Biomechanical Evaluation of Temporomandibular Joint Disc by Using 3-D Finite Element Analysis During Loading

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Abstract

Many factors may induce craniomandibular disorders, such as heavy loading, which may lead to joint wear and even disc perforation. Currently, there are no universal devices or methods to quantify the loading of the joint. This study aimed to create a universal three-dimensional temporomandibular joint (TMJ) finite element model which simulated different conditions by combing radiographic examinations and computer-aided design software. Five different loading conditions were applied on the articular disc of the joint along the axis of the condylar neck of the mandible: 5 N, 20 N, 35.5 N, 50 N, and 100 N. Our analysis determined that during loading, stress is distributed in the intermediate zone of the articular disc of the TMJ. The highest levels of stress and strain are concentrated on the posterolateral side of the disc. When joint load ranging from light to heavy was applied, stress and strain were distributed from the medial and lateral areas of the intermediate zone, gradually spreading to the entire intermediate zone. In conclusion, the model of this study was able to develop a universal model simulating the biomechanical influence of the joint disc under different loading conditions.

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Introduction

The human mandible is connected to the skull by the temporomandibular joint (TMJ), which provides considerable activity. Although the surface of the temporomandibular joint is not smooth, there is a cartilaginous articular disc in between. It increases the contact area between the surfaces of the joints, thereby reducing contact pressure and absorbing some stress under function.[1] In early research, it was believed that the TMJ of a mammal was not a loading-bearing joint, as it does not experience force during movement of the lower jaw and chewing. Later studies in the mid-20th century showed a load on the joint during chewing. Increasing or sustaining this load might cause further craniomandibular disorders.[2]

Ideally, the strength and direction of the force should be measured directly and separately at the mandible and joints to distinguish a difference. However, there are limitations to these experiments in reality, especially in animal models.[3] Therefore, indirect methods to observe joint forces were developed and valued, including photoelastic models,[4] numerical models,[5] or finite element (FE) methods.[6–8]

The finite element method has been widely used in modern times. After the structural characteristics of the joints are determined, along with advances in other auxiliary testing devices, the finite element method module can be more accurately simulated from a two-dimensional model to a three-dimensional projection.

It is impossible to fully present joint force and stress distribution from a two-dimensional FE model due to experimental constraints and assumptions. Three-dimensional FE model was first established by Beek[7,8] to measure joint surface and geometric shape of the human joint by using an electromagnetic tracking device. However, FE modeling of this joint has not yet been fully established.

Therefore, the aim of this study was to develop a universal method to construct a three-dimensional finite element model employing radiological image examinations and computer-aided design software. These results could

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simulate the biomechanical influence of the joint disc under different loading conditions.

Materials and methods

3D finite element of the TMJ model

Condyle and mandible geometry were obtained by applying the attached CBCT software (KaVo eXam Vision, KaVo Dental GmbH, Germany) randomly from the database with approval of our Institutional Review Board. To improve efficiency of resources in the calculation, only the right articular eminence and half lower mandible were used to establish a research model. The data were transferred to the computer-aided design software (Rapidform XOR, INUS Technology, Inc., Seoul, Korea), which depicts the surface information of the 3D image (Figure.1) and materializes the surface information into a solid model, thereby creating a volumetric three-dimensional object. Eventually, the solid model was imported to the finite element software (ANSYS 12.0, ANSYS, Canonsburg, PA, USA) for subsequent analysis (Figure.2a). The size of the articular disc was determined based on the MRI imaging study by Chen.[9] The mediolateral width of the disc is approximately the same as the width of the medial and lateral sides of the condyle; the dorsoventral position of the disc was set at the noon position.

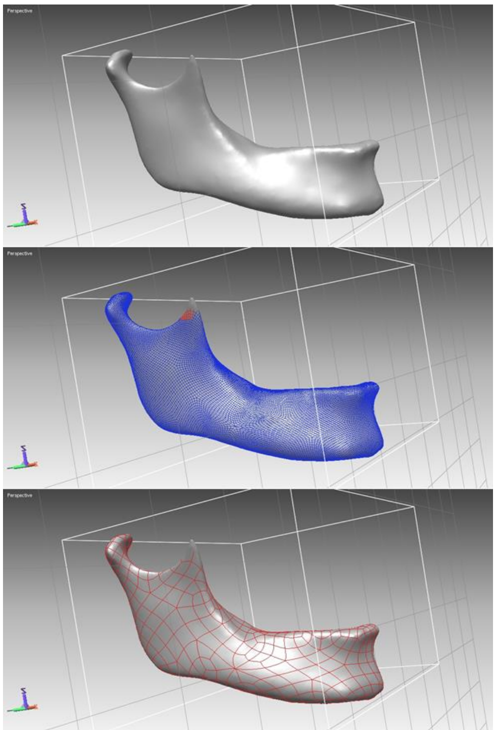

Figure.1 Image operation process. (a) model input from CBCT, (b) surface information by auto surfacing, (c) solid model reconstruction.

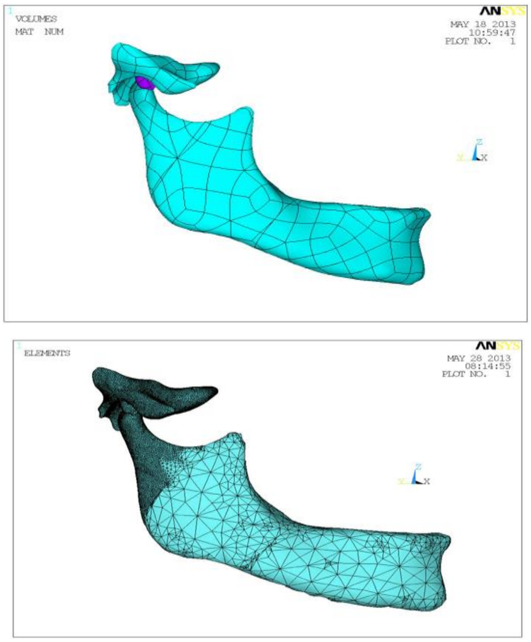

Figure.2 The FE model. (a) three components of TMJ (b) free mesh with smart sizing.

General setting of the FE model

A variety of element types are available in the ANSYS software. In this study, the component of TMJ was simulated by SOLID92 elements, which are suitable for irregular three-dimensional geometric models. In addition, the material properties were adopted from previous literature, which assumed all structures were linear, isotropic, and homogeneous.

Limited by the image output settings, in this intact model, the value of Young's modulus of the bone component were averaged to 7300MPa and Poisson's ratio to 0.3.[7] On the other hand, based on anatomical histology, the articular disc is mostly composed of collagen fibers and thus the value of Young's modulus was set to 6.8MPa and Poisson's ratio to 0.3 for the articular disc.[10]

Model meshing of the FE model

Due to the complex geometry of the intact model in this study, a 3-D finite element model was constructed using free meshing. The element size is divided into 10 levels by taking advantage of smart sizing, which could increase element density around the curvature area and thus improve the accuracy of the result.

To reduce the number of elements and calculation time without affecting the results, the general size of the mesh was set as 0.6 mm based on a convergence test, while it was a large size when moving away from the loading area (Figure.2b). The whole finite element model was comprised of 537,527 nodes and 390,693 elements.

Boundary and loading conditions

To avoid rigid body motion when the object was loaded, the superior surface of the articular eminence was fixed. The mechanical interaction among articular eminence, joint disc, and mandible was assumed to be frictionless contact behavior with no separation slip.

According to a previous study by Beek[7], the disc would have mild displacement when the joint is under load from the center of the condyle to the joint disc along the long axis of the condyle neck. In the study, it focused on the joint disc when it was relatively static under increasing loading which simulated five conditions: 5 N, 20 N, 35.5 N, 50 N, and 100 N on the articular disc of the joint along the axis of the condylar neck of the mandible. The equivalent stress, third principal stress and shear stress on the joint disc would be analyzed.

Validation of the FE model

To validate the FE model, the experimental model was set as a fixed end at the upper end of articular eminence and the lower teeth, based on the in vitro test conducted by DeVocht[11], Then, it applied half-loading from the chin and mandibular angle at 45 degrees, in accordance to the half model in FE.

Results

The validation of the FE model

The resultant stress on the disc was 2.49 MPa in the study, which equates to 5.6 MPa in DeVocht's study. Compared with previous studies, the two results are in the same numerical range.

Biomechanical evaluation of the disc

Applied force will spread to the entire disc under center loading of the condyle to the joint disc. Therefore, the overall stress can be revealed from the equivalent stress. The equivalent stress under 5 N was 0.766MPa, under 20 N was 2.806MPa, under 35.5N was 4.636 MPa, under 50 N was 6.354 MPa, and under 100 N was 11.809 MPa (Figure.3). The stress was mostly distributed in the intermediate zone of the disc, especially on posteriorlateral side. The anterior band of the disc exhibited relatively less stress concentration. The stress distribution spreads from the lateral and medial side of the intermediate zone to the entire intermediate zone and the posterior band of the disc under increasing load.

It observed the third principal stress to determine directionality of the stress. The result of the third principal stress is as follows: -0.353 MPa in 5 N, -0.989 MPa in 20 N, -1.566 MPa in 35.5 N, -2.13 MPa in 50 N, and -3.842 MP a in 100 N (Figure.4). The distribution pattern is similar to the trend of equivalent stress. It is worth noting that the anterior band is concentrated by tensile force.

Equivalent strain and shear stress can reveal the most severe deformation area of the object. The results of the shear stress are as follows: 0.436 MPa in 5 N, 1.589 MPa in 20 N, 2.615 MPa in 35.5 N, 3.584 MPa in 50 N, and 6.643 MPa in 100 N (Figure.5). The distribution of shear stress was concentrated on the intermediate zone, especially in lateral areas.

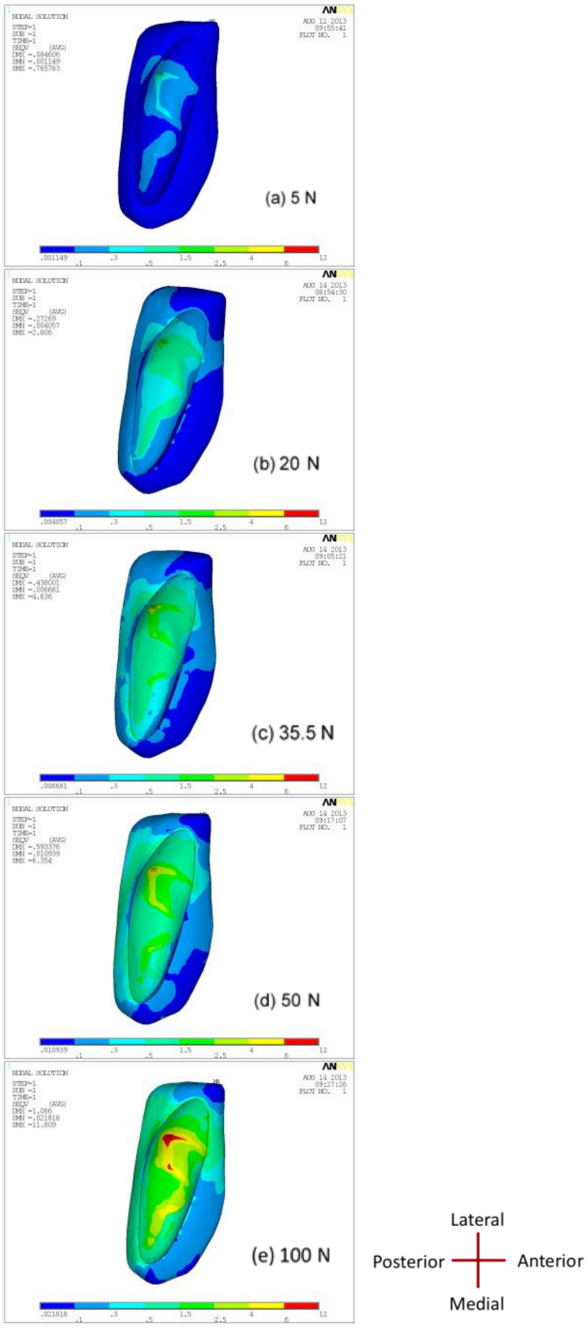

Figure.3 The von Mises stress under loads of (a) 5 N, (b) 20 N, (c)35.5 N, (d)50 N, (e)100 N.

Discussion

Model simulations using nuclear magnetic resonance have the advantage of non-invasively assessing soft tissue without radiation. However, image resolution and associated error are common problems.[6,12] Traditionally, the major limitation of the two-dimensional finite element model of the TMJ is the inability to interpret the magnitude and distribution of force on the medial and lateral sides of the disc.[7] To improve on this, it developed a novel method for three-dimensional biomechanical evaluation and digital simulation of the disc by combining CBCT and CAD software. The image slice can be set at 0.2~0.4mm, with a greater resolution than nuclear magnetic resonance. Analysis can also be performed on hard tissue structures. In addition, the most common issue in computed tomography is the relatively large dose of radiation. Fortunately, the current cone-shaped computed tomography used in dentistry can greatly reduce the size of the radiation dose. According to the ICRP103 specification of the International Commission on Radiological Protection (ICRP) in 2007, the radiation of CBCT is about one hundred, approximately equal to dozens of periapical films. Thus, the dose is far less than the recommended yearly maximum radiation dose of 5 μSv.[13]

The FE model in this study simulated surfaces with dense mesh in the vicinity of the disc, which improves the accuracy and stability of the results. Our results are similar to the studies conducted by Beek[7] and Koolstra[14]. The maximum equivalent stress was concentrated on the lateral side of the intermediate zone, while the shear stress was largest either. This might explain the clinical observation of perforations in the intermediate zone of the disc.[15] When the joint is subjected to repeated small loads or incidental high-impact loads, such as clenching or grinding teeth, the disc deformation will spread to the entire intermediate zone, thus causing wear of the disc. The trend of the third principal stress distribution is similar to previous results reported by Palomar.[16] Compressive stress is concentrated on the intermediate zone and the tensile stress is applied on the posterior band during teeth biting.

The advantage of finite element analysis is that it provides an overall magnitude and distribution of stress and strain on our model. Although there is no consensus on the ideal settings for materials properties, the results of this study still provide a qualitative reference. In the future, additional information on material properties of joint tissues and improved MRI resolution can help build more accurate models containing both hard and soft tissues. A more accurate model could better evaluate TMJ under different loading conditions to provide clinical diagnosis and determine treatment effects.

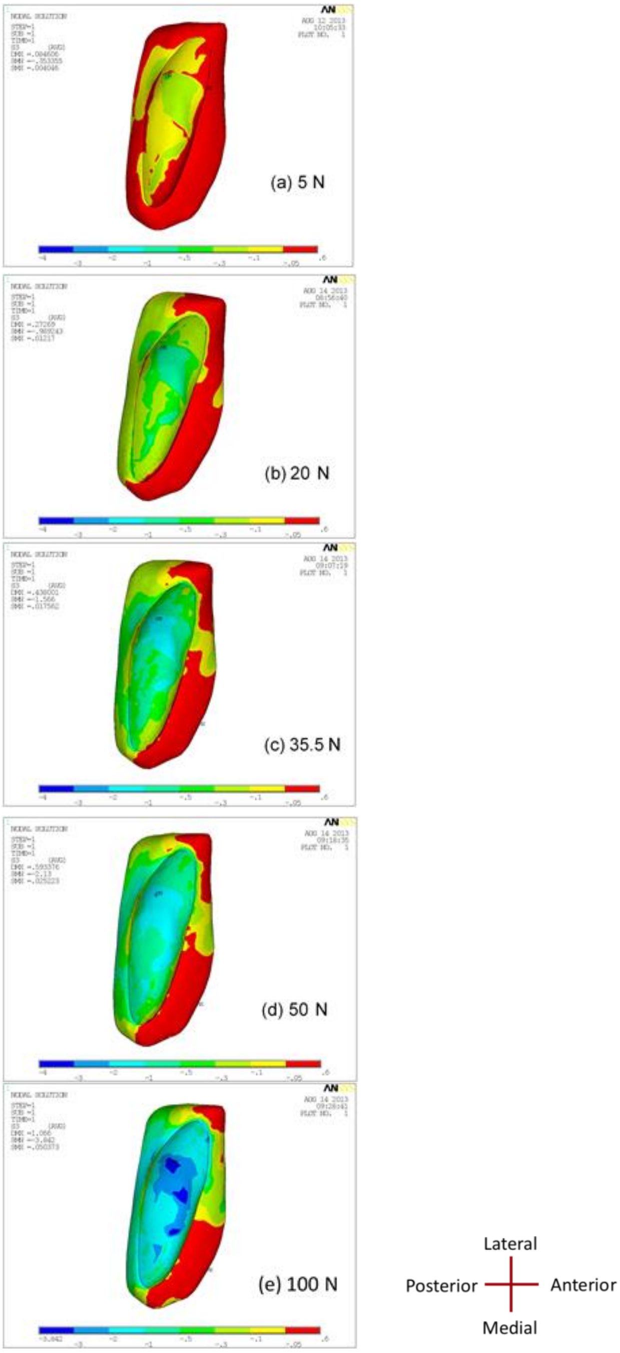

Figure.4 The third principal stress under loads of (a) 5 N, (b) 20 N, (c)35.5 N, (d)50 N, (e)100 N.

Conclusions

In this study, it could conclude that: (1) The equivalent stress is distributed overwhelmingly to the posterolateral area of the intermediate zone of the TMJ disc; (2) the third principal stress is located primarily in the intermediate zone and posterior band of the TMJ disc; (3) the shear stress is more heavily concentrated in the lateral side of the intermediate zone of TMJ disc. The model of this study was to

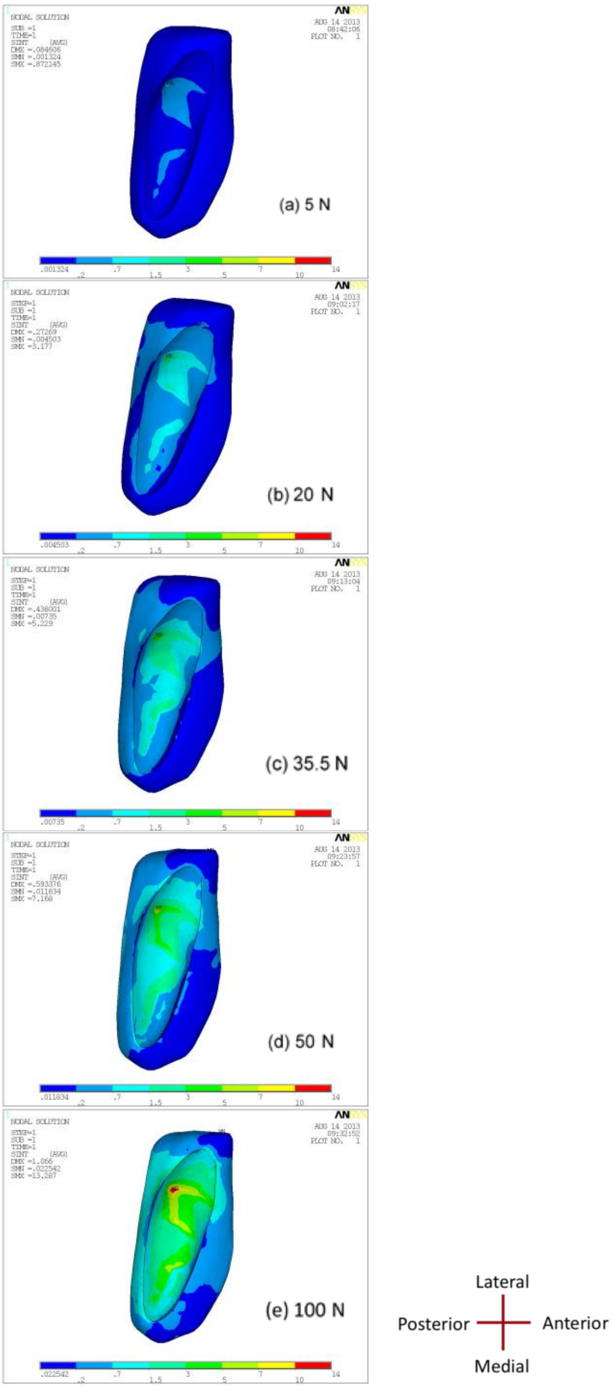

Figure 5. The shear stress under loads of (a) 5 N, (b) 20 N, (c)35.5 N, (d)50 N, (e)100 N.

develop a universal model simulating the biomechanical influence of the joint disc under different loading conditions. Besides, by taking the advantage of FE model, smart sizing for mesh, convergence and validation test would obtain more efficient and accurate results than previous study. It could help develop survey or diagnostic tools for evaluating clinical situations in the future.

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Declaration of Interest

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