Original Article

Influence of Friction at Articular Surfaces of the Temporomandibular Joint on Stresses in the Articular Disk: A Theoretical Approach with the Finite Element Method

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Abstract: The present study was designed to assess stress and displacement of the temporomandibular joint (TMJ) disk during jaw opening with different frictional coefficients (μ) from 0.0001 to 0.5 at the TMJ disk and bony component interfaces using three-dimensional finite element (FE) models of individual TMJs based on magnetic resonance (MR) images. An asymptomatic female volunteer and a female patient with anterior disk displacement without reduction were selected, and serial sagittal and frontal slices of their MR images were used for the TMJ reconstruction procedure. The condylar movement was recorded during jaw opening by a Gnatho-hexagraph and used as the loading condition for the subsequent stress analysis of the model. In the asymptomatic subject, relatively high von Mises stresses were observed in the anterior and lateral regions of the disk during jaw opening, and the superior boundary, contacting with the glenoid fossa, exhibited lower stresses than those on the inferior boundary facing the condyle. In the symptomatic subject, although the stress value in the disk was relatively low, the posterior connective tissue exhibited high stress throughout jaw opening. Additional increments in stress values and disk displacement were observed as the coefficient of friction increased, especially in the asymptomatic subject. It is concluded that an augmentation in the friction between the disk, glenoid fossa, and condyle produces an increment in stress and displacement of the disk. (*Angle Orthod* 2003;73:319–327.)

Key Words: TMJ stress; Finite element method; Jaw opening; Joint friction

INTRODUCTION

The temporomandibular joint (TMJ) is well known as a load-bearing organ in the human body. The articular surfaces are highly incongruent, which provides the mandibular condyle with a large degree of mobility.[1] The articular disk is placed between the articular surfaces, and this is assumed to decrease the contact pressure on the bone components by increasing the contact area between the incongruent joint surfaces.[2]

The role of the TMJ disk in the progression of TMJ disorders is controversial. It has been postulated that disk displacement precedes the onset of degenerative changes in the TMJ.[3] The high association of articular degeneration with disk malposition has led some investigators to suggest that the degenerative process predisposes disk displacement.[4]

In previous studies, several theoretical approaches have been attempted to better understand the biomechanical environment in the TMJ.[5–7] The finite element (FE) method has proven to be a useful tool for examining these mechanical quantities in structures with complex geometry.[8] Chen and Xu[5] and Devocht et al[9] developed two-dimensional FE models of the TMJ in order to simulate the condylar motion relative to the glenoid fossa. These analyses, however, were limited to the two-dimensional sagittal plane and thus unavailable for investigating the three-dimensional

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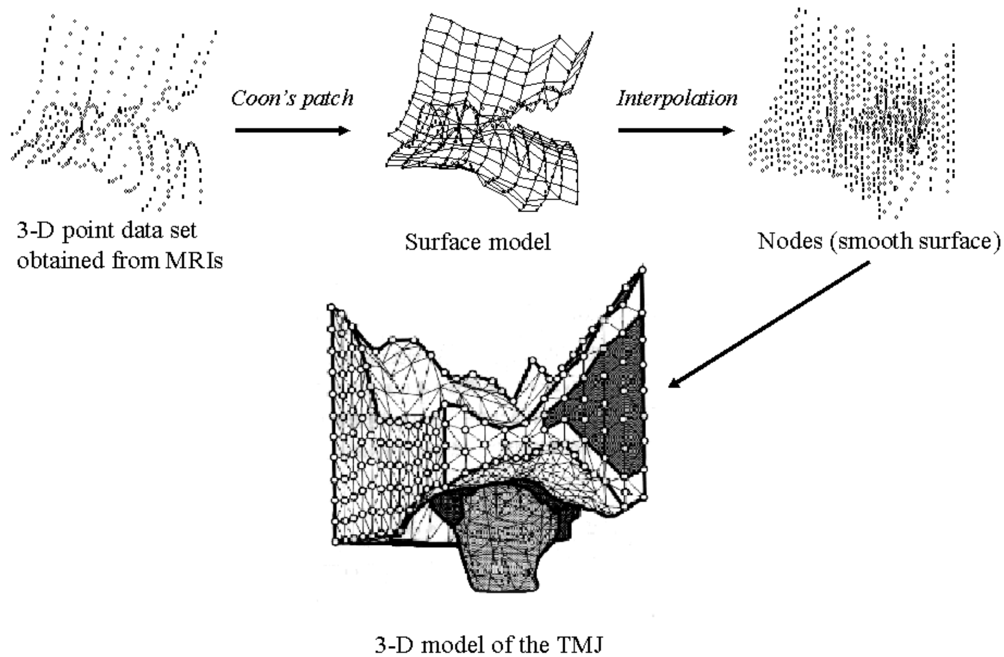


FIGURE 1. Reconstruction procedure of the smooth surface of the TMJ components.

distribution of the stresses induced in the TMJ. Lately, a three-dimensional reconstruction of the TMJ has been developed, and a few analyses of the TMJ stress using three-dimensional FE models have been published.[10,11] These analyses enable us to construct a geometrical model, and these models have provided information about various stresses induced in the TMJ.

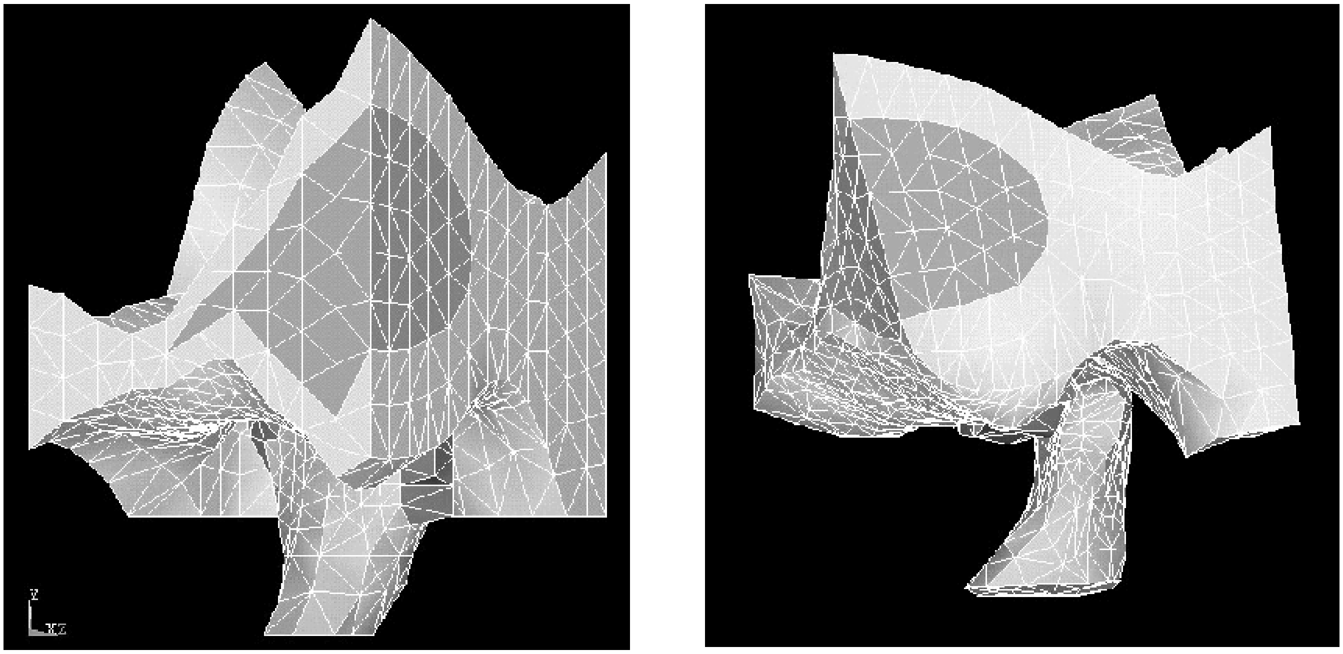
The condylar movement during jaw opening produces marked disk motion. When the disk slides along the articular surfaces during jaw opening, shear loading of the disk has been considered negligible because of the very low friction.[12] Furthermore, owing to the presence of synovial fluid, the coefficient of friction in the joint can assumed to be almost zero.[13,14] Degradation of the hyaluronic acid (HA) in the synovial fluid is associated with a decrease in viscosity; however, only solid contact may exist between the articular surfaces if there is no boundary lubrication between them, and this will result in an increase of the frictional coefficient.[13–16] The influence of the frictional coefficient upon disk dynamics, therefore, is of great importance for understanding the onset of TMJ internal derangement. Because of the three-dimensional contact problems that arise in modeling with such a complex geometry as the TMJ, three-dimensional analysis of TMJ stresses induced during jaw opening has not been conducted yet.

Recently, we developed an individual three-dimensional modeling program for the TMJ based on magnetic resonance (MR) images.[17] In this study, three-dimensional FE models of the human TMJ were developed based on MR images of a symptom-free volunteer and a symptomatic patient with anterior disk displacement without reduction using the modeling program. Thus, the purpose of this study was to evaluate the influence of friction between articular surfaces on the biomechanical responses in the disk during jaw opening.

MATERIALS AND METHODS

Geometric reconstruction of TMJ components and FE discretization

An adult female volunteer with no history of present or past TMJ disorders and a symptomatic subject with internal derangement of the TMJ were selected for this study. The symptomatic subject exhibited anterior disk displacement without reduction. MR images were taken at maximum intercuspation. The three-dimensional FE models were constructed based on contiguous sagittal and coronal slices of the MR images. The outline of reconstruction technique is given below. The three-dimensional reconstruction of the TMJ components was conducted separately using the data sets of sagittal and coronal slices. Surface model S was defined based on the three-dimensional point data set P of the glenoid fossa and condyle. Four adjacent points were selected from the point data set P in such a way that those points served as corners of a quadrate for Coon's patch of a bicubic function. This enabled us to have a smooth surface model of the entire bony components of the TMJ, and the patched surface model represented the reconstructed cortical surface. A surface patch was divided into smaller k $\times$ k subpatches in order to refine the discretized surface model (Figure 1). The upper boundary of the articular disk was the contour of the glenoid fossa and articular eminence,



(A) (B)

FIGURE 2. Three-dimensional FE models of TMJ. (A) Asymptomatic subject model. (B) Symptomatic subject model.

and the lower boundary was the articular surface of the condyle. As a result, the two point data sets Ps and Pc were obtained in different coordinate systems from the images from the sagittal and coronal slices, respectively. Because the intersectional points of the imaged sagittal and coronal slices are commonly included in Ps and Pc, the parameters of the coordinate transformation between the two coordinate systems of the sagittal and coronal images were determined. As a result, the distance of the intersectional points of Ps and those of Pc′ transformed from Pc were minimized. By referring to both the sagittal and coronal slices, interpolated contours by Ferguson's curve for Pc′ and Ps were averaged, and the resultant data set P* was obtained for the three-dimensional geometry of the TMJ components. The shapes of the lateral and medial end portions of the condyle and articular disk could not be traced from the sagittal slices of the MR images. Therefore, the shapes of the lateral and medial portions were determined only using the set of coronal slices.

With regard to the FE modeling of the bony components, a constant thickness of one mm was considered for each of the subpatches toward the inner normal direction of the surface model, making tetrahedrons along the surface of the bony components. These tetrahedrons worked as four-node FEs for the cortical bone. The interior surface of the discretized cortical shell was also divided into FEs of a tetrahedron for the cancellous bone. Concerning the articular disk, the upper and lower boundaries were modeled based on the shapes of the articular surfaces, and interface elements were placed at the bone-disk interface so as to allow the disk to deform and to move tangentially between the articulating surfaces without penetration. The articular capsule was modeled through anatomical consideration because of the detective limit of the MR images. The cavity adjacent to the articular disk was equivalent to the connective tissue.

As a result, the number of nodes was 1047 in the glenoid fossa, 380 in the condyle, and 697 in the soft tissues including the articular disk. The TMJ models had 2024 nodes and 8056 elements in all (Figure 2).

TABLE 1. Material Properties

	Elastic Modulus (MPa)	Poisson's Ratio
Cortical bone	13,700	0.30
Cancellous bone	7930	0.30
Articular disc	44.1	0.40
Connective tissue	0.49	0.49
Articular capsule	0.49	0.49

Conditions for jaw opening analysis

Using the developed models, the analysis of stress in the TMJ during jaw opening was conducted. The material properties of the TMJ components used in this analysis were determined as summarized in Table 1 by referring to pre-

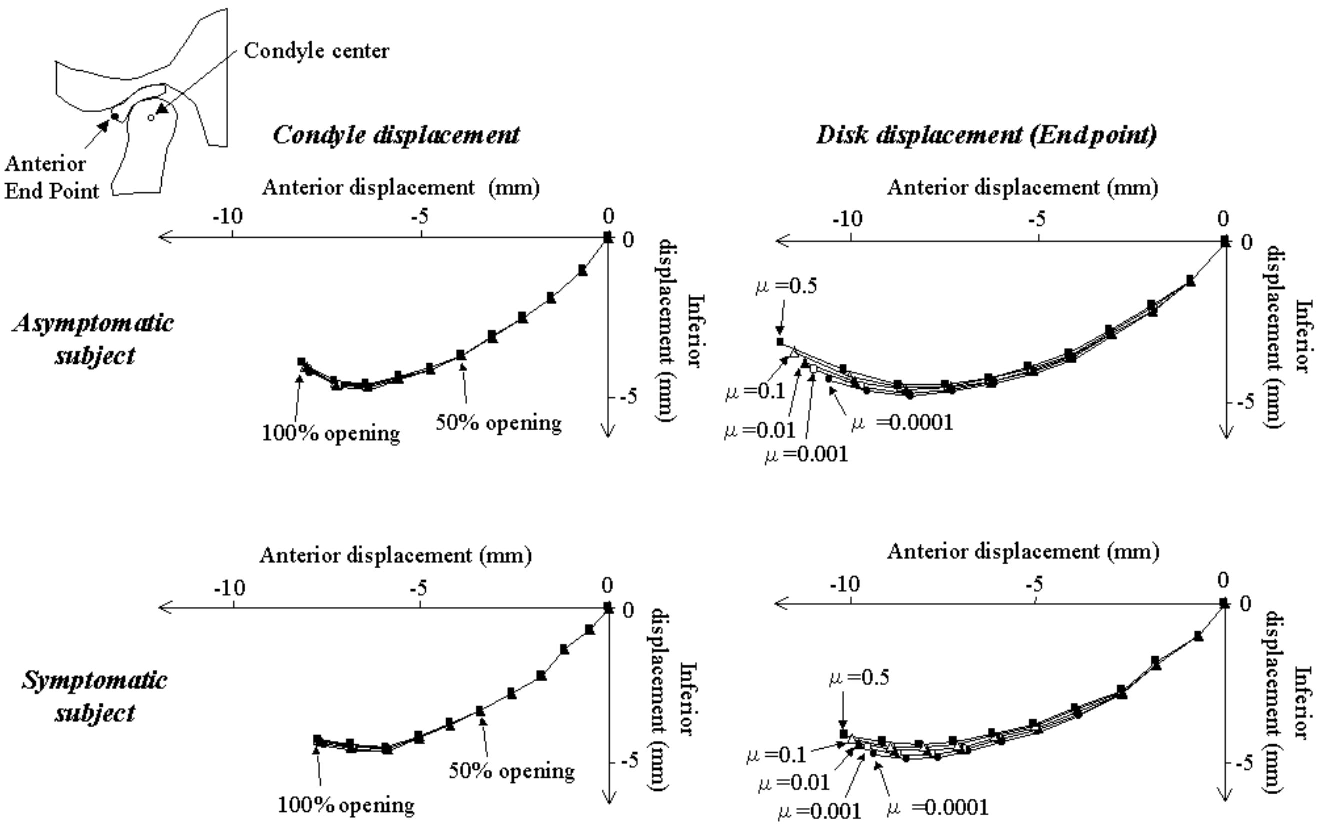


FIGURE 3. Displacements of the condylar center and the anterior end point of disk. Friction coefficient: ● indicates 0.0001; ○, 0.001; ▲, 0.01; △, 0.1; ■, 0.5.

vious studies.[7,17] The fixed boundary condition was assigned to the peripheral nodes of the glenoid fossa, so the TMJ model was restrained at the superior region of the temporal bone to avoid a sliding movement of the entire model. As the loading condition, as described by Chen and Xu,[5] the condylar displacement was enforced at the distal end of the condylar part, which was referred to as the condylar neck area.

The condylar movements during mouth opening were recorded by use of the Gnatho-hexagraph (JM-1000, Ono Sokki Co, Yokohama, Japan).[18] By enforcing this movement to the distal end of the condyle model, the FE model of the condyle moves incrementally along the condylar trajectory recorded by the Gnatho-hexagraph system. The stress/strain in the equilibrium position at rest was defined as the baseline environment because it is still unknown whether the TMJ disk is preloaded when the jaw is in the closed position. With such a condylar displacement specified, the disk was forced to move by the stretched ligaments and the pressure exerted between the condyle and the glenoid fossa. In this analysis, the von Mises stress distributions in the TMJ soft tissues were evaluated from the intercuspal position (0% opening) to maximum jaw opening (100% opening) with 10% increments of opening.

With respect to the frictional coefficient at the bone-disk interface, the parametric study was conducted for values ranging from $\mu = 0.0001$ to 0.5 because the frictional coefficients in the other synovial joints reported previously scattered between 0.001 and 0.3.[13,14,19] In addition, the influence of biomechanical response to the frictional coefficient in the TMJ was evaluated from the displacement and resultant stresses in the TMJ disk.

RESULTS

For the asymptomatic subject, sliding movement occurred along the upper and lower boundaries of the disk and connective tissues; nevertheless, no penetration of the disk either into the fossa or the condyle was observed. Meanwhile, in the symptomatic subject the disk was pushed forward during jaw opening, and the disk deformed progressively.

At the fully opened joint position, ie, 100% jaw opening, the position of the condylar center was almost the same regardless of the value of friction coefficient examined. On the contrary, the anterior end point of the disk exhibited different positions at 100% jaw opening, depending on the value of the friction coefficient (Figure 3). Especially in the asymptomatic subject, the anterior end of the disk was displaced more when the friction coefficient was greater.

The series of stress analyses conducted had a common characteristic in that a progressive elevation of the frictional

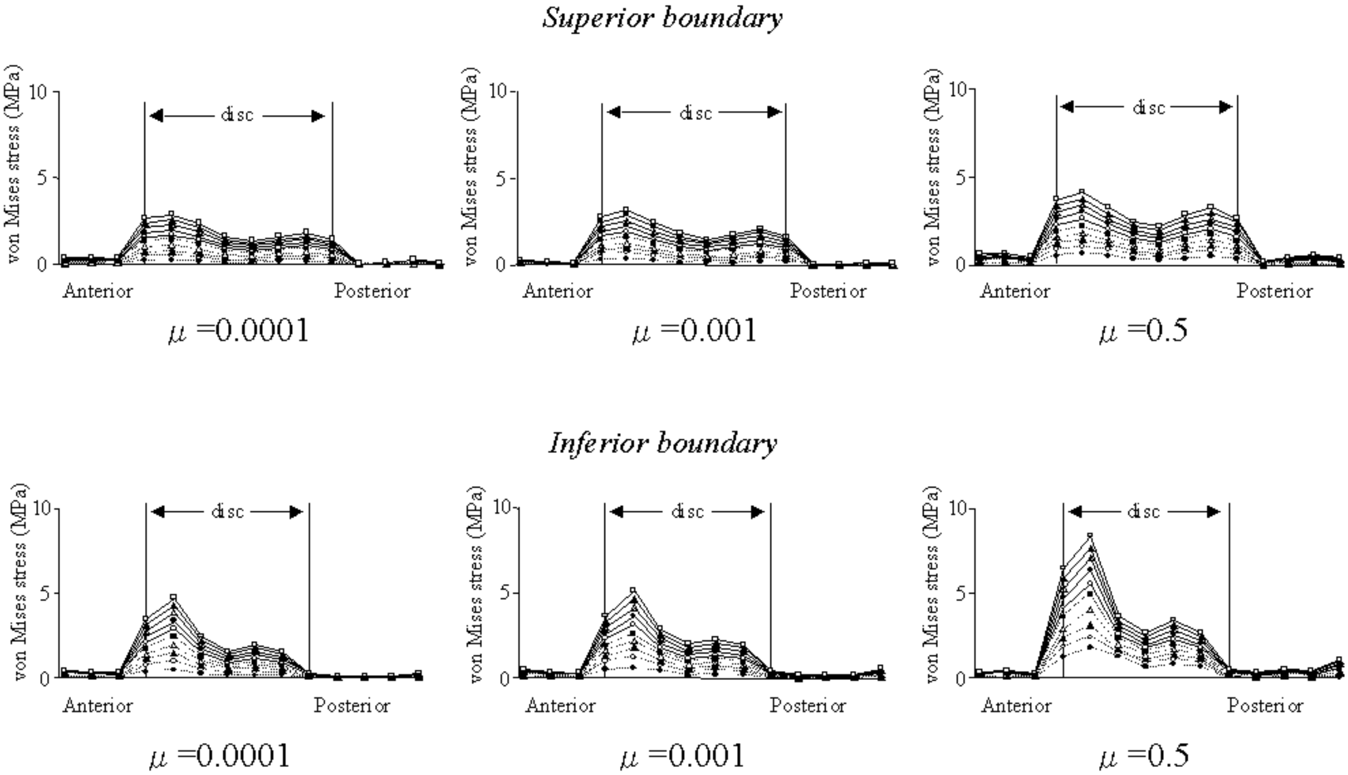


FIGURE 4. The von Mises stress distribution in the anteroposterior direction on the surfaces of the disk and connective tissue of the asymptomatic subject at jaw opening increments (%). - -●- - indicates 10%; - -○- -, 20%; - -▲- -, 30%; - -△- -, 40%; - -■- -, 50%; —○—, 60%; —●—, 70%; —△—, 80%; —▲—, 90%; —□—, 100%.

coefficient was followed by a proportional increase in the von Mises stress values. This phenomenon was also observed throughout the jaw opening from the closed position up to the 100% jaw opening, and these stress levels were greater on the inferior boundary than on the superior boundary.

For the asymptomatic subject, the von Mises stress distribution in the disk in the anteroposterior direction showed that larger stresses were concentrated in the anterior region of the superior and inferior boundaries (Figure 4). In the mediolateral direction, stress values were greater in the medial region on the inferior boundary and in the lateral region on the superior boundary (Figure 5). With regard to the connective tissues, stress values in the course of 0% to 100% jaw opening showed stress values that were smaller than those in the TMJ disk. Meanwhile, for the symptomatic model, relatively high stresses were found in the middle and posterior areas of the disk at the beginning of jaw opening, and the stress level increased during opening (Figures 6 and 7). With respect to the posterior connective tissues, the stress level for the symptomatic subject was higher than that for the asymptomatic subject. In particular, the region adjacent to the posterior band of the disk exhibited a relatively high stress even at the beginning of jaw opening. The von Mises stresses in the disk and connective tissues were found to follow the same pattern during jaw opening and increased with an increase in the frictional coefficient.

DISCUSSION

It is generally recognized that the increase in friction in synovial joints is caused by a change in the lubrication mechanism.[20,21] HA is one of the principal components of synovial fluid, constituting 0.14–0.36% in normal subjects.[22] Some investigators have reported that hyaluronate alone is the primary constituent of synovial fluid responsible for lubrication of the diarthrodial joint.[19,23] Although the exact role of HA in synovial fluid is unclear, injection of HA into joints improves mobility and suppresses pain and inflammation.[24,25] On the other hand, the lubricating ability in the synovial joint has not been dependent upon the concentration of HA and the molecular weight of HA.[25] With regard to the frictional coefficient as a lubricating characteristic, no appropriate information has been reported for the TMJ. In other synovial joints, the frictional coefficients between the surfaces of cartilage were within the range of 0.001–0.1.[13,14,21,25]

Variations in the frictional coefficients were dependent not only on the lubricant but also on the duration of the applied load. Forster and Fisher[13,14] investigated the influ-

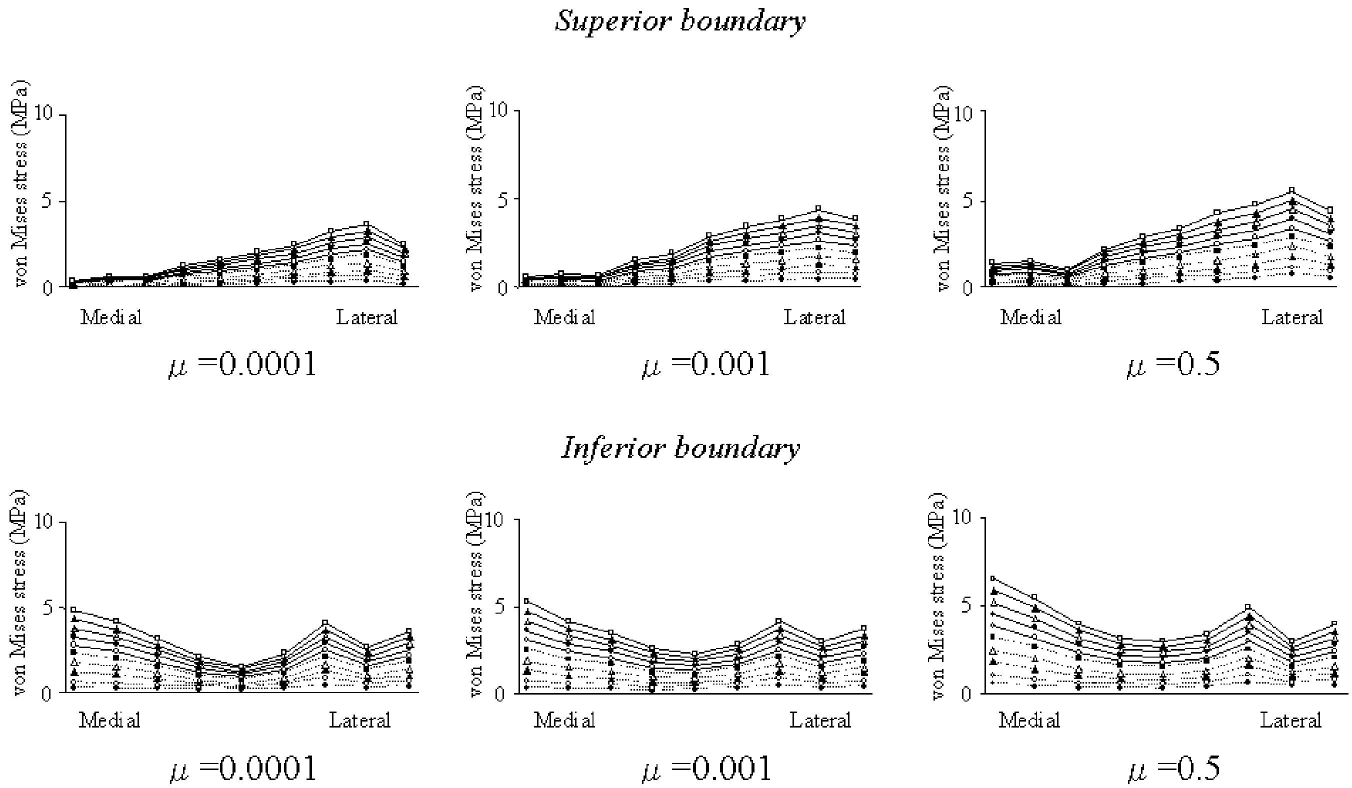


FIGURE 5. The von Mises stress distribution in the mediolateral direction on the surfaces of the disk and connective tissue of the asymptomatic subject at jaw opening increments (%). - -●- -, indicates 10%; - -○- -, 20%; - -▲- -, 30%; - -△- -, 40%; - -■- -, 50%; —○—, 60%; —●—, 70%; —△—, 80%; —▲—, 90%; —□—, 100%.

ence of loading time on the frictional coefficients of articular cartilage and demonstrated that the coefficient of friction rose gradually with increasing stationary loading time, up to a value of approximately 0.3 at 45 minutes upon cartilage-on-cartilage contact and up to 0.5 at 120 minutes upon cartilage-on-metal contact. Therefore, the coefficient of friction in the TMJ model of this study was determined and used in the range of 0.0001–0.5.

The displacement of the disk gradually increased with the elevation of the frictional coefficient between the disk and articular surface, accompanied by an increase in stress values. Consequently, the von Mises stress was strongly augmented in the entire region of the disk as the frictional coefficient increased and the mandibular movement progressed. This scalar quantity is commonly used to represent the total stress to which the articular disk is being subjected and is, therefore, a reasonable indication of where wear or failure can be expected to occur. According to the present study, relatively high stresses were observed in the anterior (anteroposterior direction) and lateral (mediolateral direction) regions of the disk during jaw opening, and therefore, we could speculate that wear might occur in these regions. Furthermore, the superior boundary in contact with the glenoid fossa was subjected to lower stresses than those in the inferior boundary facing the condyle. Therefore, stress distribution in the TMJ is substantially influenced by the increase of the frictional coefficient as reported by previous studies.[13,26]

Most internal derangements of the TMJ exhibit an abnormal functional and anatomical relationship between the disk and bony components. The displaced disk is subject to excessive or dysfunctional loading during clenching,[7] and subsequently, the repeated loadings presumably induce perforation of the posterior disk attachment.[27] The major factor inducing disk displacement, however, is still unclear, although TMJ internal derangements are considered to be multifactorial diseases. In the initial stage of TMJ internal derangements, an inflammatory or dysfunctional biomechanical environment is incident in the TMJ.[4] A dysfunctional environment such as sustained prolonged loading is presumably associated with an increase in the friction coefficient. As mentioned previously, only solid contact may exist between the TMJ disk and the articular surface after prolonged loading, and there is probably no boundary lubrication between them. In addition, Forster and Fisher[13] used laser profilometry to compare the surface roughness of the articular cartilage before and after a continuous load. They demonstrated a significant increase in surface roughness from Ra = 0.8 micron to Ra = 2.1 micron. Thus, they confirmed that surface wear was occurring after a contin-

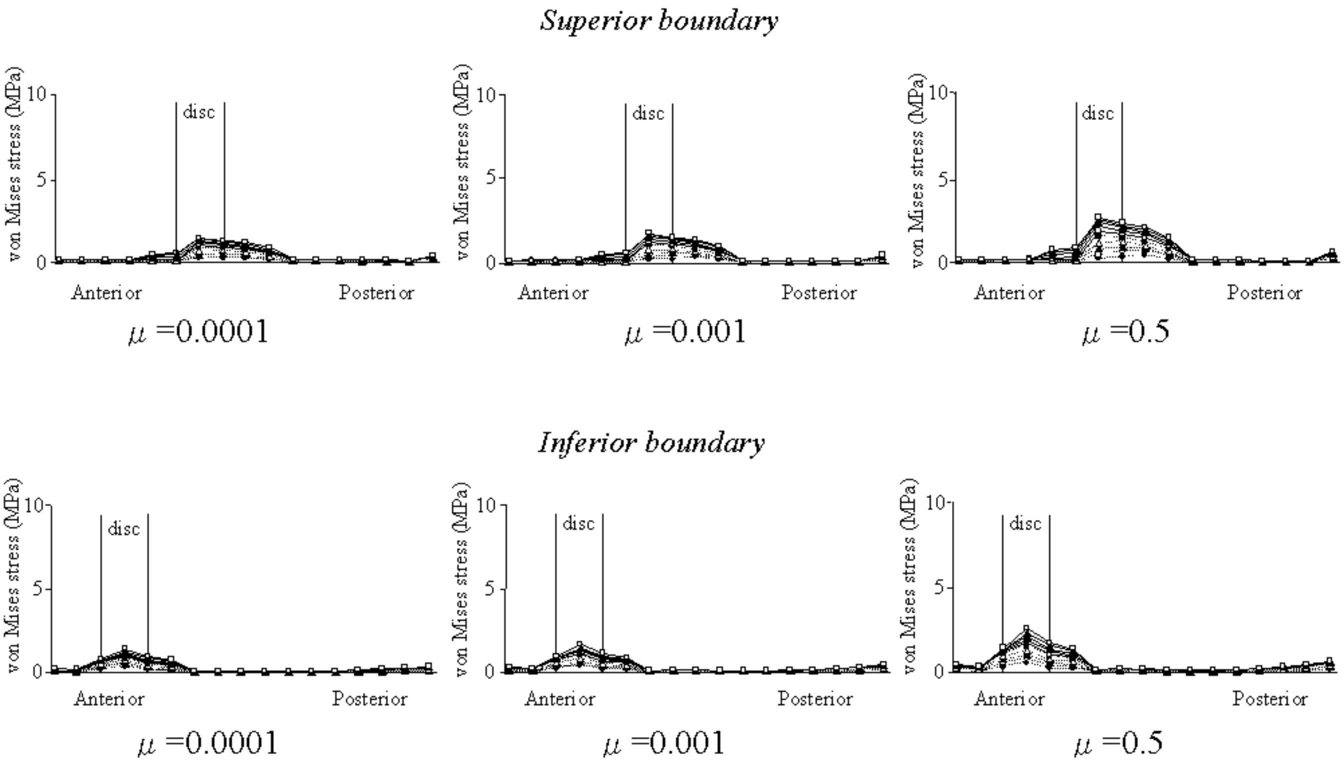


FIGURE 6. The von Mises stress distribution in the anteroposterior direction on the surfaces of the disk and connective tissue of the symptomatic subject at jaw opening increments (%). - -●- - indicates 10%; - -○- -, 20%; - -▲- -, 30%; - -△- -, 40%; - -■- -, 50%; —○—, 60%; —●—, 70%; —△—, 80%; —▲—, 90%; —□—, 100%.

uous load was applied. Honda et al[28] investigated the mechanisms of cartilage destruction caused by excessive mechanical loads and suggested that an excessive mechanical load directly changes the metabolism of cartilage by reducing the matrix components and causing a quantitative imbalance between metalloproteinases and tissue inhibitors of matrix metalloproteinases. Both in the morphological and biochemical aspects, the articular surface is subject to surface wear by means of a continuously applied mechanical load. In the light of these findings, it is suggested that the frictional coefficient of the articular surface becomes greater when an imbalanced environment occurs in the synovial joint. In the present study, with an increase of the frictional coefficient between articular surfaces, the disks moved forward more during mouth opening. The increment of frictional coefficients in the joint is probably induced by the morphological and biochemical changes as mentioned previously. Meanwhile, several researchers have demonstrated that disk displacement occurs in 30–45% of children and young adults.[29,30] These results suggested that the disk displacement might result from a single traumatic event but not a chronic sustained load as shown in our study. As a result, our theoretical argument could not explain disk displacement in children and young adults. Future studies, therefore, need to examine the effect of traumatic event on the joint lubrication.

For the symptomatic subject, von Mises stress induced in the disk during jaw opening were higher in the middle and posterior portions of the disk and progressively increased through opening. Furthermore, stress values were higher in the posterior connective tissue adjacent to the disk than those in the asymptomatic subject. An important function of the posterior connective tissue is to maintain the positional relation between the condyle, disk, and glenoid fossa during jaw opening.[31,32] The existence of large dilated venous vessels at the posterior attachment area in the human disk with anterior displacement has also been reported.[33] These findings indicate that negative pressure causes venous dilation and the flow of blood into the posterior connective tissue. The posterior connective tissues exhibit a soft and flexible nature, owing to a lower elastic modulus, although an energy-dissipation mechanism exists in these tissues.[32] The large stresses in the posterior tissues, as shown in the present study, would possibly lead to an irreversible deformation even though the posterior connective tissues could replace the disk as a pseudodisk in patients with anterior disk displacement.[34] In this regard, it is possible to assume that an appropriate treatment for the patient with TMJ internal derangement is reduction of the excessive or abnormal stresses acting on the disk and posterior connective tissues.

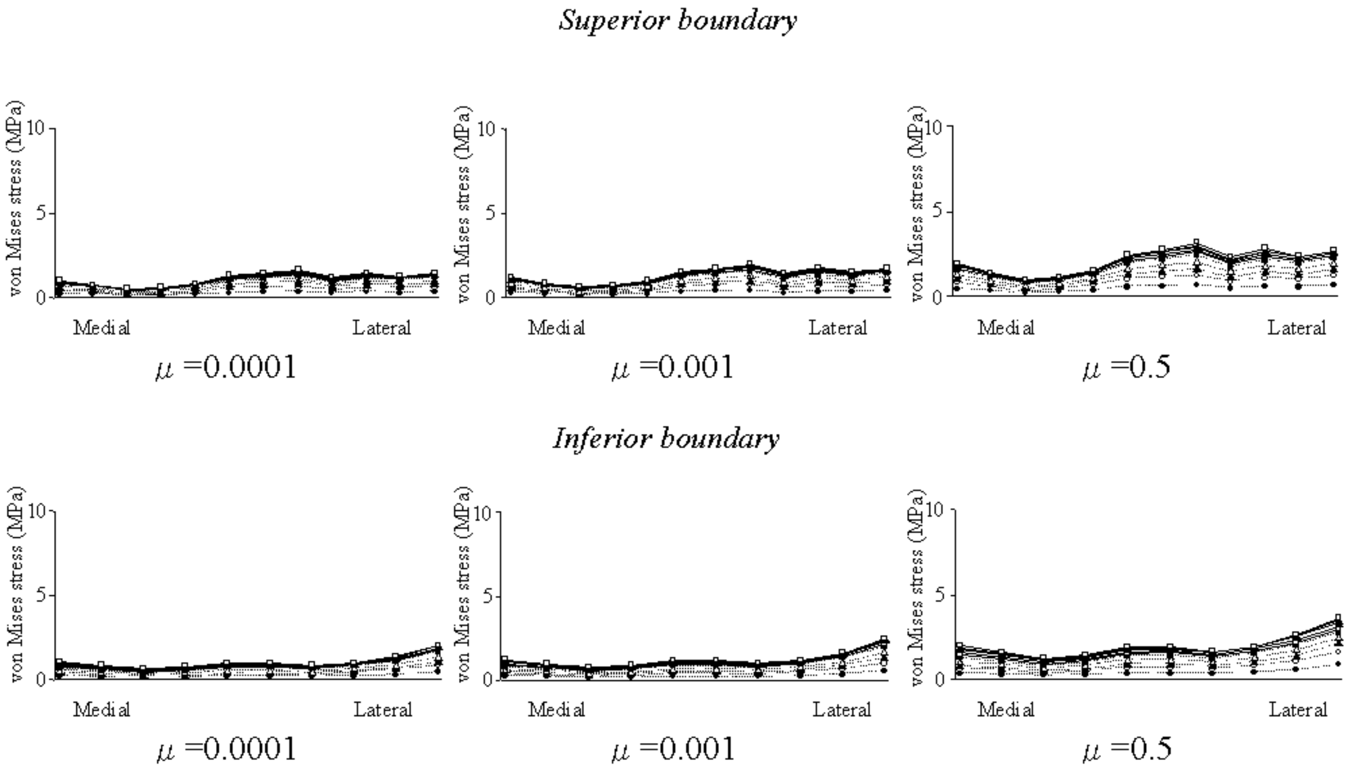


FIGURE 7. The von Mises stress distribution in the mediolateral direction on the surfaces of the disk and connective tissue of the symptomatic subject at jaw opening increments (%). - -●- - indicates 10%; - -○- -, 20%; - -▲- -, 30%; - -△- -, 40%; - -■- -, 50%; —○—, 60%; —●—, 70%; —△—, 80%; —▲—, 90%; —□—, 100%.

CONCLUSION

On the basis of the preceding considerations, we conclude that there was a gradual increase of stress values not only due to jaw opening but also due to an increment in the frictional coefficient. It is assumed that an augmentation in the friction between the disk, glenoid fossa, and condyle produces an increment in the stress distribution, presumably leading to a histochemical breakdown displacing the disk into an anterior position.

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