

Stress analysis in the mandibular condyle during prolonged clenching: a theoretical approach with the finite element method

C Nishio^{1,2}, K Tanimoto¹, M Hirose¹, S Horiuchi³, S Kuroda³, K Tanne¹, and E Tanaka^{3*}

¹Department of Orthodontics and Craniofacial Development Biology, Hiroshima University Graduate School of Biomedical Sciences, Hiroshima, Japan

²Department of Orthodontics, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

³Department of Orthodontics and Dentofacial Orthopedics, The University of Tokushima Graduate School of Oral Sciences, Tokushima, Japan

The manuscript was received on 30 July 2008 and was accepted after revision for publication on 3 April 2009.

DOI: 10.1243/09544119JEIM485

Abstract: Parafunctional habits, such as bruxism and prolonged clenching, have been associated with functional overloading in the temporomandibular joint (TMJ), which may result in internal derangement and osteoarthritis of the TMJ. In this study, the distributions of stress on the mandibular condylar surface during prolonged clenching were examined with TMJ mathematical models. Finite element models were developed on the basis of magnetic resonance images from two subjects with or without anterior disc displacement of the TMJ. Masticatory muscle forces were used as a loading condition for stress analysis during a 10 min clenching. In the asymptomatic model, the stress values in the anterior area (0.100 MPa) and lateral area (0.074 MPa) were relatively high among the five areas at 10 min. In the middle and posterior areas, stress relaxation occurred during the first 2 min. In contrast, the stress value in the lateral area was markedly lower (0.020 MPa) than in other areas in the symptomatic model at 10 min. The largest stress (0.050 MPa) was located in the posterior area. All except the anterior area revealed an increase in stress during the first 2 min. The present result indicates that the displacement of the disc could affect the stress distribution on the condylar articular surface during prolonged clenching, especially in the posterior area, probably leading to the cartilage breakdown on the condylar articular surface.

Keywords: temporomandibular joint, finite element, parafunction, clenching

1 INTRODUCTION

The temporomandibular joint (TMJ) is composed of two articulating bones and soft tissue (Fig. 1). The TMJ is anatomically structured to withstand various loads during mastication [1, 2] owing to its mechanism of stress absorption and energy dissipation. The presence of the fibrocartilaginous disc [3–5] and articular cartilage [5] is believed to prevent peak

loads. Also, the cancellous bone of the mandibular condyle can resist compressive and tensile deformations during loading of the TMJ with minimum amount of bone mass because of its plate-like trabeculae structure [6–8].

The loading in the TMJ could stimulate remodeling, involving increased synthesis of extracellular matrices [9]. Remodelling is an essential biological response to normal functional demands, ensuring homeostasis of joint form, function, and occlusal relationships. However, if there is a failure of this biomechanical equilibrium within the TMJ, the articular components may be subjected to degeneration. Arnett *et al.* [10, 11] proposed an explanation for the pathophysiology of the degenerative

*Corresponding author: Department of Orthodontics and Dentofacial Orthopedics, University of Tokushima Graduate School of Oral Sciences, 3-18-15 Kuramoto-cho, Tokushima, 770-8504, Japan.
email: etanaka@dent.tokushima-u.ac.jp

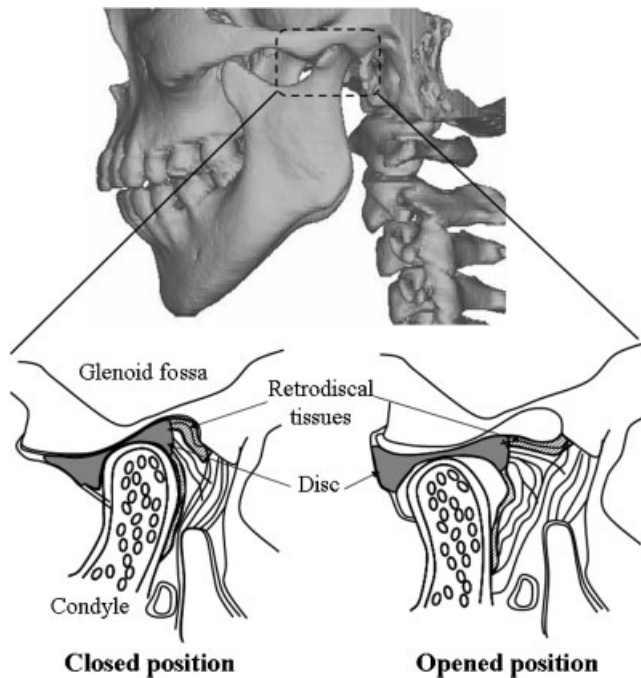


Fig. 1 Computed tomography image and schematic illustration of the TMJ. The TMJ consists of the bony components (glenoid fossa and condyle), and soft tissues (TMJ disc and retrodiscal tissues)

changes as resulting from dysfunctional articular remodelling. This dysfunction can be caused by a decreased adaptive capacity of the articulating structures of the joint or can be due to the excessive or sustained physical stress that exceeds the normal adaptive capacity of the TMJ articular structures.

Parafunctional habits, such as bruxism and prolonged clenching, have been associated with functional overloading in the TMJ, which may result in degenerative changes [11–13]. It has been reported that patients with parafunction in the form of clenching demonstrated a significantly higher TMJ asymmetry index than those with no disorders [14]. Furthermore, parafunctional hyperactivity of the lateral pterygoid muscle (LPM) has been reported to lead to masticatory muscle pain [15–17]. Since the superior head of LPM attaches partly to the articular capsule of the TMJ and directly or indirectly to its articular disc [18, 19], it has been hypothesized that dysfunction of this muscle can lead to degenerative changes [15, 16]. Tanaka *et al.* [20] recently investigated the effect of hyperactivity of LPM on the disc during prolonged clenching using a finite element (FE) model of the TMJ. The findings suggested that the hyperactivity of the LPM might be involved in the progression of abnormal anterior disc displacement. However, these studies have been

focused on only the TMJ disc, and little information is available about the stress distribution on the articular condylar surface during prolonged clenching, which may result in degenerative joint changes such as osteoarthritis (OA).

To examine the possible relationship between prolonged clenching and TMJ biomechanics, two FE models of the TMJ were constructed. Each model was based on magnetic resonance (MR) images from one healthy subject and one symptomatic subject with anterior disc displacement. In this study, the distributions of stress on the mandibular condylar's surface during prolonged clenching were analysed. Furthermore, the effect of the disc displacement on the stress distribution was evaluated. It was hypothesized that parafunctional clenching might result in increased stress on the condylar articular surface and that the symptomatic joint will show different stress distribution on the mandibular condylar surface during parafunctional clenching compared with the asymptomatic joint.

2 MATERIALS AND METHODS

2.1 MR imaging and model reconstruction

MR images were obtained from the right TMJ of an adult female volunteer (age, 25 years) with no history of TMJ disorders and a symptomatic adult female subject (age, 27 years) with anterior disc displacement. According to the criteria of Wilkes [21], the symptomatic subject was diagnosed radiographically as stage III with anterior disc displacement without reduction. Contiguous sagittal and coronal MR images of the TMJ (thickness, 3 mm) were taken from the subjects in maximum intercuspation occlusion. The contours of the glenoid fossa, articular disc, and condyle were traced on acetate papers by two trained technicians. These sagittal and coronal tracings were used for the configuration of the three-dimensional geometry of TMJ components by a computer. The reconstruction technique has been described in detail elsewhere [22]. Briefly, from both the sagittal and the coronal tracings, the articular surfaces were approximated separately using Coon's patches. As the shapes of the most lateral and medial portions of the condyle and articular disc could not be traced from the sagittal MR images, they were determined only by use of the coronal slices.

The upper and lower boundaries of the disc were shaped according to the upper and lower articular surfaces. In order to allow the disc to deform and

move along the articulating surfaces without penetration, interface elements were placed at the bone–disc interface. The model of the glenoid fossa was restrained for all degrees of freedom at its superior region. Because of the detection limit of the MR images, the tissue surrounding the articular disc, including the joint capsule and retrodiscal tissue, was modelled as a homogeneous mass of connective tissue.

The numbers of nodes for the asymptomatic and symptomatic models were 1761 and 1279 respectively in the bone components, and 17 874 and 7600 respectively in the soft tissue including the disc (Fig. 2).

2.2 Boundary conditions and stress analysis

The cortical bone was assumed to be linear elastic (elastic modulus, 13 700 MPa; Poisson's ratio, 0.30) [23]. The material properties of the articular disc and connective tissue facing the condylar articular surface were modelled using a Kelvin model. This linear viscoelastic model is composed of two linear springs with elastic constants μ_1 and μ_2 , combined with a dashpot with the viscosity coefficient η . The relation between the stress σ and the strain ε under compression is formulated as

$$\sigma + \tau_\varepsilon \dot{\sigma} = E_R (\varepsilon + \tau_\sigma \dot{\varepsilon}) \quad (1)$$

where $\tau_\varepsilon = \eta/\mu_1$ and $\tau_\sigma = (\eta/\mu_2)(1 + \mu_2/\mu_1)$ are time constants for strain relaxation and stress relaxation respectively. The relaxed elastic moduli E_R are 15.8 MPa and 0.2 MPa for the TMJ disc and con-

nective tissues respectively [24, 25]. When a stress $\sigma(0) = \sigma_0$ is applied instantaneously at time $t = 0$, the initial condition of equation (1) is given by

$$\tau_\varepsilon \sigma_0 = E_R \tau_\sigma \varepsilon(0) \quad (2)$$

If the stress is kept constant at $\sigma(t) = \sigma_0$ for $t \geq 0$, the time-dependent behaviour of the strain $\varepsilon(t)$ can be written

$$\varepsilon(t) = \frac{\sigma_0 \tau_\varepsilon}{E_R [\tau_\varepsilon + (\tau_\sigma - \tau_\varepsilon) e^{-t/\tau_\sigma}]} \quad \text{for } t \geq 0 \quad (3)$$

The dashpot is completely relaxed as the time tends to infinity. The stress–strain relation then becomes that of the undamped spring given by

$$\varepsilon(\infty) = \frac{\sigma_0}{E_R} \quad (4)$$

From the initial condition (1), another elastic constant E_0 (the elasticity of the two parallel springs) is defined as

$$\varepsilon(0) = \frac{\sigma_0}{E_0} \quad (5)$$

where

$$E_0 = \frac{E_R \tau_\sigma}{\tau_\varepsilon} \quad (6)$$

Here the instantaneous moduli E_0 are 30.9 MPa for the TMJ disc and 1.5 MPa for connective tissues [24, 25]. Finally, by modification of equation (3), the relaxation modulus $E(t)$ is written as

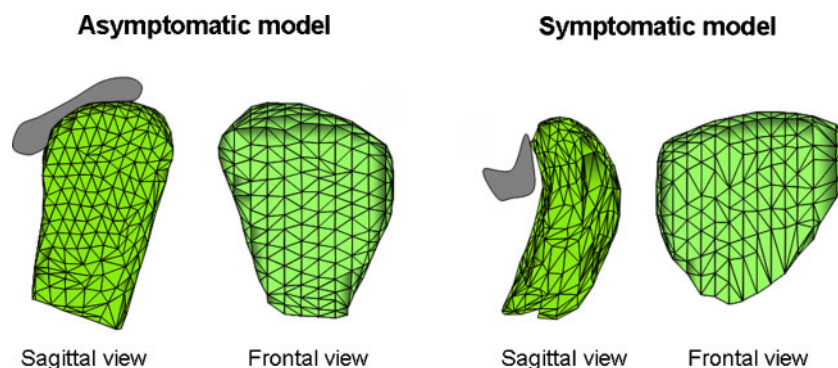


Fig. 2 Sagittal and frontal views of the asymptomatic and the symptomatic FE models. The numbers of nodes for the asymptomatic and symptomatic models were 1761 and 1279 respectively in the bone components, and 17 874 and 7600 respectively in the soft tissue, respectively. The grey areas indicate the TMJ disc

$$\begin{aligned}
 E(t) &= \frac{\sigma_0}{\varepsilon(t)} \\
 &= \frac{E_R [\tau_\varepsilon + (\tau_\sigma - \tau_\varepsilon) e^{-t/\tau\sigma}]}{\tau_\varepsilon} \\
 &= E_R + (E_0 - E_R) e^{-t/\tau\sigma}
 \end{aligned}$$

The viscoelastic constants E_0 , E_R , and τ_ε for the human TMJ disc and connective tissue were estimated from compressive tests using experimental animals [24, 25] (Table 1).

The model of the glenoid fossa was restrained for all degrees of freedom at its superior region. The mandible was modelled as a rigid body. It was constrained at the rearmost point of occlusal contact and at the central point of the anterior teeth on the mandible for mediolateral displacements, leaving three degrees of freedom in the sagittal plane. The FEs of bony components were used to define the contacting condition at the bone–soft tissue interface. Based on previous data obtained from experimental friction tests [26, 27], contact in the TMJ was modelled by using contact elements between the disc and both articular surfaces with a Coulomb friction with a value of 0.01 for both TMJ models.

Joint loading was simulated with forces of four unilateral masticatory muscles (masseter, tempor-

alis, and medial and lateral pterygoid muscles). They were applied as spar elements. The insertion and origin points of these muscles, together with the central point of the anterior teeth (interincisal point) and the rearmost point of occlusal contact, were estimated from the frontal and lateral cephalograms of each subject (Fig. 3). The muscles were linked to the mandibular rigid body at their insertion points (Fig. 3). Their physiological cross-sectional areas (PCS) were defined as shown in Table 2 [28, 29]. With respect to the attachment of the lateral pterygoid muscle, the muscle was equally attached to the disc and condylar neck. Clenching was simulated by simultaneous activation of the four muscles at 20 per cent of their maximum.

Stress analysis was executed by the FE analysis program ANSYS (Houston, Pennsylvania, USA). The von Mises stress distribution on the mandibular condylar surface was evaluated during 10 min clenching.

3 RESULTS

For the asymptomatic joint, the stress distributions on the condylar articular surface during prolonged clenching at two different times (time, 0 s and 10 min) are shown in Fig. 4. Figure 5 showed the

Table 1 Material properties of TMJ components

Material	E_0 (MPa)	E_R (MPa)	τ_ε	Poisson's ratio
Cortical bone	13 700			0.30
Cancellous bone	7930			0.30
Articular disc*	30.9	15.8	31.2	0.40
Connective tissue†	1.5	0.2	11.6	0.40

*Data from Tanaka *et al.* [24].

†Data from Tanaka *et al.* [25].

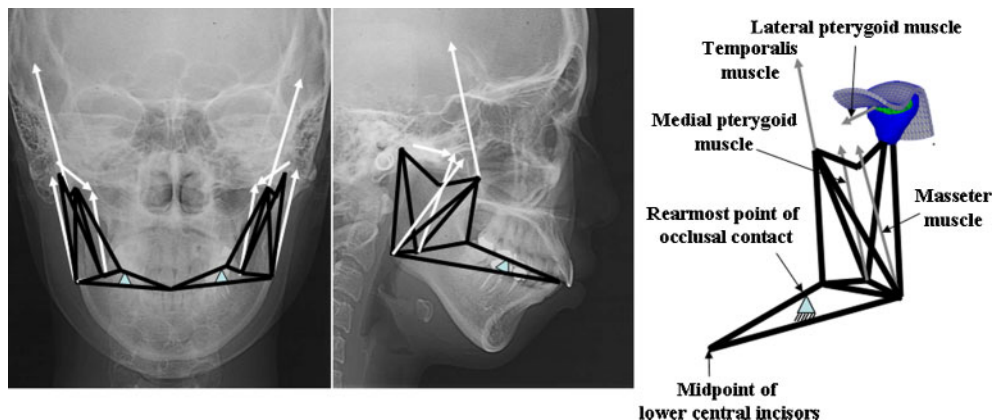


Fig. 3 Mandibular rigid body with muscle spar elements and the rearmost point of occlusal contact

Table 2 PCSs of the masticatory muscles

Masticatory muscle	PCS (cm ²)*	Total PCS (cm ²)*	Maximum muscle force (N) [†]
Medial pterygoid muscle		4.4	207.6
Lateral pterygoid muscle		0.8	37.3
Masseter muscle, superficial part	5.7	8.0	376.0
Masseter muscle, deep part	2.3		
Temporalis muscle, anterior part	3.5	9.1	427.7
Temporalis muscle, middle part	4.5		
Temporalis muscle, posterior part	1.1		

*Data from Koolstra *et al.* [28].

[†]Data from Koolstra and van Eijden [29].

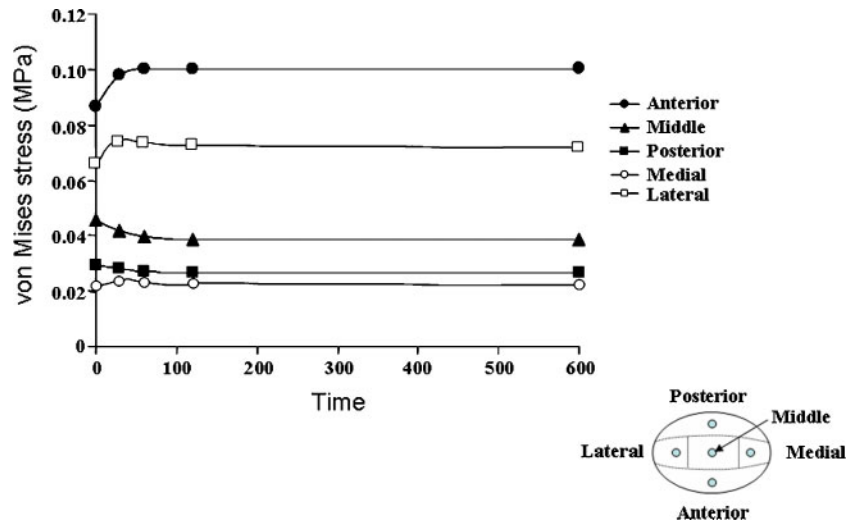


Fig. 4 Time histories of stresses at five reference points on the condylar articular surface of the asymptomatic joint during prolonged clenching. Five reference points are located in the centre of the five (anterior, middle, posterior, lateral, and medial) areas

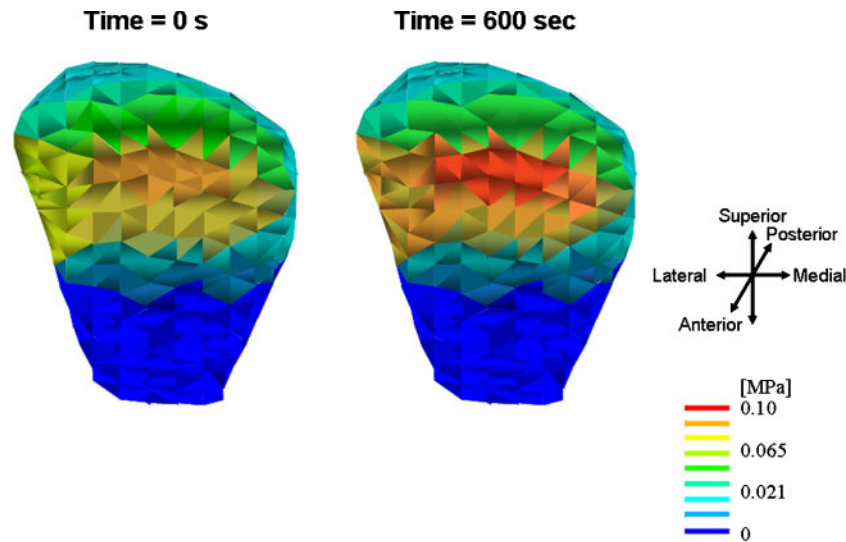


Fig. 5 von Mises stress distribution on the condylar articular surface in the asymptomatic joint at two different time points

stress distributions with the duration of clenching on the representative points of the five areas on the condylar articular surface. At the onset of clenching

(time, 0 s), relatively higher von Mises stresses were located in the anterior area (0.087 MPa) and lateral area (0.065 MPa) of the mandibular condylar surface.

During clenching for the first 60 s, the stress values increased at the anterior area and lateral area (0.100 MPa and 0.074 MPa respectively) and remained constant up to loading for 10 min. Meanwhile, the stress values of the middle area and posterior area at the onset of clenching (time, 0 s) were 0.046 MPa and 0.029 MPa respectively. These stresses decreased slightly and reached a steady level after 1 min, which implies that stress relaxation occurred in these areas. In the medial area, the stress level (0.023 MPa) was almost constant throughout clenching.

For the symptomatic joint, the stress distribution pattern on the condylar articular surface was con-

siderably different from that for the asymptomatic joint, although the von Mises stresses were smaller (Figs 6 and 7). At the onset of clenching (time, 0 s), the largest stress (0.049 MPa) was located in the anterior area. However, the stress value of the anterior area decreased gradually during the first 2 min and reached a steady level (0.038 MPa) after clenching for 10 min. Meanwhile, in the remaining four areas the stress values increased during the first 2 min. The posterior area showed the largest stress (0.050 MPa) after clenching for 10 min. The middle area also revealed slight stress increases during the first 2 min and the stress value after clenching for 10 min (0.038 MPa) became the same as that in

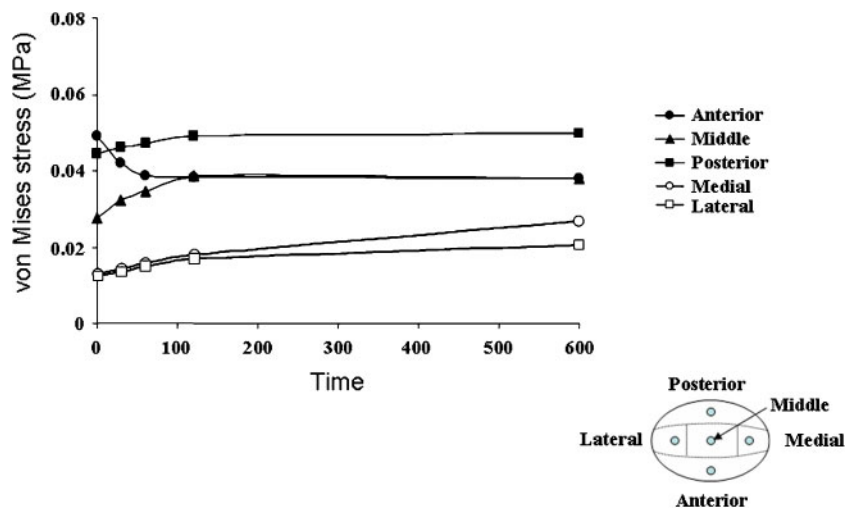


Fig. 6 Time histories of stresses at five reference points on the condylar articular surface of the symptomatic joint during prolonged clenching. Five reference points are located in the centre of the five (anterior, middle, posterior, lateral, and medial) areas

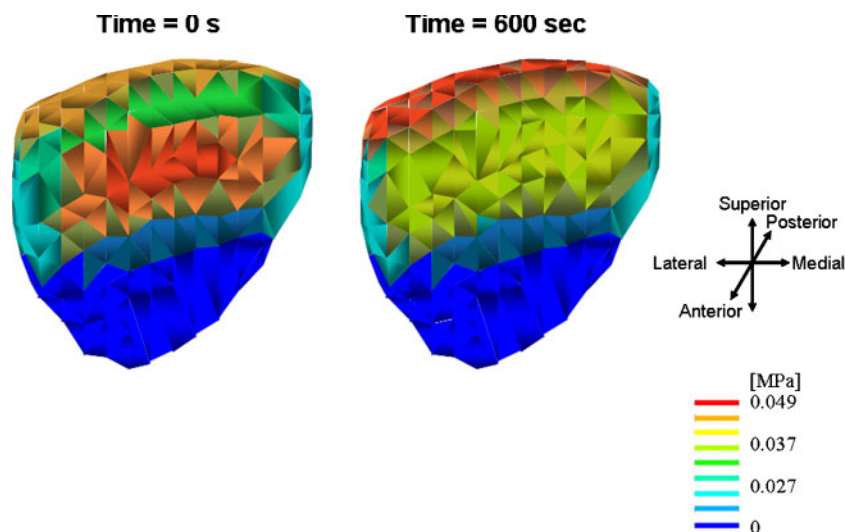


Fig. 7 von Mises stress distribution on the condylar articular surface in the asymptomatic joint at two different time points

the anterior area. Meanwhile, the stress levels of the lateral area and medial area (0.015 MPa and 0.013 MPa respectively) were extremely small at the onset of clenching (time, 0 s) and gradually increased to 0.020 MPa and 0.027 MPa respectively from prolonged clenching.

4 DISCUSSION

Arnett *et al.* [10] proposed two mechanisms by which functional overloading contributes to degenerative changes in the TMJ. First, direct biomechanical stress derived from parafunctional clenching can disrupt the integrity of articular cartilage and inhibit important biological functions of affected cell populations; second, it is possible that cartilage damage resulting from excessive loading of the TMJ is secondary to an ischaemia reperfusion injury [30]. However, direct experimental evidence in support of the premise that parafunctional clenching produces degenerative changes in the TMJ is limited. In the present study, the hypothesis proposed was that parafunctional clenching might result in an increased stress on the condylar articular surface. In the asymptomatic joint, the anterior and middle areas of the condylar articular surface did not exhibit stress relaxation behaviour although the increase in stress values was relatively small. Also, in the symptomatic joint, all areas except for the anterior area exhibited a gradual increase in the von Mises stresses with increasing duration of clenching. This finding suggests that parafunctional clenching might indeed be involved in the increment in stress, irrespective of anterior disc displacement. Therefore, to the present authors' knowledge, this study is the first to evaluate the effect of the parafunction on the stress distribution on the condylar articular surface by means of FE models of the TMJ.

Several theoretical approaches have been attempted to understand better the biomechanical environment in the TMJ. However, the number of experimental studies has been limited because of the difficulty in reaching the joint without surgical exposure. In addition, the insertion of experimental devices could damage the structure of the joint and influence the mechanical behaviour [4]. The FE method has been proven to be a suitable tool for approximating the stress distribution in the structures of the TMJ [4, 13, 29, 31, 32]. FE analysis has been successfully used in this field because it enables stresses to be estimated in the TMJ without an invasive approach. Evidently, biomechanical models of the human TMJ are not real and perfect,

while they are based on a number of assumptions and simplifications. With respect to the present analysis the following remarks have to be made.

First, the cartilage layers covering the articulating surfaces of the bones were not included. The biomechanical properties of the articular cartilage include its viscoelastic behaviour [33, 34] as well as the TMJ disc. In the present study, the disc and retrodiscal tissue were represented as viscoelastic structures by means of a standard viscoelastic Kelvin model. Although a poroelastic or biphasic model is considered suitable for modelling the response of hyaline cartilage, they seem to be less appropriate for the TMJ disc and retrodiscal tissues. Recently, the viscoelastic model according to Kelvin has been suggested to be more adequate for stress analysis in the TMJ during clenching than biphasic or poroelastic models [35, 36]. Therefore, it is necessary that the thin cartilage layer covering the condylar surface would be modelled as viscoelastic material. However, no viscoelastic parameters for human condylar articular cartilage have been reported.

Second, the material properties of the disc and retrodiscal tissue were modelled according to experimental data obtained from canine discs and bovine retrodiscal tissue [24, 25] because no reliable material parameters for humans are available in the literature. Furthermore, these material properties were reported to be different for the pathological and healthy tissues [2, 37]. The tensile properties of these tissues are different from the compressive properties [2, 38]. Therefore, these tissues could be regarded as anisotropic materials. In the present study the anisotropic behaviours of the disc and retrodiscal tissue were not taken into account, because they were mainly subjected to compression. Nevertheless, further study using an anisotropic model should be conducted in future.

Third, based on a previous study [29], clenching by a 20 per cent activation of the masticatory muscle was used for the stress analysis. According to Hiraba *et al.* [15], a considerable amount of background activity (5–32 per cent of the maximum activity) can be detected when the jaw closed in the intercuspal position without teeth clenching. Therefore, a relatively small percentage of maximum force was chosen as the loading condition in this study. In addition, the condylar displacements after 10 min clenching were 0.21 mm and 0.44 mm in the asymptomatic and symptomatic joints respectively (data not shown), which were almost similar to those measured by a jaw-tracking device.

Finally, friction was implemented as a Coulomb-type friction model. This is a simplification with

respect to the characteristics of friction between a deformable structure and a rigid surface [39]. However, although the model consisted of a deformable articular disc moving along a rigid articular surface, it represented the contact between deformable cartilaginous structures, where fluid pressurization would reduce friction considerably. As the increased amount of friction was applied to mimic the effects of damaged cartilage, the present simplification was considered adequate.

In this study, the results indicated that the stress distributions on the mandibular condylar surface were different for the asymptomatic and symptomatic joints. In the asymptomatic joint, the larger stresses at the onset of clenching were located on the anterior and lateral parts of the condylar surface. These stresses revealed a slight increase during clenching for the first few seconds, but reached a steady level by the end of the prolonged clenching. This indicates the stress relaxation on the surface of the mandibular condyle. Therefore, even if prolonged clenching occurs, the stress relaxation function of the condylar articular surface in the asymptomatic joint and the subsequent strain-energy dissipation within the joint tissues could protect them from the excessive or abnormal stresses. Meanwhile, in the symptomatic joint, although the anterior part of the mandibular condylar surface also showed the largest stress, these stress values decreased gradually in the first 2 min and reached a steady level. This is a consequence of the stress relaxation of the anterior part. All the other areas exhibited a gradual increase, especially the posterior area which exhibited the largest stress at the end of the 10 min clenching. The possible explanation for the stress distribution is that the anterior displacement of the disc might not play an important role as a stress absorber during function, and, as a result, the posterior area of the condylar articular surface may be subjected to functional overloading. Furthermore, it is reported that the mandibular condylar cartilage reveals the regional difference of the compressive property and that the posterior area is softer and more fragile in biomechanical nature than the anterior area of the mandibular condylar cartilage [20, 40]. Therefore, continuous overloading, such as 10 min clenching, on this specific posterior area of the mandibular condyle, may result in cartilage breakdown and consequently leads to the degenerative disease as OA.

It can be concluded that the displacement of the disc could affect the stress distribution on the condylar articular surface during prolonged clench-

ing especially in the posterior area, probably leading to cartilage breakdown on the condylar articular surface. This result also indicates that the disc displacement may be involved in the progression of TMJ degenerative disorders.

ACKNOWLEDGEMENT

This study is in part supported by a Grant-in-aid for Scientific Research from the Japan International Cooperation Agency.

REFERENCES

- 1 Tanaka, E., Aoyama, J., Tanaka, M., Murata, H., Hamada, T., and Tanne, K. Dynamic properties of bovine temporomandibular joint disks change with age. *J. Dent. Res.*, 2002, **81**(9), 618–622.
- 2 Tanaka, E. and van Eijden, T. Biomechanical behaviour of the temporomandibular joint disc. *Crit. Rev. Oral Biol. Med.*, 2003, **14**(2), 138–150.
- 3 Tanne, K., Tanaka, E., and Sakuda, M. The elastic modulus of the temporomandibular joint disc from adult dogs. *J. Dent. Res.*, 1991, **70**(12), 1545–1548.
- 4 Beek, M., Koolstra, J. H., van Ruijven, L. G., and van Eijden, T. M. G. J. Three-dimensional finite element analysis of the human temporomandibular joint disc. *J. Biomech.*, 2000, **33**(3), 307–316.
- 5 Hu, K., Qiguo, R., Fang, J., and Mao, J. J. Effects of condylar fibrocartilage on the biomechanical loading of the human temporomandibular joint in a three-dimensional, nonlinear finite element model. *Med. Engng Phys.*, 2003, **25**(2), 107–113.
- 6 Giesen, E. B. W., Ding, M., Dalstra, M., and van Eijden, T. M. G. J. Mechanical properties of cancellous bone in the human mandibular condyle are anisotropic. *J. Biomech.*, 2001, **34**(6), 799–803.
- 7 van Ruijven, L. J., Giesen, E. B. W., and van Eijden, T. M. G. J. Mechanical significance of the trabecular microstructure of the human mandibular condyle. *J. Dent. Res.*, 2002, **81**(10), 706–710.
- 8 van Eijden, T. M. G. J., van der Helm, P. N., van Ruijven, L. J., and Mulder, L. Structural and mechanical properties of mandibular condylar bone. *J. Dent. Res.*, 2006, **85**(1), 33–37.
- 9 Stegenga, B., de Bont, L. G., and Boering, G. Osteoarthritis as the cause of craniomandibular pain and dysfunction: a unifying concept. *J. Oral Maxillofacial Surg.*, 1989, **47**(3), 249–256.
- 10 Arnett, G. W., Milam, S. B., and Gottesman, L. Progressive mandibular retrusion-idiopathic condylar resorption. Part I. *Am. J. Orthod. Dentofacial Orthop.*, 1996, **110**(1), 8–15.
- 11 Arnett, G. W., Milam, S. B., and Gottesman, L. Progressive mandibular retrusion-idiopathic condylar resorption. Part II. *Am. J. Orthod. Dentofacial Orthop.*, 1996, **110**(2), 117–127.

- 12 **Israel, H. A., Diamond, B., Saed-Nejad, F., and Ratcliffe, A.** The relationship between parafunctional masticatory activity and arthroscopically diagnosed temporomandibular joint pathology. *J. Oral Maxillofacial Surg.*, 1999, **57**(9), 1034–1039.
- 13 **Pérez-Palomar, A. and Doblaré, M.** Finite element analysis of the temporomandibular joint during lateral excursions of the mandible. *J. Biomech.*, 2006, **39**(12), 2153–2163.
- 14 **Miller, V. J., Yoeli, Z., Barnea, E., and Zeltser, C.** The effect of parafunction on condylar asymmetry in patients with temporomandibular disorders. *J. Oral Rehabil.*, 1998, **25**(9), 721–724.
- 15 **Hiraba, K., Hibino, K., Hiranuma, K., and Negoro, T.** EMG activities of two heads of the human lateral pterygoid muscle in relation to mandibular condyle movement and biting force. *J. Neurophysiol.*, 2000, **83**(4), 2120–2137.
- 16 **Okeson, J. P.** (Ed.) *Management of temporomandibular disorders and occlusion*, 1998 (CV Mosby, St Louis, Missouri).
- 17 **Murray, G. M., Phanachet, I., Uchida, S., and Whittle, T.** The role of the human lateral pterygoid muscle in the control of horizontal jaw movements. *J. Orofacial Pain*, 2001, **15**(4), 279–305.
- 18 **Heylings, D. J., Nielsen, I. L., and McNeill, C.** Lateral pterygoid muscle and the temporomandibular disc. *J. Orofacial Pain*, 1995, **9**(1), 9–16.
- 19 **Naidoo, L. C.** Lateral pterygoid muscle and its relationship to the meniscus of the temporomandibular joint. *Oral Surg., Oral Med., Oral Pathol., Oral Radiol., Endodontics*, 1996, **82**(1), 4–9.
- 20 **Tanaka, E., Hirose, M., Inubushi, T., Koolstra, J. H., van Eijden, T. M. G. J., Suekawa, Y., Fujita, R., Tanaka, M., and Tanne, K.** Effect of hyperactivity of the lateral pterygoid muscles on the temporomandibular joint disc. *Trans. ASME, J. Biomech. Engng*, 2007, **129**(6), 890–897.
- 21 **Wilkes, C. H.** Internal derangements of the temporomandibular joint. Pathological variations. *Arch. Otolaryngol. Head Neck Surg.*, 1989, **115**(4), 469–477.
- 22 **Tanaka, E., Del Pozo, R., Tanaka, M., Kawaguchi, A., Shibazaki, T., and Tanne, K.** Stress analysis in the TMJ during jaw opening by use of a three-dimensional finite element model based on magnetic resonance images. *Int. J. Oral. Maxillofacial Surg.*, 2001, **30**(5), 421–430.
- 23 **Huiskes, R.** On the modelling of long bones in structural analyses. *J. Biomech.*, 1982, **15**(1), 65–69.
- 24 **Tanaka, E., Tanaka, M., Miyawaki, Y., and Tanne, K.** Viscoelastic properties of canine temporomandibular joint disc in compressive load-relaxation. *Arch. Oral. Biol.*, 1999, **44**(12), 1021–1026.
- 25 **Tanaka, E., Del Pozo, R., Sugiyama, M., and Tanne, K.** Biomechanical response of retrodiscal tissue under compression. *J. Oral Maxillofacial Surg.*, 2002, **60**(5), 546–551.
- 26 **Kawai, N., Tanaka, E., Takata, T., Miyauchi, M., Tanaka, M., Todoh, M., van Eijden, T., and Tanne, K.** Influence of additive hyaluronic acid on the lubricating ability in the temporomandibular joint. *J. Biomed Mater. Res. A*, 2004, **70**(1), 149–153.
- 27 **Tanaka, E., Kawai, N., Tanaka, M., Todoh, M., van Eijden, T., Hanaoka, K., Dalla-Bona, D. A., Takata, T., and Tanne, K.** The frictional coefficient of the temporomandibular joint and its dependency on the magnitude and duration of joint loading. *J. Dent. Res.*, 2004, **83**(5), 404–407.
- 28 **Koolstra, J. H., van Eijden, T. M. G. J., Weijs, W. A., and Naeije, M.** A three-dimensional mathematical model of the human masticatory system predicting maximum possible bite forces. *J. Biomech.*, 1988, **21**(7), 563–576.
- 29 **Koolstra, J. H. and van Eijden, T. M.** Combined finite-element and rigid-body analysis of human jaw joint dynamics. *J. Biomech.*, 2005, **38**(12), 2431–2439.
- 30 **McCord, J. M.** Oxygen-derived free radicals in postischemic tissue injury. *N. Engl. J. Med.*, 1985, **312**(3), 159–163.
- 31 **Korioth, T. W., Romilly, D. P., and Hannam, A. G.** Three-dimensional finite element stress analysis of the dentate human mandible. *Am. J. Phys. Anthropol.*, 1992, **88**(1), 69–96.
- 32 **Tanaka, E., Del Pozo, R., Tanaka, M., Asai, D., Hirose, M., Iwabe, T., and Tanne, K.** Three dimensional finite element analysis of human temporomandibular joint with and without disc displacement during jaw opening. *Med. Engng Phys.*, 2004, **26**(6), 503–511.
- 33 **Tanaka, E., Yamano, E., Dalla-Bona, D. A., Watanabe, M., Inubushi, T., Shirakura, M., Sano, R., Takahashi, K., van Eijden, T., and Tanne, K.** Dynamic compressive properties of the mandibular condylar cartilage. *J. Dent. Res.*, 2006, **85**(6), 571–575.
- 34 **Tanaka, E., Rego, E. B., Iwabuchi, Y., Inubushi, T., Koolstra, J. H., van Eijden, T. M. G. J., Kawai, N., Kudo, Y., Takata, T., and Tanne, K.** Biomechanical response of condylar cartilage-on-bone to dynamic shear. *J. Biomed Mater. Res. A*, 2008, **85**(1), 127–132.
- 35 **Allen, K. D. and Athanasiou, K. A.** Viscoelastic characterization of the porcine temporomandibular joint disc under unconfined compression. *J. Biomech.*, 2006, **39**(2), 312–322.
- 36 **Koolstra, J. H., Tanaka, E., and van Eijden, T. M. G. J.** Viscoelastic material model for the temporomandibular joint disc derived from dynamic shear tests or strain-relaxation tests. *J. Biomech.*, 2007, **40**(10), 2330–2334.
- 37 **Tanaka, E., Shibaguchi, T., Tanaka, M., and Tanne, K.** Viscoelastic properties of the human temporomandibular joint disc in patients with internal derangement. *J. Oral Maxillofacial Surg.*, 2000, **58**(9), 997–1002.
- 38 **Detamore, M. S. and Athanasiou, K. A.** Structure and function of the temporomandibular joint disc: implications for tissue engineering. *J. Oral Maxillofacial Surgery*, 2003, **61**(4), 494–506.
- 39 **Brizmer, V., Kligerman, Y., and Etsion, I.** Elastic-plastic spherical contact under combined normal

and tangential loading in full stick. *Tribol. Lett.*, 2007, **25**(1), 61–70.

40 Hu, K., Radhakrishnan, P., Patel, R. V., and Mao, J. J. Regional structural and viscoelastic properties

of fibrocartilage upon dynamic nanoindentation of the articular condyle. *J. Struct. Biol.*, 2001, **136**(1), 46–52.