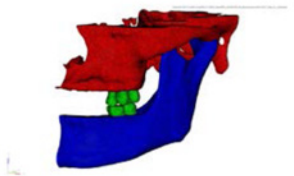
(a) Tooth and mandible (b) Mandible

(c) Tooth

Fig. 3 FE model 1



(a) Model 1 (1 tooth case) (b) Model 2 (2 teeth case)



(c) Model 3 (5 teeth case)

Fig. 4 FE models of 3 cases

Table 1 Size and number of elements of each model

Model	Size of element (mm)	No. of elements
Model 1	0.2~0.4	253,065
Model 2	0.2~0.4	88,790
Model 3	0.2~0.4	624,990

Table 2 Material properties used in the models[20]

Parts	Elastic modulus (GPa)	Poisson ratio
Molar Tooth	20	0.3
Periodontal ligament (PDL)	0.005	0.49
Cortical bone	14.5	0.323
Cancellous bone	1.37	0.3

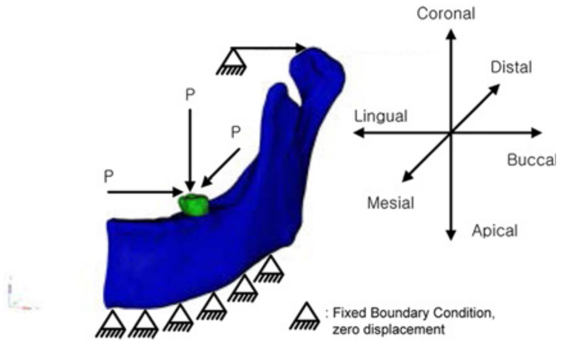


Fig. 5 The directions of three forces in the case of model 1 (1tooth case)

2.1.2 Finite element modeling

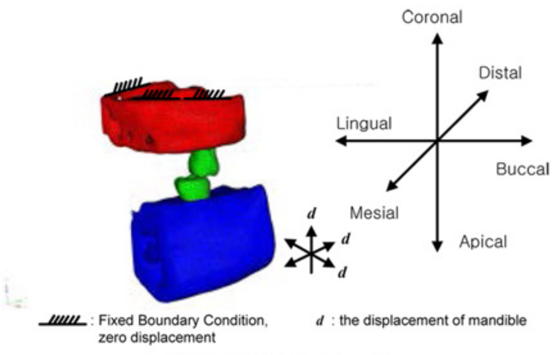
For FE models of the maxilla, the teeth and the mandible, 4-node tetrahedral elements are used. The number of finite elements for three different models is a total of 253,065 finite elements for model 1 (1 tooth case), 88,790 finite elements for model 2 (2 teeth case), and 624990 finite elements for model 3 (5 teeth case), as listed in Table 1 and shown in Fig. 3 and 4. The 4-node tetrahedral element has a degree of freedom in anterio-superior, axial, and anterio-posterior direction at each node. Stress and strain at each direction are calculated at a single integration point per element.[29] The generated finite element models include the linear material properties and contact formulations between the maxilla, the teeth, and the mandible. Furthermore, the effect of periodontal muscle is considered in the model by adding tied contact formulations on the surfaces of the periodontal muscle and the mandible. The contact formulations for periodontal muscle are to save computational time. Also, FE models for muscles are replaced by loading and restraint prescriptions. Loading is prescribed in form of displacement control, and restraint conditions are prescribed at the bottom edge of the skull in order to prevent the collapse of the skull. Non-linear geometrical analyses are performed using commercial software, ABAQUS version 6.10-3 (Dassault Systèmes, Vélizy-Villacoublay, France). Contact formulation is included between the teeth with friction coefficient of 0.2, referred to Wierszycki et al..[30]

2.2 Material properties

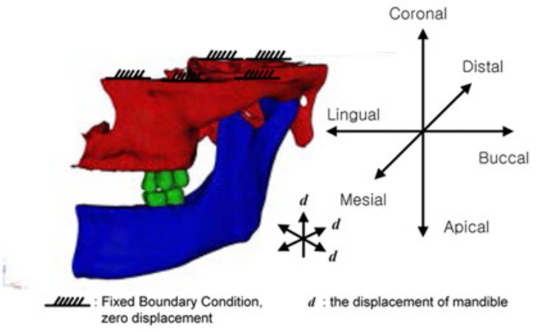
For material properties of teeth, maxilla and mandible, elastic modulus and Poisson's ratio are provided from previously reported data as shown in Table 2. Teeth are composed primarily of 3 materials: dentin, enamel and cementum. The cementum and the enamel represent a considerably small volume of the tooth and can be assimilated into the volume of the dentin. Compared to PDL (periodontal ligament) which has a highly soft material, dentin contains very hard material and deforms only a little when the molar is loaded. The elements are grouped separately for the parts of periodontal ligament and the cortical bone. Then, each element group is modeled with corresponding material properties. For all groups, linear elastic material behaviors are used, since the study assumes that stresses on maxilla, teeth and mandible do not undergo their elastic limit under masticatory action. The interface between the teeth and the ligament, as well as between the cortical and cancellous bone are treated as perfect bond.

2.3 Restraints and loading conditions

In case of model 1, condylar process area with top surface of the molar is restrained in order to simulate behaviors of occlusion without modeling complex maxilla. Molar and the restraint directions of condylar process and molar are chosen as variables, and differences in mechanical behaviors are compared. As illustrated in Fig. 5, coronal-



(a) Model 2 (2 teeth case)



(b) Model 3 (5 teeth case)

Fig. 6 Loading and restraint prescriptions of model 2 and 3

apical, lingual-buccal, and mesial-distal directional loads are applied as described in a previously reported paper by Merdji et al..[20] The most coronal plane of the crown is subjected to a load of 3 MPa in both the lingual-bucacal and the mesial-distal directions. In addition, load of 10 MPa in coronal-apical direction is applied to the center of the occlusal surface of the crown.

The same modeling methods as model 1 are used to model 2 and 3. However, loading is prescribed in a form of displacement control instead of pressure as in the case of model 1. Displacement control allows simulation of occlusion as well as stable numerical procedure. There are three directions of the displacement control: coronal-apical direction, mesial-distal and buccal-lingual directional movement. For simulating, mesial-distal and buccal-lingual directional movement, and three sequential steps are defined in the model. For the first step, a coronal-apical directional movement is simulated for mesial-distal or buccal-lingual directional movement, respectively. For all cases, 2 mm displacement for each directional movement is simulated as shown in Fig. 6.

2.4 Stress and strain measurements

From the FE analyses, von Mises stress distribution of maxilla, teeth and mandible is observed from the FE analyses. The von Mises stress, which is called effective stress, has been widely used to determine the absolute stress value regardless of the stress direction and the yield characteristics of materials. This value is calculated using Eq. (1).

$$\sigma = \left[\frac{(\sigma_1+\sigma_2)^2+(\sigma_2+\sigma_3)^2+(\sigma_1+\sigma_3)^2}{2}\right]^{0.5} \tag{1}$$

σ_i : stress components in i directions

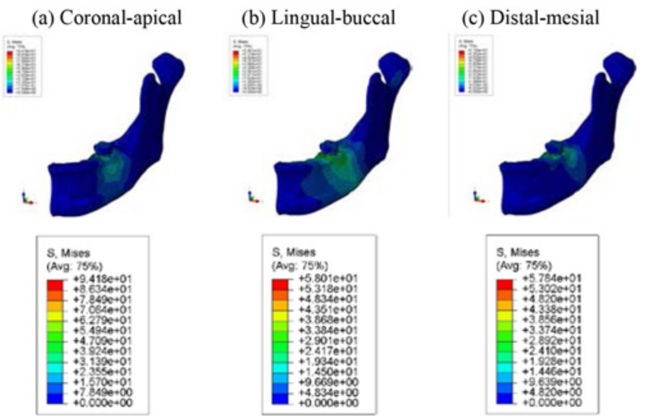

(a) Coronal-apical (b) Lingual-buccal (c) Distal-mesial

Fig. 7 Results of model 1

3. Verification of FEA Procedure in Model 1 (1 tooth case)

In this section, analytical results from model 1 (1 tooth case) is presented; this is stress distributions and the max. strain of maxilla, teeth and mandible depending on the directions of masticatory behaviors. In case of model 1, von Mises stresses under the effect of axial and horizontal loading in the coronal-apical, lingual-buccal and distal-mesial loading conditions were illustrated in Fig. 7(a) to (c). From Fig. 7(a), it was observed that high stresses were distributed over the area of the periodontal ligament of mandible when the load is applied to the coronal-apical directional load. This means that masticatory force of coronal-apical direction from the tooth was transmitted to the mandible, and stress was increased from near the periodontal ligament and was gradually decreased while this was magnified for the mandible. Also, the distribution of stress was indicated at the periodontal ligament near the inside and the outside of the mandible surface. The distribution of stress of Fig. 7(b) lingual-buccal directional load in the model 1 was wider than that of Fig. 7(c) distal-mesial directional load that the masticatory direction in molar tooth was acted on perpendicular to the plane of the outside of the mandible surface. This is ascribed to the fact that the masticatory force of lingual-buccal direction is worked larger than that of distal-mesial direction in the tooth. Also, the value of stress in distal-mesial direction was smaller than those of lingual-buccal direction.

In order to investigate the feasibility of CAE procedure in this study, the analytical results were compared with the results of previous work in Figs. 8 and 9. The analytical results of PDL showed that the max. von Mises stress was appeared near the boundary surface between tooth and PDL in Fig. 8. There were also slightly different values in stress for each case when the results from model 1 were compared with the results reported by Merdji et al..[20] The differences in von Mises stress values came from the geometrical differences and FE analysis procedure between this study and the previous work.[20] This phenomenon is estimated to come from the shape of tooth and mandible using CT images and the analytical procedures of the model. However, this study showed similar results of stress distributions as the previous work.

In Fig. 8, the values of stress were compared with the tooth of model 1 with previously reported data by Merdji et al..[20] Max. stress was observed between a tooth and the periodontal ligament of mandible. The reason is that lingual-buccal directional force causes larger stress than

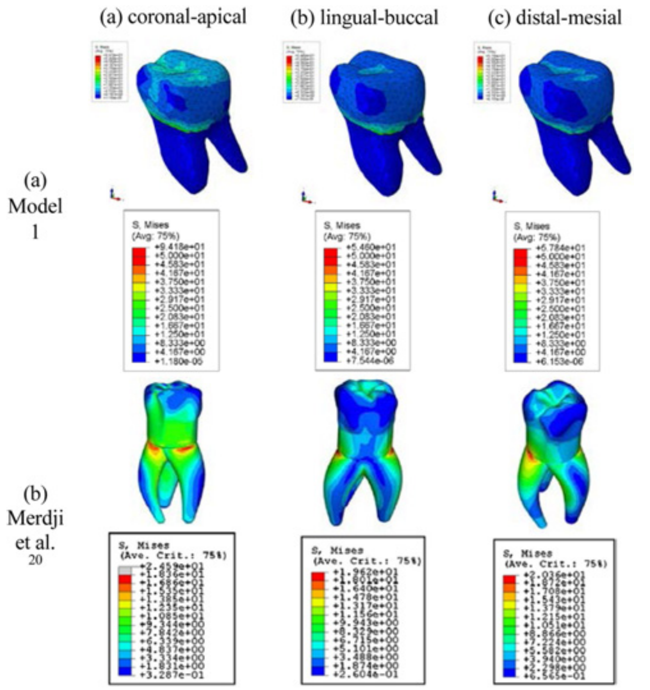


Fig. 8 Comparison of the results of molar tooth of model 1 and Merdji et al. (Adapted from Ref. 20 with permission)

distal-mesial direction when the tooth is moved and contacted with the periodontal ligament of mandible in case of model 1.

4. Occlusal Examples

Previously, researchers[17-20,22,23] have reported on FE modeling technique based on CT images of the skull and performed FE analysis to investigate the mechanical behaviors of teeth and mandible.

Based on FE analysis, it is possible to show the effect of bone density on stresses in mandible during mastication and to define the mechanical behavior of a partially edentulous mandible as a function of cancellous bone density.[31] Andre et al.[31] performed parametric analyses to analyze the influence of cancellous bone density (25%, 50%, 75%) on the development of mandibular stress and strain during simulation of masticatory forces in the anterior region. Accordingly, maximum von Mises stress and equivalent strain values in cancellous bone were found close to the loading area. The peak stress and strain values were occurred in the mandibular anterior region, and equivalent stresses increased with bone density under the same masticatory force.

Also, Xu et al.[32] suggested a masticatory system of human for FE modeling, such that a fixed maxillary jaw and a mobile mandibular jaw were joined by two temporomandibular joints (TMJ). To obtain the stress distribution in the TMJ discs during jaw closing, Savoldelli et al.[33] performed analysis with high-resolution FE model. In their paper, stress evolution in the TMJ under various loadings induced by mandibular trauma, surgery or parafunction was investigated. As a result, maximum stress was appeared on the surface of disc in contact with the bones.

3D FE analysis for deformation of the human mandible was also reported to show stability of OMI (orthodontic mini-implants).[28] Three FE models were constructed using CT images of 3 adults having different mandibular plane angles. With an OMI placed between number 45 tooth and number 46 tooth of each model, analytical results of POMI-CSTN (peri-othodontic mini-implant compressive strain) under clenching and orthodontic traction forces from three FE models were compared to each other. The three models with different mandibular plane angles showed that compressive strains around the OMI were distributed mesiodistally rather than occlusogingivally. The maximum POMI-CSTN developed by clenching failed to exceed the normally allowed compressive cortical bone strains; however, additional orthodontic traction force to the OMI may increase POMI-CSTNN to compromise OMI stability.

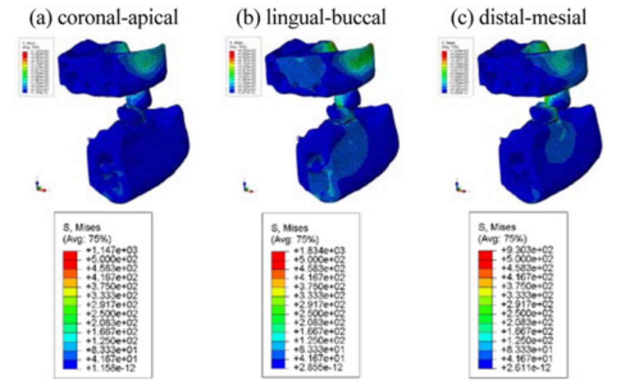


Fig. 9 Results of model 2

The previous studies have found that stress and strain distributions on maxilla, teeth and mandible are important to understanding the mechanical behaviors under mastication and can be found from FE analyses. This section summarizes the analytical results of stress propagations at 4 major time intervals during mastication and comparison of von Mises stresses for each component under different loading conditions which are important in prosthodontics and orthodontics. In addition, max. von Mises stress values on teeth, cortical and cancellous bone were quantitatively analyzed. In order to achieve this, the validated modeling approaches used to generate model 1 were applied to model 2 and 3, where coronal-apical, lingual-buccal and distal-mesial directional loadings were prescribed in a form of displacement control.

4.1 Model 2 (2 teeth case)

The validated modeling technique is used in model 1 to model 2 having maxilla and upper teeth. In this model, the mechanical behaviors of maxilla, teeth and mandible under mastication can be found by applying loading condition as displacement control.

The analytical results of stress on maxilla, teeth and the mandible of model 2 were illustrated in Fig. 9. In Fig. 9, as mandible moves upward, von Mises stresses was propagated from tooth to cancellous bone of the maxillar and the mandible. In the boundary of the cortical bone and the tooth, high stress distribution was found, which means that the mastication force is translated from the contact between the upper and the lower teeth to cortical bone followed by cancellous bone. This could be estimated to be the force of mastication in lingual-buccal case causing larger stresses than that of mastication in distal-mesial case since only two teeth were contacted with each other. The distributions of stress are

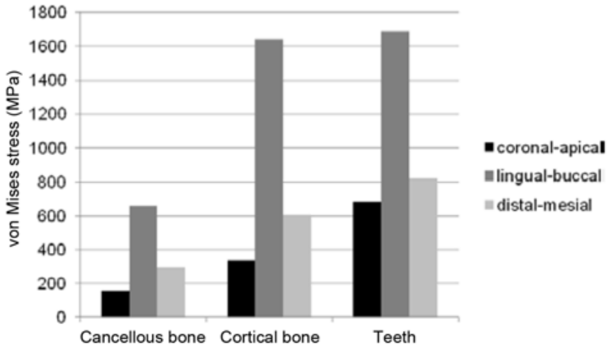


Fig. 10 Histograms of comparison of von Mises stresses for each component under the different loading conditions in model 2

also illustrated in Fig. 9.

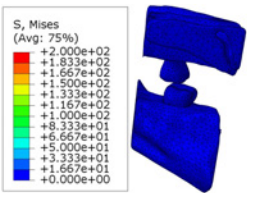
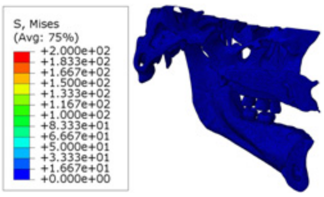
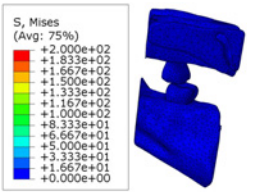
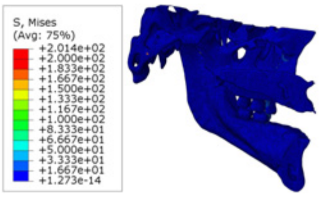
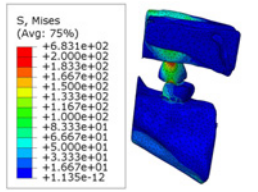
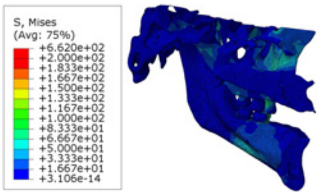
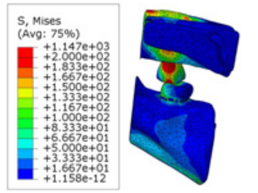
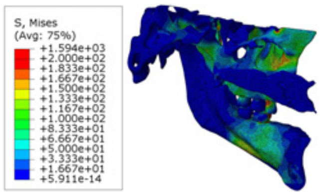
Histogram of the comparison of von Mises stresses for each component under different loading conditions in model 2 was shown in Fig. 10. The results of von Mises stress distributions were appeared in case of coronal-apical, lingual-buccal, and distal-mesial loading conditions. Relatively large stress around the teeth and cortical bone was occurred by the lingual-buccal loading condition. Also, the transmitted stress was translated from teeth to cortical and cancellous bone gradually. High stress distribution of lingual-buccal loading case is estimated that the stress of teeth is occurred due the direction of tooth roots in periodontal ligament. This phenomenon suggests the possibility that FE analysis of full skull model is accomplished under the masticatory behaviors and that the masticatory force is transmitted from teeth to brain. Also, it is considered that the modeling configuration skill required of a designer or an engineer is needed to improve the accuracy of analysis and the sensitivity of analysis of each case. Progressive results of von Mises stress distributions of coronal-apical directional loading case during mastication in model 2 were illustrated as shown in Table 3.

4.2 Model 3 (5 teeth case)

However, model 3 was applied only to the coronal-apical directional loading because other directional loading cases did not converge at step 2 movement stage which was lingual-bucccal or distal-mesial directional. The problem was estimated step 2 stage of movement problems after 2 mm coronal-apical directional moving in occlusal condition between upper teeth and lower teeth. It was investigated that the total teeth movements were influenced between the bumpy surface on each upper teeth and each lower teeth.

Progressive results of von Mises stress distributions of coronal-apical directional loading case during mastication in model 3 were illustrated as shown in Table 3. Distributions of von Mises stress of coronal-apical directional loading of model 3 were widely spread from teeth to maxilla and mandible. According to the stress propagates from teeth to cancellous and cortical bone, stress decrease as propagated from cortical to cancellous bone. If the number of teeth is increased, the contact surfaces between each tooth and tooth can be increased. In that case, the stress propagates can be give reference values and the directions to experimental and clinical research. In orthodontics, the use of model 3 can be referred to the teeth movements in orthodontic just as the directions of tensing and moving of teeth.

Table 3 Progressive results of von Mises stress distributions

	Model 2 (coronal-appical load)	Model 3 (coronal-appical load)
0.0 mm		
1.2 mm		
1.5 mm		
2.0 mm		

5. Conclusions

In this study, the CAE procedure is suggested to predict the mechanical behaviors of maxilla, teeth and mandible during mastication using the loading condition and displacement conditions. The proposed FE models can evaluate the structural and the mechanical behaviors of maxilla, teeth and mandible effectively even if the models are modified to simulate the mastication situations. The displacement control as the loading condition can be more acceptable than applying direct load when the mastication behavior is simulated.

In addition, it is possible that the tendency of stress distribution from teeth to cortical and cancellous bone can be identified in this model. Accordingly, this FE analysis procedure can be extended to full skull models for masticatory behaviors. But, as the increase of teeth, extended full maxilla and mandible, the detailed models in the masticatory behaviors are demanded to obtain FE analytical results. Also, the number of teeth in detailed models and the displacement controls of FE analysis can improve the results of FE analysis about masticatory behaviors.

ACKNOWLEDGMENT

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