Stress distribution in the temporomandibular joint produced by orthopedic chincup forces applied in varying directions: A three-dimensional analytic approach with the finite element method

Kazuo Tanne, DDS, DDSc,[a] Eiji Tanaka, DDS, DDSc,[b] and Mamoru Sakuda, DDS, DDSc[b]
Hiroshima and Osaka, Japan

Stress distribution in the temporomandibular joint (TMJ) during chincup therapy was investigated by means of a three-dimensional finite element model of the mandible, including the TMJ. An orthopedic chincup force of 400 *gf* (3.92 N) was applied at the pogonion of the mandible in the directions ranging from −50° to 40°, relative to the line connecting the pogonion and condyle. Compressive stresses, widely distributed on the condyle and glenoid fossa and in the articular disk, were larger in the posterior area than in the anterior and middle regions, when the force direction was from −50° to 0°, whereas the forces applied in the remaining directions produced relatively uniform stress distributions. An interesting finding was that tensile stresses were induced in the anterior region of the articular disk, irrespective of force direction, although the remaining areas experienced compressive stresses. It is shown that changes in stresses in the TMJ are highly pertinent to the direction of chincup forces. When the directional angle was around −50°, the variation in stresses in the TMJ was greatest. As the angle was changed to 30° or 40°, the stresses approached a certain level of compressive stress, which indicated the force direction as an optimal application of orthopedic chincup force in terms of biomechanically balanced stress distribution for the TMJ components. (Am J Orthod Dentofac Orthop 1996;110:502-7.)

For the treatment of mandibular prognathism, orthopedic approaches with chincup have been successfully used in clinical orthodontics since the nineteenth century for controlling mandibular growth of patients manifesting such skeletal features as large anteriorly positioned mandibles.[1-3]

The effects of chincup force on craniofacial growth, in particular that of the mandible, have been well documented in the publications.[4-12] Redirection and inhibition of mandibular growth, backward repositioning of the mandible and remodeling of the mandibular shape were described in cephalometric studies.[4-8] Experimental studies showed retardation of ramal growth, closure of the gonial angle, and decrease of the prechondroblastic layer of the condyle.[9-12]

These changes are assumed to be due to mechanical stimuli to the cartilaginous layer of the condyle or to the entire mandible, such as for long bones with a similar structure.[13-16] Thus biomechanical components such as strains or stresses from orthopedic forces should be studied to further explore the association with morphologic changes of the mandible. Such investigations may be of great importance in further elucidating the mechanism of remodeling of the mandible, providing orthodontists with clinical implications for orthopedic chincup therapy.

This study was designed to investigate by means of finite element analysis, the nature of stress distributions in the temporomandibular joint (TMJ), produced by chincup forces applied in varying directions.

MATERIALS AND METHODS

A three-dimensional model of the mandible, including the TMJ, was developed for stress analysis with the finite element method (FEM). A dried young human skull was cut into transverse sections of approximately 10 mm in thickness, parallel to the Frankfort horizontal plane. Photographs were taken of the sections and then traced precisely on acetate paper. All the sections were divided into a finite number of elements and stacked perpendicular to the Frankfort horizontal plane. During

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[a]Department of Orthodontics, Hiroshima University School of Dentistry, Hiroshima.
[b]Department of Orthodontics, Osaka University Faculty of Dentistry, Osaka.
Reprint requests to: Dr. Kazuo Tanne, Department of Orthodontics, Hiroshima University School of Dentistry, 1-2-3 Kasumi, Minami-Ku, Hiroshima 734, Japan.

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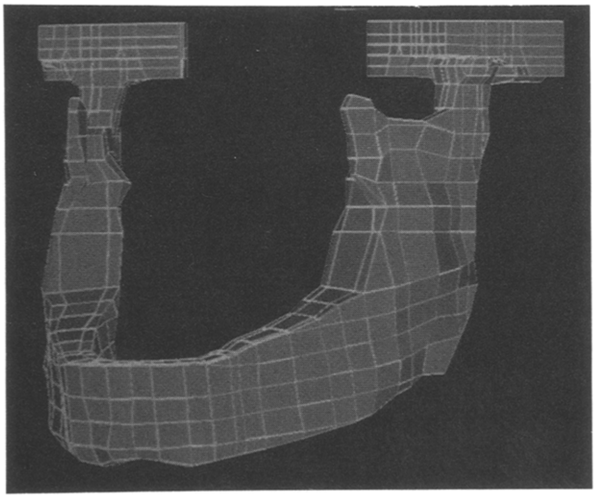

Fig. 1. Three-dimensional FEM model of mandible including TMJ. Model is fixed at superior region of temporal bone.

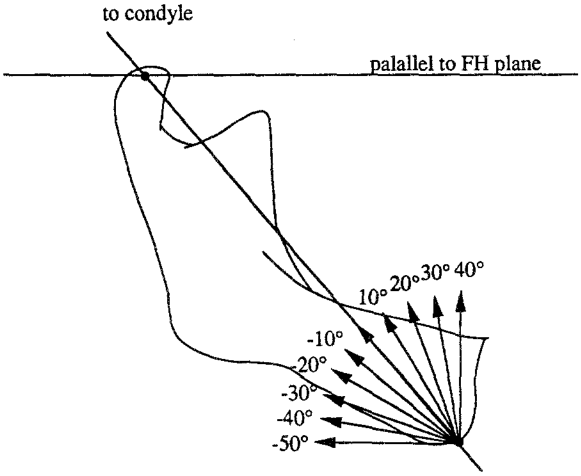

Fig. 2. Direction of chincup forces relative to line connecting condyle and pogonion of mandible.

Table I. Mechanical properties of various component in the model

Material	*Elastic modulus (MPa)*	*Poisson's ratio*
Compact bone	1.37×10^4	0.30
Cancellous bone	7.93×10^3	0.30
Articular disk	4.41×10	0.40
Articular cartilage	7.90×10^{-1}	0.49

All the materials in the model are assumed elastic and isotropic therefore the relevant parameters, elastic modulus, and Poisson's ratios, are defined for each material according to previous experimental data.[20-23]

the procedures described above, shapes of the elements were repeatedly modified to satisfy geometrical equivalence of the model to the actual skeleton. The TMJ comprises the condyle, glenoid fossa, and articular disk and cartilaginous layer. An articular disk was constructed as a biconcave shape between the mandibular condyle and glenoid fossa of the temporal bone to occupy the TMJ space with an average thickness of 2.0 mm.[17] The articular cartilaginous layer of 0.2 mm thickness was established to cover the surfaces of the condyle and the glenoid fossa.[18] Finally, construction of the model was completed, consisting of 2088 nodes and 1105 solid elements (Fig. 1).[19]

The mechanical properties of the compact and cancellous bones, articular disk and cartilaginous layer in the model were defined according to experimental data in previous studies,[20-23] as shown in Table I. The model was fixed at the superior region of the temporal bone to prevent a sliding movement of the model. On the occlusal plane of the lower dentition, vertical displacements were restrained within a range of the mean periodontal ligament space or approximately 0.25 mm. For the loading condition, an orthopedic force of 400 *gf* (3.92 N) was applied analytically at the pogonion of the mandible in the model in varying directions from −50° to 40°, relative to the line connecting the condyle and pogonion (Fig. 2), to simulate clinical application of chincup to adolescent patients with mandibular prognathism.

Stress analysis was executed on a personal computer system (PC-9801 VM, NEC Corp., Tokyo) with a FEM program ANSYS (Swanson Analysis Systems Inc., Houston, Texas). Stresses induced in the TMJ by a chincup force were compressive in nature in a preliminary study,[24] therefore the minimum principal stress was investigated for the condyle and glenoid fossa. For the articular disk, normal and shear stresses derived from three principal stresses were evaluated.[25] Further, these stresses were investigated for each of the anterior, middle, posterior, medial, and lateral areas of the TMJ, which were defined on the basis of anatomic findings by Rees.[26]

RESULTS

Stress distributions on the condyle are shown in Fig. 3. Compressive stresses were produced widely in the five areas. In the anteroposterior direction: compressive stresses in the posterior area (approximately -5.5 to -3.0×10^{-2} MPa) were larger than those in the anterior and middle regions when the force direction was from −50° to 0°. The forces applied in the remaining directions produced relatively uniform stress distributions, although stresses in the anterior region became slightly greater than in the posterior and middle areas. In the mediolateral direction, stress distributions were more uniform in comparison with the previously mentioned changes in the anteroposterior direction. In the lateral, middle, and medial regions, compressive stresses were larger in the lateral and medial regions than in the middle area when more horizontally directed forces were applied.

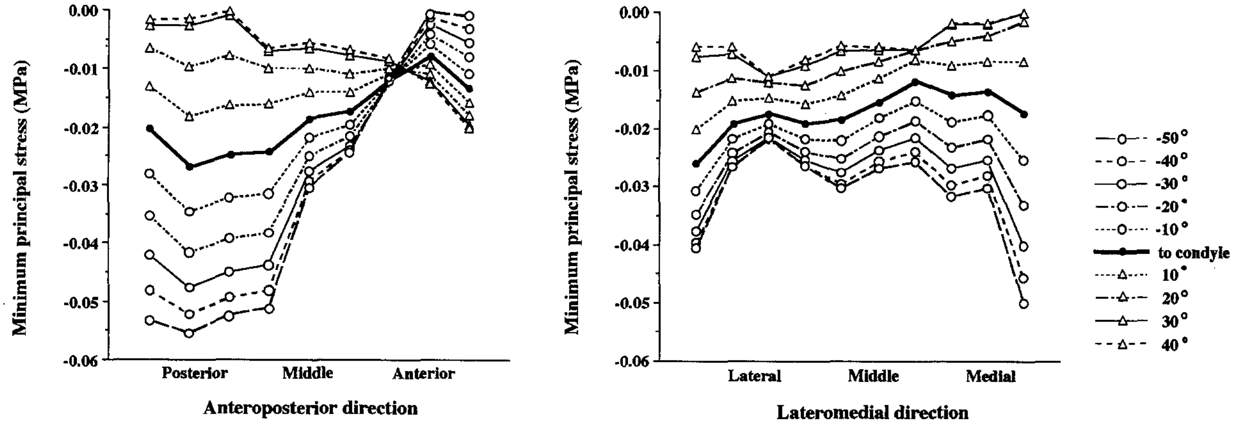

Fig. 3. Stress distributions on surface of condyle.

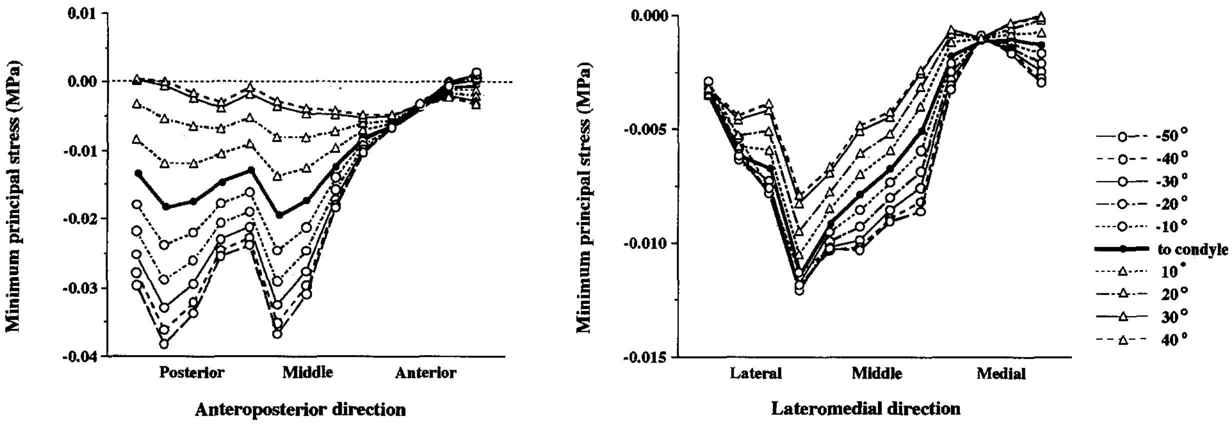

Fig. 4. Stress distributions on surface of glenoid fossa.

A similar tendency in stress distribution was observed on the surface of the glenoid fossa, which excluded the stresses in the middle region (Fig. 4). Compressive stresses were greater in the middle area than in the lateral and medial regions. Meanwhile, upward forces produced more uniform stress distributions in the five areas, although variation in stresses in the lateral, middle, and medial regions was still substantial.

Fig. 5 shows stress distributions in the articular disk. Normal stresses were the greatest in the posterior area (approximately -2.5 to -1.0×10^{-2} MPa) when the forces were applied in the directions from $-50°$ to 0°, and the stress distributions became more uniform as the direction became more superior. It is interesting that tensile normal stresses were induced in the anterior area, irrespective of force direction. Another finding was that stresses approached a constant level at two transitional zones from the posterior to middle and from the middle to anterior region. Meanwhile, shear stresses gradually approached a uniform level of approximately 2.0×10^{-3} MPa as the directional angle changed from $-50°$ to 40°.

Fig. 6 shows changes in stresses in the five areas of the articular disk associated with varying directions of chincup forces. When the directional angle was round $-50°$, the variation in stresses in the five areas was the greatest. As the angle became 30° to 40°, the stresses exhibited a constant level, indicating more balanced stress distribution.

DISCUSSION

For growing patients with mandibular prognathism, orthopedic chincup therapy is of great significance in terms of controlling or redirecting craniofacial growth. Morphologic and biologic changes of the mandible from orthopedic chincup forces have been investigated extensively by means of cephalometric and experimental studies.[4-12,27-29]

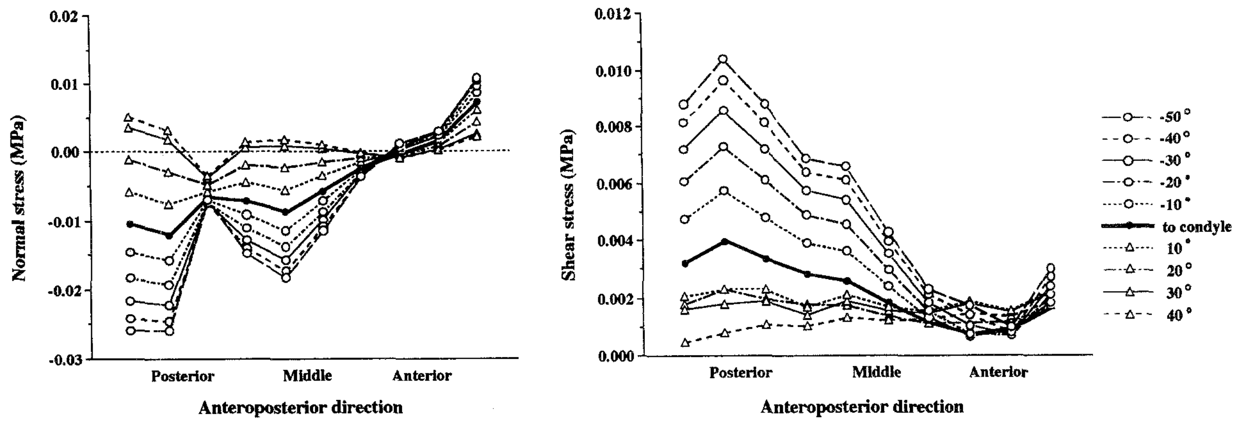

Fig. 5. Stress distributions in articular disk.

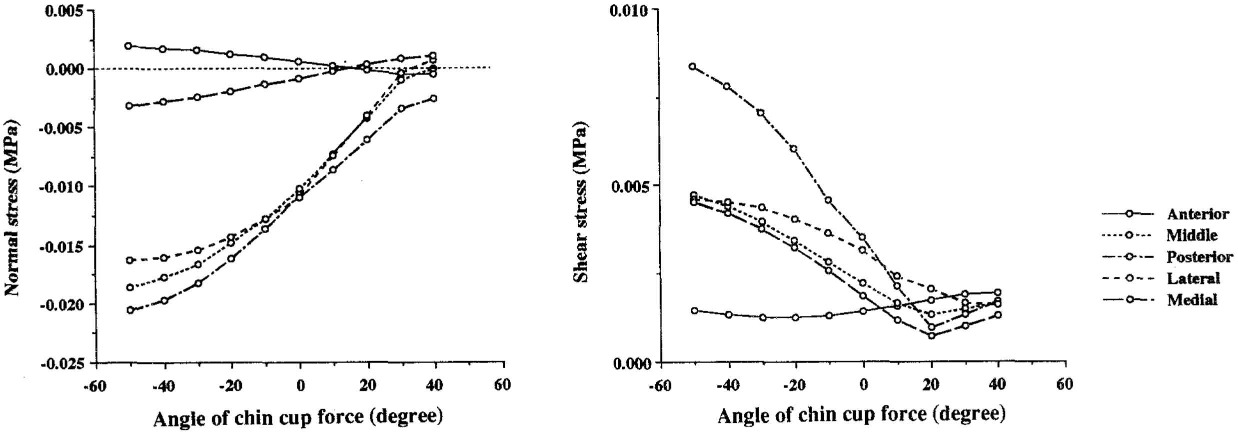

Fig. 6. Changes in stresses in five areas in association with varying directional angles to line described in Fig. 2.

These studies revealed backward repositioning, no substantial change in the dimension, remodeling of the ramus and gonial angle, and decrease in prechondroblastic layer on the condyle. A significant change of the cranial flexure angle was also shown,[30] which indicated an orthopedic effect of chincup forces on the midcranial fossa. From these morphologic changes of the mandible, an assumption that compressive stress on the condyle is related to inhibition of condylar growth of the mandible may be derived.

To explore the association between mechanical stress and bone remodeling, biochemical and biomechanical studies have been carried out. A biochemical approach has demonstrated that hydrostatic compressive force of $-50 g/cm^2$ (-4.9×10^{-3} MPa) and -100 g/cm^2 (-9.8×10^{-3} MPa) produced maximum increase of 30% in DNA synthesis and 60% in glycosaminoglycan synthesis for cultured chondrocytes from mandibular condylar cartilage,[31] which is contrary to the hypothesis. Biomechanical studies have revealed that principal stress or the relevant strain energy density is a key determinant to remodeling of the alveolar and craniofacial bones incident to functional and orthopedic forces.[16,32,33] For long bones, it is also indicated that mechanical strains from functional or dynamic forces play a role in altering the shape of bones.[13-16,33] With respect to the association between bone remodeling and stresses, the following sequence is postulated. Compressive and tensile stresses generate different electrical potentials that further activate osteoclasts and osteoblasts in the stressed areas. Then, remodeling of bones, such as resorption and deposition, will be produced by the cellular activity. However, details of the mechanism are still unclear and hence biomechanical, histologic, and biochemical approaches should be integrated in future studies.

The model used in this study was developed, based on a dried young human skull with acceptable normal occlusion and craniofacial structure. Further, a refinement of the model was executed in terms of the size and shape of the mandible. For the TMJ, biconcave shape of the articular disk with nonuniform thickness was also represented. Because static loading in the TMJ was studied in this study, all the materials of the model were assumed elastic and isotropic; therefore the relevant parameters, such as elastic modulus and Poisson's ratio, were determined according to previous experimental data. Thus it is indicated that the model may be used as an analytic model with standard shape and mechanical behavior, as was shown in a previous study.[19] Therefore the results obtained in this study could provide insight into the stress distributions in the TMJ produced by chincup forces, because little information is available on this subject.

Stresses on the condyle and in the articular disk in this study were approximately -5.5×10^{-2} and -3.0×10^{-2} MPa at maximum, respectively. It could not be determined whether these values are optimal. However, it should be noted that the nature of stress distributions is influenced by the direction of chincup forces and the most balanced stress distribution is achieved by a slightly superiorly directed force.

Another concern in chincup therapy is whether the treatment is pertinent to the occurrence of temporomandibular disorder (TMD). As experienced in clinical orthodontics, chincup force surely induces mandibular or condylar position in a more superior or posterior vector.[4,6,8,28,29] Condylar position relative to the articular eminence and glenoid fossa is one of the etiologic considerations of TMDs,[34-36] internal derangement of the TMJ in particular. Further, stresses in the articular disk were compressive and tensile in the posterior and anterior areas, respectively, although both the stress levels were within the elastic range or less than 1.5 MPa, as revealed in a preliminary report.[22] Therefore it is possible that these positional changes of the mandible or condyle and biomechanical alterations of the articular disk during chincup therapy may lead to internal derangement of the TMJ if orthopedic mandibular retractive forces are applied to patients essentially involved in abnormal positional relation between the condyle and articular disk. However, such cause-effect concerns may be relieved by the finding that the maximum stress levels exerted by chincup forces are substantially smaller than those during normal jaw functions such as clenching and chewing.[19,37,38] Thus chincup therapy is not likely to induce any serious problem in terms of stress levels in various TMJ components, if anatomic relations between various TMJ components are maintained. It is of value for orthodontists to understand that biomechanical equilibrium in the TMJ is achieved by somewhat upward chincup forces, relative to the condyle-pogonion line. Such application of chincup force would also produce optimal changes in the mandible and on the condyle without producing a lack of biomechanical equilibrium in the TMJ space.

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