Stress Distributions in the TMJ During Clenching in Patients With Vertical Discrepancies of the Craniofacial Complex

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This study was designed to investigate stresses in the TMJ during clenching in patients with skeletal discrepancies in the vertical direction. A three-dimensional model of the mandible including the TMJ was used for finite element analysis for the stresses. The model, referred to as a standard model, consists of 2,088 nodes and 1,105 solid elements, comprising the cortical and cancellous bones, articular disc and cartilage layer, and periodontal ligament. The standard model was modified by varying the gonial and mandibular plane angles to simulate vertical discrepancies between the maxilla and mandible observed in open and deep bites. Stresses were analyzed on the surfaces of the condyle, the glenoid fossa, and the articular disc, and the values were compared to those found with the standard model. Stresses increased substantially for the condyle, the glenoid fossa, and the articular disc with greater gonial and mandibular plane angles, and those changes were more obvious in association with the divergent mandibular plane. Thus, the nature of stress distributions in the TMJ was substantially affected by vertical discrepancies of the craniofacial skeleton. It is also suggested that these changes in stresses produce a lack of biomechanical equilibrium in the TMJ, which may have some association with temporomandibular disorders.
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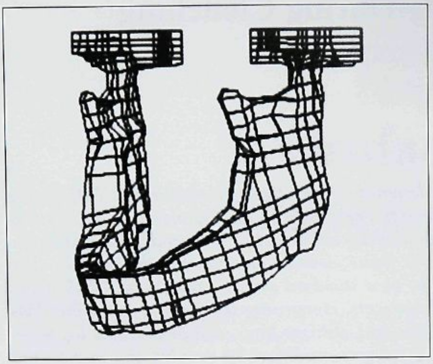
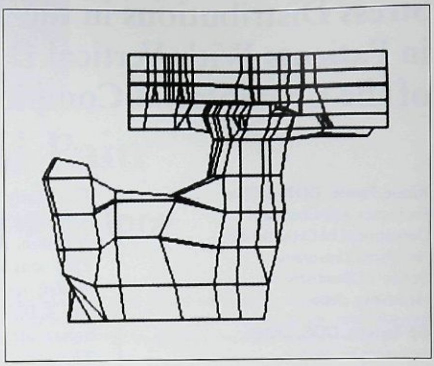
key words: temporomandibular joint, stress distribution, craniofacial morphology, temporomandibular disorders

Temporomandibular disorders (TMD) have become an important topic in the field of dentistry and orthodontics. Various studies have been conducted to elucidate the nature of TMD and the relevant causes.[1-6] Variable factors have been indicated in these studies as the cause of TMD; thus, the etiology of TMD is assumed to be multifactorial. Among these factors, it has been speculated that malocclusion associated with skeletal and dentoalveolar problems is related in part to the occurrence of TMD. With respect to this matter, clinical and experimental studies have been carried out to elucidate the nature of TMD in association with malocclusion as an etiologic factor.[7-10]

Stresses in the temporomandibular joint (TMJ) during jaw movements are considered to be of great importance for maintaining normal structure and function of the TMJ components, as is the case for other synovial joints in the human body.[11] Various approaches have been attempted for measuring mechanical loading in the TMJ.[12-18] Scott[12] and Steinhardt[13] examined the human TMJ histologically and revealed a lack of the protective epiphyseal carti-





Figs 1a and 1b Three-dimensional model of the mandible including the TMJ *(left)* and blowup *(right)* of the TMJ for finite element analysis. The model consists of 2,088 nodes and 1,105 solid elements.

lage layer in the TMJ commonly observed in other synovial joints. From a biomechanical aspect, Hylander[14] and Brehnan and associates[15] revealed that substantial loads were induced in the TMJ during jaw movements and that the loads were the largest during maximum clenching. Further, Haskell et al[16] and Maeda et al[17] demonstrated by means of finite element analysis that stresses were induced by clenching in the forward and upward directions relative to the glenoid fossa. Tanaka and associates[18] investigated stress distributions in the TMJ in more detail and described that stresses in the TMJ produced by clenching were substantially different from area to area and that the compressive stresses were the greatest in the anterior and lateral areas of the TMJ. From a clinical aspect, deformations of the condyle such as erosion, flattening, and eburnation are occasionally observed in the anterior area of the condyle in patients with TMD.[19–21] Frequently these patients exhibit vertical discrepancies between the maxilla and mandible.[21,22] From these findings, it is suggested that biomechanical changes from stresses may be associated with deformation of the hard and soft tissues in the TMJ. However, the association of such skeletal discrepancies with stresses in the TMJ has not been investigated.

The purpose of this study was to investigate the influences of vertical discrepancies of the craniofacial skeleton on stresses in the TMJ during clenching by use of finite element analysis.

Materials and Methods

A three-dimensional model of the mandible including the TMJ was created for finite element analysis from the dry skull of a young human being. First, the skull was cut into transverse sections parallel to the Frankfort horizontal plane. Photographs of both the dorsal and ventral aspects were taken of the sections, and the anatomic structures observed on the photographs were traced on acetate paper. These two-dimensional drawings were divided into a finite number of elements, ensuring that the geometric shape of the model matched the anatomic structures. All the meshed sections were stacked perpendicular to the Frankfort horizontal plane to create a three-dimensional configuration of the model.

The articular disc was developed between the mandibular condyle and glenoid fossa, establishing elements approximately 2.0 mm thick.[23] The surface of the condyle was designed to be covered with the articular cartilage layer 0.2 mm thick on average.[24] Finally, the model was constructed with 2,088 nodes and 1,105 solid elements[18] (Figs 1a and 1b). Hereafter this model is referred to as a standard model. Five components were integrated in the model, and the material constants were defined for each of the components on the basis of previous experimental data[25–27] (Table 1).

For loading conditions, muscle forces and the lines of actions were determined. The force vectors were first determined according to the anatomic areas of muscle insertion and origin; ie, two points or nodes located in the center of the areas of muscle insertion and origin were defined as the points for the line of muscle force. The magnitude of muscle forces was determined to exert a resultant force of 500 N under such an assumption that the forces are proportional to the cross-sectional areas.[28-31] During loading, the model was restrained at the superior region of the temporal bone to avoid sliding movement of the model.

For stress analysis, the standard model was modified to represent vertical discrepancies in the complex, maintaining the number of nodes and elements for the standard model. The shape of the mandible was changed by varying the gonial and mandibular plane angles to simulate vertical discrepancies clinically observed in open and deep bites. The gonial angle in Japanese women was changed from 110.1 degrees to 134.1 degrees in 6.0-degree increments (mean, 122.1 degrees). The mandibular plane angle to the Frankfort horizontal plane (FMA) was similarly varied from 18.5 to 42.5 degrees in 6.0-degree increments.

Stress analysis was executed on a Titan computer (Kubota, Osaka, Japan) by use of an analysis program (ANSYS, Swanson Analysis Systems, Houston). Three principal stresses were analyzed for the condyle and glenoid fossa. For the articular disc, octahedral normal and shear stresses were obtained from the three principal stresses. These stresses were evaluated for five different areas (anterior, middle, posterior, medial, and lateral) of the TMJ[32] in association with various skeletal patterns.

Table 1 Mechanical Properties of Different Components of the Model

	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	1.37×10^4	0.30
Cancellous bone	7.93×10^3	0.30
Articular disc	4.41×10	0.40
	(Stress range < 1.50 MPa)	
	9.24×10	
	(Stress range > 1.50 MPa)	
Periodontal membrane	4.90×10^{-1}	0.49
Articular cartilage	7.90×10^{-1}	0.49

Results

Mean stresses in the condyle and glenoid fossa changed with varying gonial angles in a similar manner (Fig 2). The stresses were almost invariably within the range of 110.1 to 122.1 degrees of the angle. The stresses exhibited an increase in the absolute value when the angles were more than 122.1 degrees. It is interesting that changes in stresses are nonlinear in nature and more prominent on the condyle in the anterior and posterior regions than in the glenoid fossa and other areas, eg, stresses in the anterior and posterior areas of the condyle changed from −1.64 and 0.66 MPa at 122.1 degrees to −2.09 and 1.19 MPa at 134.1 degrees, respectively. For the articular disc, patterns of normal and shear stresses were somewhat different (Fig 3). Normal stresses in the anterior and posterior areas tended to increase in the absolute value with gonial angles greater than 122.1 degrees, whereas the stresses in the remaining areas were almost constant. Meanwhile, shear stresses experienced substantial increases in most areas, almost 1.5 times the values at 122.1 degrees, when the angles became greater than 122.1 degrees.

Stresses associated with varying mandibular plane angles exhibited more obvious changes than those with varying gonial angles. Changes in stresses were nonlinear and particularly drastic when the angle became more than 36.5 degrees (Figs 4 and 5). Mean principal stresses on the glenoid fossa and condyle were almost constant within the range from 18.5 to 36.5 degrees, and increased substantially in the anterior and posterior regions with angles greater than 36.5 degrees. Stresses varied from −1.64 MPa at 30.5 degrees to −2.70 MPa at 42.5 degrees in the anterior area of the condyle and from 0.66 MPa at 30.5 degrees to 1.99 MPa at 42.5 degrees in the posterior area (Fig 4). Normal stresses in the articular disc showed tendencies similar to those in the bony structures; however, shear stresses in all the five areas exhibited substantial increases when the angles became greater than 36.5 degrees. In particular, the stresses in the posterior area at maximum were approximately 2.4 times more than those at 30.5 degrees (Fig 5). These findings indicate substantial shear deformation of the articular disc associated with more severe vertical discrepancies.

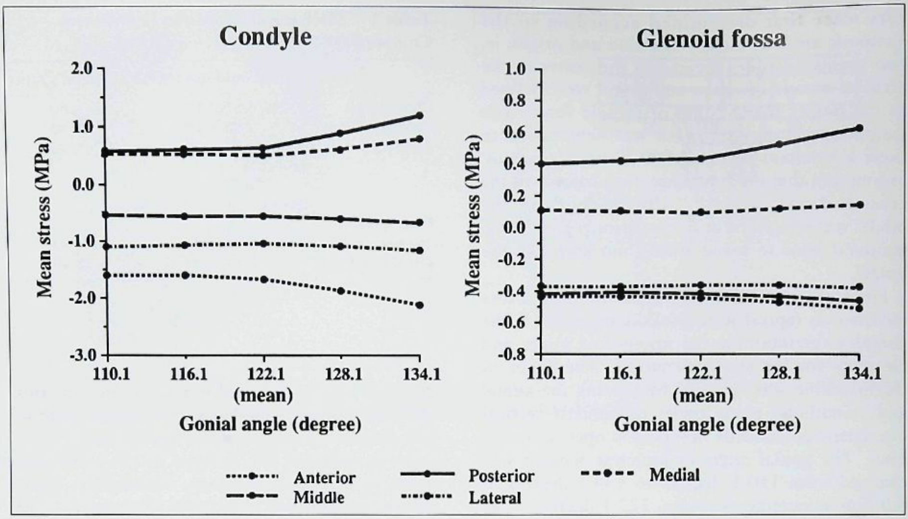


Fig 2 Changes in stresses on the surfaces of condyle and glenoid fossa in association with varying gonial angles.

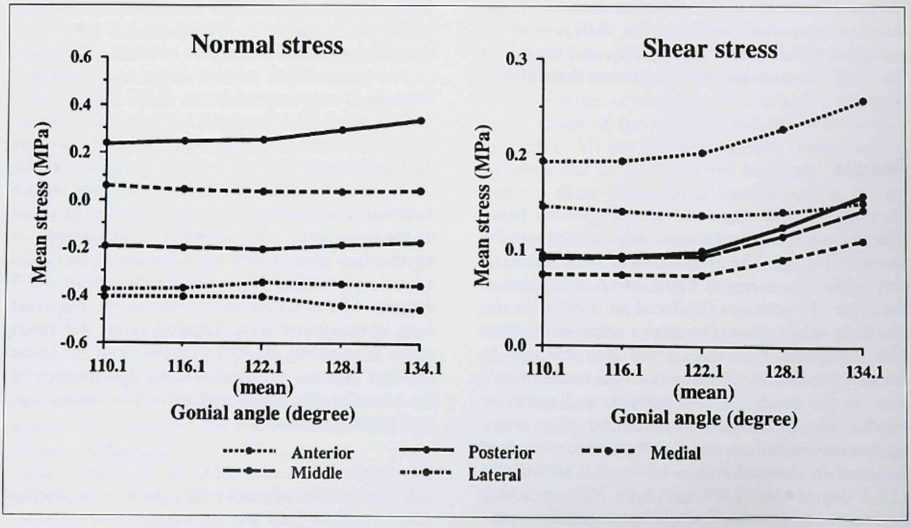


Fig 3 Changes in stresses in the articular disc in association with varying gonial angles.

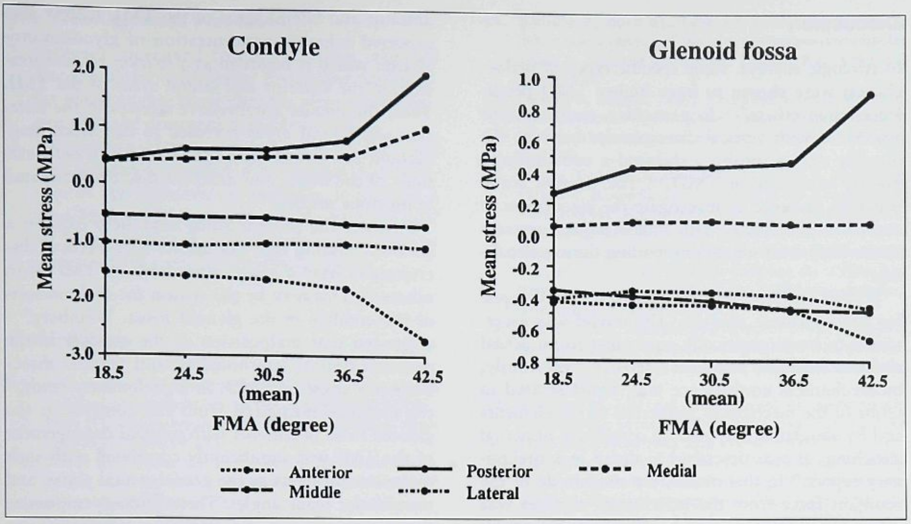


Fig 4 Changes in stresses on the surfaces of condyle and glenoid fossa in association with varying mandibular plane angles (FMAs).

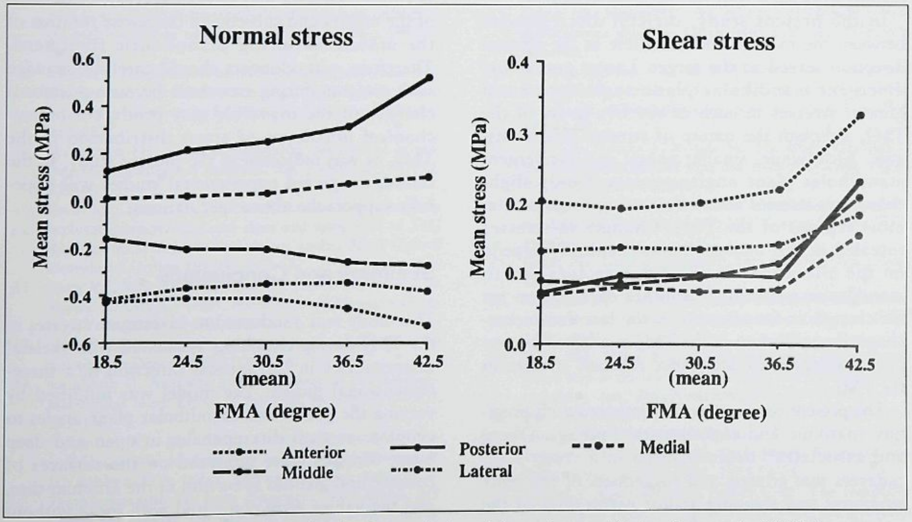


Fig 5 Changes in stresses in the articular disc in association with varying mandibular plane angles (FMAs).

Discussion

In etiologic surveys, some specific types of malocclusion were shown to have higher TMD prevalences than others.[7-10] In particular, malocclusions associated with vertical discrepancies between the maxilla and mandible exhibited a substantially greater incidence of TMD.[7,10] The present study was thus designed to investigate the association of vertical discrepancies with biomechanical stresses in the TMJ with maximum loading during clenching.[14,15]

To this end, an analytic model was developed for finite element analysis. The model was ascertained to be geometrically equivalent to an actual skeleton used as a standard reference.[18] Previously, biomechanical equivalence was demonstrated in terms of the mechanical properties of the elements and by simulating the loading conditions of actual clenching, as was described in detail in a preliminary report.[18] In this model, the magnitude of the resultant force from the masticatory muscles was defined as a constant 500 N. This constant allows for the exclusion of miscellaneous factors in order to study the influences of only the skeletal discrepancies on TMJ loading. It is important to take into consideration that maximal biting force is less in TMD patients than in control subjects when stresses in the TMJ are evaluated. However, the present analysis, as an initial approximation of TMJ loading, provides an insight into the nature of TMJ loading associated with various skeletal factors.

In the present study, skeletal discrepancies between the maxilla and mandible in the vertical direction served as the target. Larger gonial and divergent mandibular plane angles produced greater stresses in each of the five areas of the TMJ, although the nature of stresses was invariable. Meanwhile, smaller gonial and convergent mandibular plane angles generated only slight changes in stresses with a decreasing magnitude in most regions of the TMJ. Changes in stresses revealed in this analysis biomechanically depend on the alterations in the force vectors due to mandibular rotations.[14] Another explanation for the changes in stresses may be the fact that biomechanical equilibrium in the TMJ is affected by vertical discrepancies and hence residual stresses in the TMJ.[14,33]

The present results may be compared with previous anatomic and experimental findings. Oberg and associates[34] demonstrated in a study with cadavers that erosion and ruggedness of the bony structures and thinning and/or perforation of the articular disc were more frequently observed in the anterior and lateral areas of the TMJ. Kopp[35] also reported a higher concentration of glycosaminoglycan, which is regarded as a marker of compression, in the anterior and lateral areas of the TMJ. Thus, the greater compressive stresses in the anterior and lateral areas revealed in this study may account for various findings pertinent to deformations of the bones and articular disc demonstrated in previous studies.[34,35]

Further, the present study may help explain a previous finding that occlusions with vertical discrepancies have a higher prevalence of TMD than others.[7,10] This may be the reason for malpositions of the condyle in the glenoid fossa. Weinberg[36-38] suggested that malposition of the condyle in the anteroposterior, lateromedial, and vertical directions is a cause of TMD. In a preliminary study,[22] the distance measured from the condyle to the glenoid fossa in patients with internal derangement of the TMJ was significantly correlated with such measurement items as the gonial, ramal plane, and mandibular plane angles. These findings emphasize that condylar position is more directly relevant to displacements of the articular disc and the subsequent internal derangement in the TMJ. Further, lack of biomechanical equilibrium in the TMJ induced by the skeletal discrepancies may produce nonlinear or plastic deformation of the articular disc, as is observed in tensile tests of the disc.[27] Clinical implications may also be derived from these observations. Orthodontic patients with vertical discrepancies may easily experience extrusion of the molars and subsequent clockwise rotation of the mandible during orthodontic treatment. Therefore, orthodontists should carefully manage such patients during treatment because positional changes of the mandible may produce a biomechanical imbalance of stress distribution in the TMJ, as was indicated in the present study. In the future, integrated experimental studies will hopefully support the above speculations.

Summary and Conclusions

This study was conducted to investigate stresses in the TMJ during clenching associated with skeletal discrepancies in the vertical direction in a three-dimensional model. The model was modified by varying the gonial and mandibular plane angles to simulate vertical discrepancies in open and deep bites. Stresses were analyzed on the surfaces of condyle and glenoid fossa and in the articular disc, and the values were compared with those without any skeletal discrepancies.

The following results were found:

1. Stresses increased for the condyle, glenoid fossa, and disc with larger gonial and mandibular plane angles; these changes were more obvious with the divergent mandibular plane.
2. The nature of stress distribution in the TMJ was substantially affected by vertical discrepancies of the craniofacial skeleton, indicating a possible model for the association between lack of biomechanical equilibrium and TMD in patients with such skeletal discrepancies.

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Resumen

Distribuciones del Estrés en la Articulación Temporomandibular Cuando los Pacientes con Discrepancias Verticales del Complejo Craneofacial Aprietan Sus Dientes

Este estudio fue diseñado para investigar el estrés en la articulación temporomandibular (ATM) cuando los pacientes con discrepancias esqueléticas en la dirección vertical aprietan sus dientes. Se utilizó un modelo tridimensional de la mandíbula incluyendo la ATM en el análisis del elemento finito para el estrés. El modelo, considerado como un modelo estándar, consistío de 2.088 nudos y 1.105 elementos sólidos, comprendiendo el hueso cortical y canceloso, el disco articular y la capa del cartílago; y el ligamento periodontal. El modelo estándar fue modificado variando los ángulos de los planos goniano y mandibular para simular las discrepancias verticales entre el maxilar superior y el inferior, observadas en las mordidas abiertas y profundas. El estrés fue analizado sobre las superficies del cóndilo, la fosa glenoidea, y el disco articular, y los valores fueron comparados a aquellos encontrados con el modelo estándar. El estrés incrementó substancialmente en el cóndilo, la fosa glenoidea, y el disco articular a medida que los ángulos de los planos goniano y mandibular aumentaban; y aquellos cambios fueron mas obvios cuando estaban asociados a los planos mandibulares divergentes. Por lo tanto, la naturaleza de las distribuciones del estrés en la ATM fue afectada substancialmente por discrepancias verticales del esqueleto craneofacial. También se indica que estos cambios en el estrés producen una falta de equilibrio biomecánico en la ATM, lo cual puede tener alguna asociación con los desórdenes temporomandibulares.

Zusamenfassung

Belastungsverteilung im Kiefergelenk während des Pressens bei Patienten mit vertikalen Abweichungen des Gesichtsschädels

Diese Studie wurde entworfen, um Belastungen im Kiefergelenk während des Pressens bei Patienten mit skelettalen Abweichungen in vertikaler Richtung zu untersuchen. Ein dreidimensionales Modell des unterkiefers einschliesslich des Kiefergelenkes wurde für eine finite Element-Analyse der Belastungen benutzt. Das Modell, als ein Standard-Modell, besteht aus 2088 Knoten und 1105 festen Elementen, einschliesslich des korticalen und trabekulären Knochens, des Discus articularis, der Knorpel-Schicht und des parodontalen Ligamentes. Das Standard-Modell wurde modifiziert, indem Gonionwinkel und Winkel der Unterkieferebene variiert wurden, um vertikale Diskrepanzen zwischen dem Ober- und Unterkiefer zu simulieren, wie sie in offenen und tiefen Bissen beobachtet werden können. Die Belastungen wurden auf den Oberflächen des Kondylus, der Fossa glenoidalis und des Diskus articularis analysiert und die Werte mit jenen verglichen, die im Standard-Modell gefunden worden waren. Die Belastungen für den Kondylus, die Fossa glenoidalis und den Diskus nahmen mit grösserem Gonion- und Kieferbasenwinkel wesentlich zu, und diese Veränderungen verdeutlichten sich mit zunehmender Divergenz. Die Belastungsverteilung im Kieferegelenk wurde von vertikalen Diskrepanzen des Gesichtsskelettes wesentlich beeinflusst. Man geht auch davon aus, dass diese Belastungsveränderungen ein gestörtes biomechanisches Gleichgewicht im Kiefergelenk verursachen können, was einen Zusammenhang mit Myoarthropathien des Kausystems haben mag.