The effect of occlusal alteration and masticatory imbalance on the cervical spine

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SUMMARY The characteristics of mandibular lateral displacement include lateral inclination of the occlusal plane and the differences between the right and left masticatory muscles. The aims of this investigation were to compare the mandibular stress distribution and displacement of the cervical spine using three-dimensional finite element models (3D FEM) to simulate masticatory movements and to clarify the association between morphological and functional characteristics and head posture.

A symmetrical standard model was produced (model-A). Model-B had higher masticatory muscle strength on the left side, model-C had symmetrical masticatory muscle strength but the occlusal plane was inclined upwards towards the right and model-D had the occlusal plane inclined upwards towards the right with higher masticatory muscle strength on the left side.

Model-A showed a completely symmetrical stress distribution pattern, while in model-B there was an uneven distribution in the mandible with higher stress on the left side. In addition, the stress distribution in the cervical spine was asymmetrical, showing displacement to the right. Model-C showed a similar mandibular tendency to model-B but the opposite tendency in the cervical spine. In model-D, the mandibular stress distribution was markedly asymmetrical, but almost symmetrical in the cervical spine with markedly decreased lateral displacement.

These results suggest that lateral inclination of the occlusal plane and imbalance between the right and left masticatory muscles antagonistically act on displacement of the cervical spine, i.e. the morphological and functional characteristics in patients with mandibular lateral displacement may play a compensatory role in posture control.

Introduction

Recently, the relationship between occlusion and posture has attracted attention (Michelotti *et al.*, 1999). In the fields of dentistry and orthopaedic surgery there have been various investigations, particularly on the relationship between cervical curvature and facial morphology (Solow and Tallgren, 1976, 1977; Houston, 1988; Huggare *et al.*, 1991; Özbek and Köklü, 1993; Salonen *et al.*, 1994). Many of these studies evaluated the relationship between antero-posterior facial skeletal morphology and cervical curvature. In orthodontics, the aim of treatment is to achieve a good occlusion with facial antero-posterior balance. However, in patients with mandibular lateral displacement, not only is improvement in maxillo-mandibular antero-posterior imbalance necessary, but also correction of the skeletal right–left difference.

Fushima *et al.* (1989) reported that the occlusal plane in patients with mandibular lateral displacement rises in the direction of the mandibular displacement. These characteristics were reproduced and evaluated using a three-dimensional finite element model (3D FEM) of the entire body. A lateral inclination of the occlusal plane induced cervical spine displacement and caused the stress distribution in this area to be asymmetrical, thus affecting posture (Motoyoshi *et al.*, 2000, 2002,

2003). Hidaka *et al.* (1996) evaluated electromyographically the lateral inclination of the occlusal plane and right–left differences in the masticatory muscles in patients with mandibular lateral displacement and observed high muscle activity in the temporal and masseter muscles on the non-displaced side. Kuboki *et al.* (1991) measured muscle function during unilateral chewing and found a small right–left difference in muscle activity immediately after the initiation of chewing, but reported that the activity of the masseter and medial pterygoid muscles on the non-chewing side rapidly decreased, resulting in dominance of muscle activity in the masseter and medial pterygoid muscles on the chewing side and the anterior portion of the bilateral temporal muscles.

The purpose of the present study was to compare the mandibular stress distribution and displacement of the cervical spine using four 3D FEMs of the entire body and to clarify the association between morphological and functional characteristics and head posture.

Materials and methods

3D FEMs of the whole human body were reconstructed based on previous studies (Motoyoshi *et al.*, 2000, 2002 2003). These 3D FEMs were resized after reconstruction using the East Indian skeletal specimen of the whole body

obtained at the Department of Anatomy, Nihon University School of Dentistry and their computed tomographic films taken at 1 mm intervals. The transformations were performed using a 3D CAD program (Motoyoshi *et al.*, 2000).

In the first FEM (model-A), the occlusal plane was symmetrical, and contraction conditions were provided as occlusal force in order to achieve equal masticatory muscle strength between the right and left sides. Based on model-A, a difference was created in the cross-sectional areas of the masseter and temporal muscles between the right and left sides, increasing the masticatory muscle strength on the left side (model-B). In model-C the occlusal plane was elevated by 6 degrees towards the right with masticatory muscle strength remaining symmetrical. In addition, a model showing a lateral inclination of the occlusal plane and asymmetrical masticatory muscle strength, which are morphological characteristics of patients with mandibular lateral displacement, was produced (model-D). In this study, assuming patients with mandibular right lateral displacement, the occlusal plane was elevated by 6 degrees towards the right, resulting in higher masticatory muscle strength on the left non-displaced side (Figure 1).

Using the four models, an analysis was performed using the 3D FE method. The physical properties of the materials were obtained from published data (Yamada, 1970; Sundaram and Feng, 1988; Motoyoshi *et al.*, 1992; Müller and Rüegsegger, 1996) (Table 1). Intervertebral discs were defined as non-linear elements (Table 2). These models consisted of 11 581 nodal points and 6107 elements (Figure 2).

Boundary conditions and analysis

The ANSYS rev. 5.6 program (Cybernet System Co., Tokyo, Japan) was used to calculate the stress and strain at each nodal point. For the FE analysis, non-linear structural analysis was performed with a convergence constant of 0.1 per cent. To simulate masticatory movements in the terminal occlusal phase, contraction conditions were given to the temporal, masseter, medial pterygoid and lateral pterygoid muscles. The contraction rate was 30 per cent. The lateral pterygoid, medial pterygoid, masseter and temporal muscles were reproduced by spar elements and the cross-sectional area was fixed at a ratio of 1:2:3:4. In model-B and model-D with asymmetrical masticatory muscle strength, a right–left difference was produced by increasing the cross-sectional area of the masseter and temporal muscles on the left side by a total of 50 mm² (Figure 3).

Nodes consisting of sole elements were restricted to 3 degrees of freedom. Considering gravity, a fall rate of 9.8×10^3 mm/seconds was given to all elements of the model.

The following computer system was used to calculate the stress and strain at each nodal point: CPU, Pentium
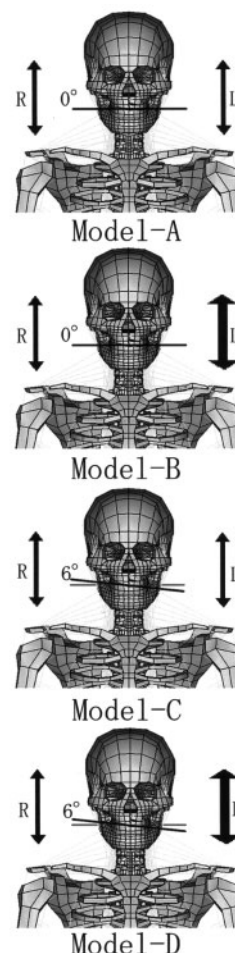
Figure 1 The four finite element models used in this study. Model-A was a standard symmetrical model. Model-B had higher masticatory muscle strength on the left side. Model-C had symmetrical masticatory muscle strength but the occlusal plane was inclined upwards towards the right by 6 degrees. Model-D, representing mandibular right lateral displacement, had the occlusal plane inclined upwards towards the right and higher masticatory muscle strength on the left side, the non-displaced side.

II 450 MHz; hard disk, 23.2 Gbytes; RAM, 256 Mbytes. The stress and strain distributions in the mandible and cervical spine were assessed using 'Von Mises' equivalent stress':

$$\text{Equivalent stress} = 1/\sqrt{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2}$$

where σ_1, σ_2, σ_3 are principal stresses and $\sigma_1 > \sigma_2 > \sigma_3$.

Results

The occlusal stress distribution in the mandible is shown in Figure 4.

Model-A showed a symmetrical stress distribution. Maximum stress was observed on the lingual side of the area corresponding to the bilateral canine root apices.

Table 1 Properties of constituent materials (Motoyoshi *et al.*, 2000).

Material	Young's modulus kgf/mm² (MPa)	Poisson's ratio	Viscosity kg-sec/mm² (N-sec/mm²)	Mass density kg/mm³
Bone	2000 (19 613.3)	0.15		2.59E–07
Suture	0.7 (6.9)	0.49		
Teeth	8000 (78 453.2)	0.15		
Cartilage	150 (1471.0)	0.4		
Intervertebral disc	0.1 (1.0)	0.35		
Skeletal muscle	0.1 (1.0)	0.3		
Food	0.1 (1.0)	0.3		
Pulpiform nucleus	211 (2069.2)		1.15E–10 (1.13E–09)	

Table 2 The material properties of the intervertebral disc elements (Motoyoshi *et al.*, 2000).

Stress kgf/mm² (MPa)	Strain
0.020 (0.196)	0.2
0.021 (0.206)	0.5
0.022 (0.216)	1.0
0.023 (0.226)	1.5
0.024 (0.235)	2.8
0.040 (0.392)	7.5
0.060 (0.588)	10.5
0.080 (0.785)	13.0
0.100 (0.981)	14.5
0.200 (1.961)	19.5
0.300 (2.942)	22.1
0.400 (3.923)	23.6
0.500 (4.903)	24.7
0.600 (5.884)	25.8
0.700 (6.865)	27.0
0.800 (7.845)	28.2
0.900 (8.826)	29.3

Figure 2 Frontal and lateral views of the finite element models used in this study. The models were produced based on previous findings (Motoyoshi *et al.*, 2000), and consisted of 11 581 nodule points and 6107 elements.
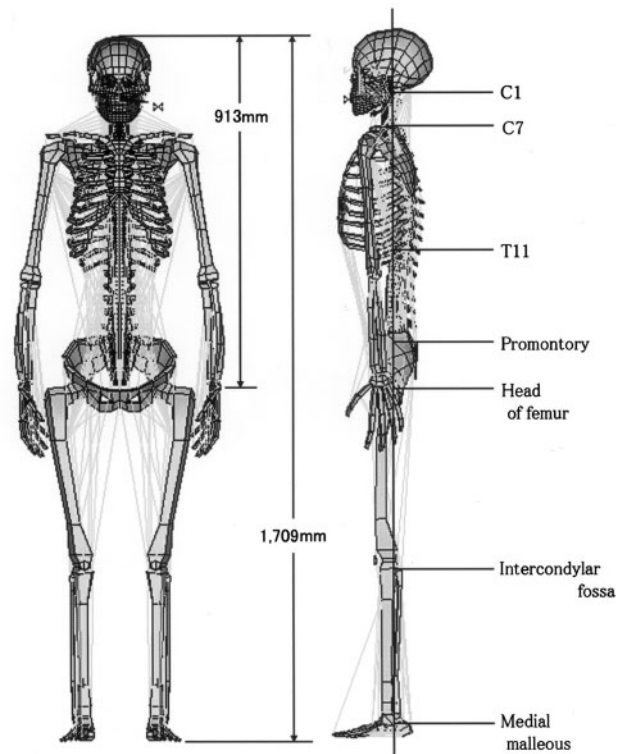
In addition, high stress was observed at the external oblique ridge of the mandibular angle and menton.

Model-B demonstrated an asymmetrical stress distribution with generally high stress on the left side. Asymmetry was particularly marked at menton. Maximum stress was observed on the lingual side of the area corresponding to the left canine root apex.

In model-C there was an asymmetrical stress distribution with generally higher stress on the left side. Asymmetry was particularly marked in the area corresponding to the molar root apex. Maximum stress was observed on the lingual side of the area corresponding to the left canine root apex.

Model-D showed a general marked stress distribution on the left side and more marked asymmetry than the other models. In particular, wide distribution from menton to the area corresponding to the left molar root apex was observed. Maximum stress was present on the lingual side of the area corresponding to the left canine root apex.

The stress distributions in the cervical spine and lateral displacements are shown in Figures 5 and 6 and Table 3.
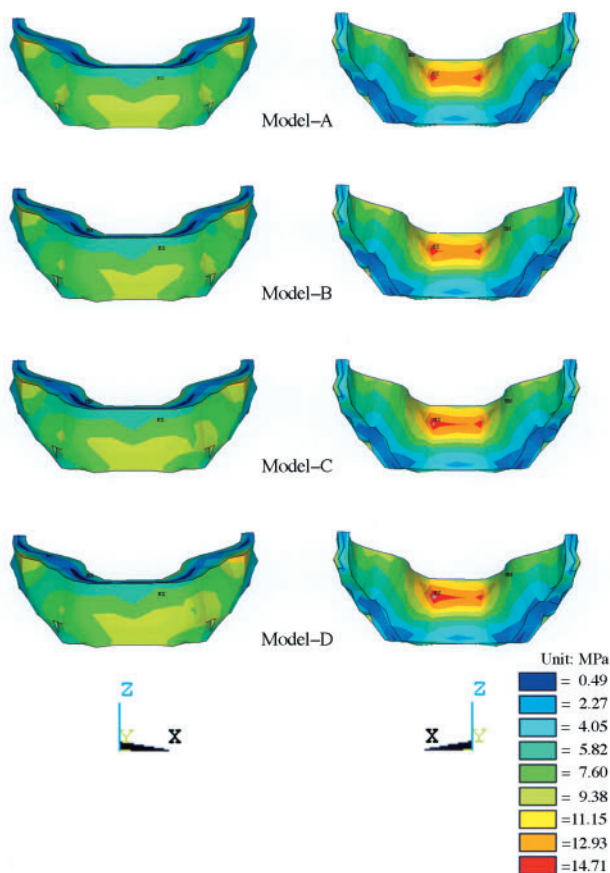
Model-A showed a symmetrical stress distribution with maximum stress in the transverse process of C1 but no displacement.

For model-B there was an asymmetrical stress distribution with high stress on the left side of C3–C7 and right displacement. Maximum stress was observed in the transverse process of C1 on the right side. A comparison of the median area of C1 revealed a displacement to the right of 2.80×10^{-3} mm.

Model-C showed an asymmetrical stress distribution with high stress on the right side of C3–C7 and left displacement. Maximum stress was observed in the transverse process of C1 on the left side. A comparison of the median area of C1 revealed left displacement of 1.96×10^{-3} mm.
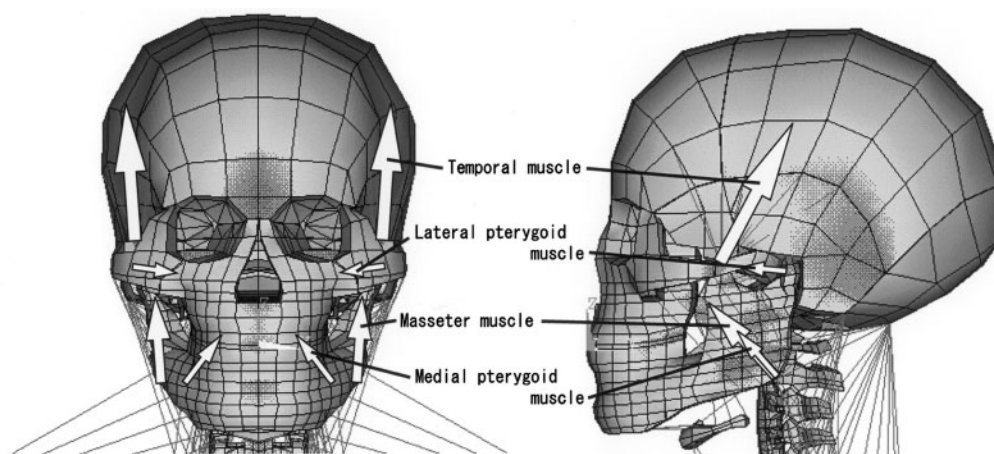
Figure 3 The lateral pterygoid, medial pterygoid, masseter and temporal muscles were reproduced by spar elements and the cross-sectional area was fixed at a ratio of 1:2:3:4. In models-B and -D with asymmetrical masticatory muscle strength, a right–left difference was produced by increasing the cross-sectional areas of the masseter and temporal muscles on the left side by a total of 50 mm^2.

Figure 4 Occlusal stress distribution of the mandible. (a) Labial and (b) lingual side views. A completely symmetrical stress distribution was observed in model-A, but an asymmetrical distribution with higher stress was observed on the left side in models-B, -C and -D.

Model-D also demonstrated an asymmetrical stress distribution, but only a slight right–left difference in C4 and C5. However, the stress distribution in this model

was similar to that for model-A. Maximum stress was observed in the transverse process of C1 on the right side, but the right–left difference was slight. In the median area of C1, right displacement of 7.87×10^{-4} mm was observed, but its absolute value was lower than that for models-B or -C.

Discussion

Masticatory simulation of the 3D FEMs

The reliability of the results is directly related to the accuracy of the model. Therefore, the cranial and spinal elements, which are the observation parts of a stress distribution, were reproduced in detail in the models. Skeletal muscle, vertebral disc and vertebral pulp were also reproduced. The masticatory muscles in the models were reproduced based on the features of a clinical report; mandibular lateral displacement includes lateral inclination of the occlusal plane and the differences between the right and left masticatory muscles (MacDonald and Hannam, 1984a,b; Fushima *et al.*, 1989; Akimoto *et al.*, 1995; Hidaka *et al.*, 1996). However, as skeletal right–left differences, such as ramus length, are considered to be second-order factors, they were ignored in the present investigation. In addition, as FE analysis is a mathematical simulation, clinical research is needed for confirmation.

Model-A (standard model)

Because model-A was symmetrical, the stress distribution was equal between the right and left sides, and no lateral displacement was observed. The lingual side of the area corresponding to the canine root apex, as the external oblique ridge, and menton showed high stress, indicating that apposition and resorption of
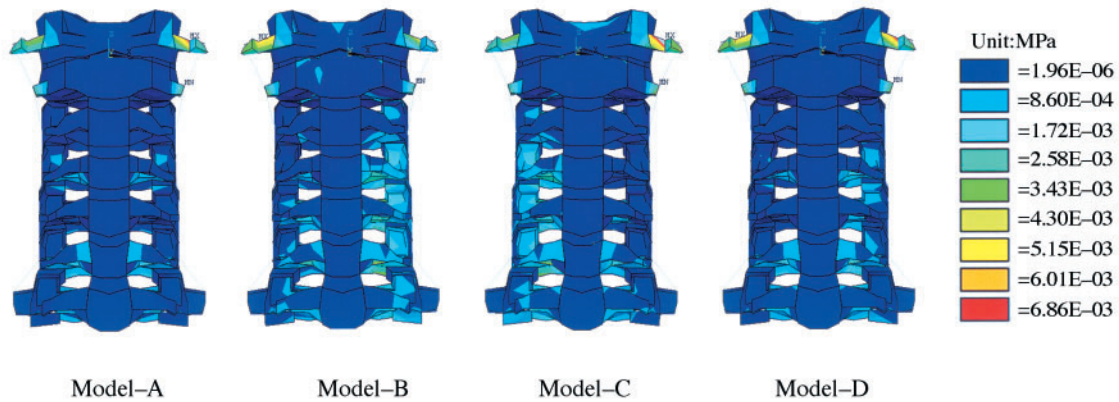
Figure 5 Stress distribution in the cervical spine. Model-A shows a symmetrical stress distribution. Model-B shows high stress at C3–C7 on the left side. Model-C shows high stress at C3–C7 on the right side. Model-D shows a slight right–left difference at C4 and C5.
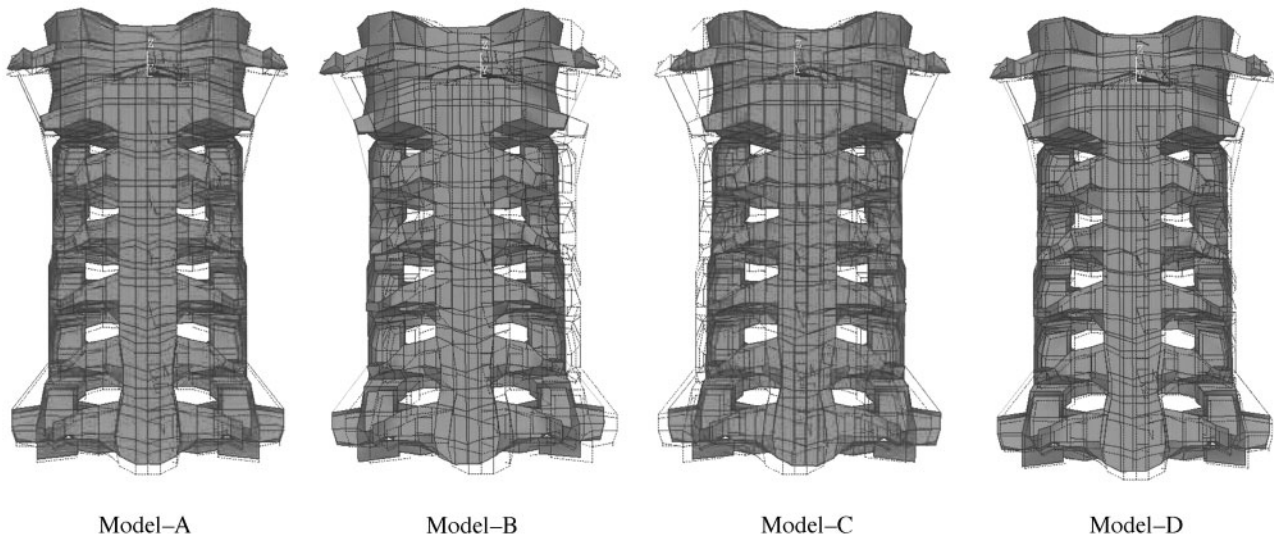
Figure 6 The cervical spine indicating displacements. Model-A shows no displacement. Displacement is observed on the right side in model-B and on the left side in model-C. Slight displacement is observed on the right side in model-D.

Table 3 Lateral displacement of the cervical spine (mm).

	Model-A	Model-B	Model-C	Model-D
C1	0.00	+2.80E–03	+1.96E–03	–7.87E–04
C2	0.00	+2.58E–03	+1.83E–03	–6.97E–04
C3	0.00	+2.35E–03	+1.70E–03	–6.00E–04
C4	0.00	+2.21E–03	+1.62E–03	–5.41E–04
C5	0.00	+2.06E–03	+1.53E–03	–4.90E–04
C6	0.00	+1.91E–03	+1.43E–03	–4.46E–04
C7	0.00	+1.75E–03	+1.31E–03	–4.02E–04

–, left; +, right.

bone may be active (Aoyama, 1994). In the cervical spine, high stress was observed at C1, suggesting its importance in maintaining posture.

Model-B (increased masticatory muscle strength on the left side)

This model represented patients with habitual unilateral chewing, in whom the activity of the masticatory muscles is often asymmetrical between the right and left sides. Kuboki *et al.* (1991) reported that the masticatory muscles act as both a positioner that functionally maintains the optimal mandibular position and a power producer that produces an actual function. The role as a power producer may be mainly determined by the masseter and medial pterygoid muscles and that as a positioner mainly by the temporal muscle. Those authors also defined the position of the total force of the masticatory muscles and found a marked shift in the total force from the median line to the masticatory side during unilateral chewing. Moss and Rankow (1968) proposed the functional matrix theory in which facial

skeletal morphology forms under the influence of the surrounding soft tissue, including the masticatory muscles. Byrd *et al.* (1990) also reported a significant difference between resected and non-resected sides of the mandible, suggesting that deformations in craniofacial morphology are due to changes in the neuromuscular activity of the masticatory muscles. These studies suggest a marked influence of muscle function on skeletal morphology. The results of the present investigation showed an asymmetrical stress distribution in the mandible with a marked right–left difference in menton, suggesting the occurrence of stress that induces asymmetrical mandibular deformation (Aoyama, 1994). In the cervical spine, an asymmetrical stress distribution, particularly high on the left side of C3–C7 and right displacement, was observed. Cervical muscles, such as the hyoid muscle group, the sternocleidomastoideus and the trapezius, work together as a string connecting the cervical spine to the mandible. Therefore, habitual unilateral chewing may be closely associated with mandibular deformation and adversely affect the cervical spine. For this purpose, periodic oral management should be performed, and attention should be paid to preventing the development of unilateral chewing habits due to changes in the oral environment such as normal dental development and loss, caries, restorative or prosthetic treatment. Periodic observation is important, particularly during growth. However, because bone changes annually by repeated remodelling, not only during growth but also in other periods (Broadbent *et al.*, 1975), guidance to acquire normal chewing habits is necessary to prevent jaw deformation and to maintain normal posture.

Model-C [model with lateral inclination (right upper elevation) of the occlusal plane]

A lateral inclination of the occlusal plane, similar to a right–left difference in the masticatory muscles, is frequently acquired and associated with poor prosthesis and restorations containing the occlusal surface, displaced and inclined teeth, and late residual or early exfoliation of primary teeth. In model-C, upward inclination of the occlusal plane towards the mandibular displaced side (Fushima *et al.*, 1989) was reproduced, which improved the previous model with lateral inclination of the occlusal plane (Motoyoshi *et al.*, 2000). As a result, this model, similar to model-B, showed high occlusal stresses on the left side of the mandible with marked differences in the area corresponding to the left molar root apex. These findings suggest that stress induces mandibular deformation (Goodship *et al.*, 1979). However, in the cervical spine, in contrast to model-B, high stress on the right side of C3–C7 and left displacement were observed. Therefore, lateral inclination of the occlusal plane may be a factor inducing changes in head posture and mandibular deformation.

Model-D (mandibular right lateral displacement)

This model represented right–left differences in the masticatory muscles and lateral inclination of the occlusal plane, which are characteristics of mandibular lateral displacement.

The influence of this on posture was evaluated. In this model, similar to model-C, the occlusal plane was inclined upwards in the direction of the mandibular displacement. According to Akimoto *et al.* (1995) and Hidaka *et al.* (1996), the cross-sectional areas of the masseter and temporal muscles were made larger on the non-displaced side. Analysis showed an asymmetrical mandibular stress distribution and wide distribution from menton to the area corresponding to the left molar root apex. The stress distribution in the cervical spine was similar to that of the symmetrical model with only a slight displacement. A previous investigation (Motoyoshi *et al.*, 2000) reported the influence of lateral inclination of the occlusal plane on the stress distribution in the cervical spine. In this model, the right–left differences in masticatory muscle activity may have acted in a direction that cancelled the influence of the inclined occlusal surface, minimizing the influence on the cervical spine. Thus, activation of the masticatory muscles on the non-displaced side in patients with mandibular lateral displacement may play a role in postural control. Indeed, Akimoto *et al.* (1995) and Hidaka *et al.* (1996) reported that activity of the masseter muscle and the anterior portion of the temporal muscle on the displaced side was significantly lower than on the non-displaced side, and contraction of the anterior portion of the temporal muscle on the non-displaced side was greater in patients with more marked lateral craniofacial displacement. However, the activity of the asymmetrically functioning masticatory muscles may result in asymmetrical mandibular stress distribution, promoting jaw deformation.

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