Original

Relationships among Occlusal Force, Condylar Surface Area, and Facial Patterns

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Abstract: The interactions between orofacial muscles and skeletal patterns are widely recognized as significant factors in craniofacial growth. Many studies have suggested that the vertical facial growth pattern correlates with occlusal forces and the activity of masticatory muscles. In particular, it has been suggested that occlusal forces produced by masticatory muscles are converted into physiological stress at the condyle in the form of functional strain. In such circumstances, the dimensions and morphology of the condyle ought to be affected. The aim of this study is to test the hypothesis that low-angle subjects with larger occlusal forces tend to have mandibular condyles with a larger surface area than high-angle subjects. Cone-beam computed tomographic scans were obtained from 14 Japanese adult subjects (17 to 33 years old, 7 high angle and 7 low angle) at 60 kV and 10 mA. Occlusal force was measured by pressure-indicating films, and the surface area of the condyle was calculated from axial CT data. The correlation between occlusal conditions and the surface area of condyles was compared between the two facial groups. We found that the low-angle group had a significantly larger surface area and volume of condyles than the high-angle group and that there was a positive correlation between occlusal forces and condylar surface area. Our findings demonstrate that occlusal force is one of the important factors that affect the mechanical environment of the condyle.

Key words: facial patterns, condylar surface area, cone-beam CT, occlusal forces, reaction force.

Mandibular growth that is influenced by co-activation of jaw muscles influences craniofacial morphology,[1, 2] and is closely related to the amount and direction of condylar growth.[3] The primary factor determining the magnitude and direction of the temporomandibular joint (TMJ) load is the interaction of muscle forces.[4] The magnitude and distribution of functional stress within the TMJ is important for the development of the TMJ.[5] However, excessive loads,[5, 6] loads with a long duration[5, 7] and loads at high frequency[5, 8] induce deformation of the articular cartilage and degradation of the cartilage matrices.

Co-activation of the jaw muscles against the craniofacial complex generates not only TMJ load but also bite force.[9, 10] Brehnan et al. showed that TMJ load occurred during chewing and disappeared in the absence of biting in an animal experiment,[11] so it can be supposed that TMJ load is a reaction force generated from the occlusion against the craniofacial complex and the contraction of muscles during mastication. Herring and Liu illustrated that there is a relationship between TMJ load, muscular force, bite force and bite point.[12, 13] Many studies have clarified the relationship between muscular activity and vertical craniofacial patterns.[14〜16] Long-faced individuals show particular features, such as lower muscular activity[14〜16] and weaker bite force[17, 18] compared with short-faced individuals. Moreover, short-faced individuals also have a larger volume and greater cross-sectional area of masticatory muscles than long-faced individuals.[15, 18, 19] In addition, Proctor and DeVincenzo reported that the direction of the masseter muscle is more perpendicular to the Sella-Nasion (SN) line among short-faced individuals than long-faced individuals.[20] As mentioned above, muscular activity, the direction of muscle forces, and occlusal conditions may affect the mechanical environment of the TMJ. In

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short, different TMJ loads ought to occur when there are different muscular activities and bite forces. Although bite force results from muscular forces acting against the craniofacial complex during biting, bite force and bite point will create different moments with respect to the condyle and this will affect the distribition of the TMJ load. Itoh et al. showed that as the force from the masseter muscle increases, the load point of the condyle shifts anteriorly.[21)] Zhang et al. have shown that occlusal conditions affect the stress distribution in the TMJ.[22)] In addition, Kurusu et al. have clarified the relationship between occlusal force and mandibular condyle morphology.[23)]

Although there have been reports showing that masticatory forces and occlusal conditions do influence the loading of the TMJ,[21, 22)] no reports exploring the relationship among bite force, condylar surface area, and facial patterns have been published. According to the equation: Stress=Load/Area, greater degrees of incongruity between loaded surfaces will result in greater concentration of stress at the joint. In order to release such a high concentration of stress, condylar endochondral ossification ought to be activated. One way to reduce such a high concentration of stress would be to increase the surface area involved. Hence, we hypothesized that low-angle subjects who have larger occlusal forces will tend to have mandibular condyles that have a larger surface area when compared to high-angle subjects.

Materials and Methods

Case selection and angular measurement

A total of 14 Japanese adult subjects (17 to 33 years old, Table 1) with malocclusion who had visited the Department of Orthodontics at the Showa University Dental Hospital were selected. All subjects signed a consent form and this study was approved by the Ethics Committee of Showa University.

Lateral cephalograms of all subjects were taken after they had been instructed to bite in the intercuspal position. The SN plane to the mandibular plane angle (SN-MP angle) shows the inclination of the mandible with respect to the anterior cranial base. A number of studies have shown that long-faced subjects present with excessive vertical facial growth accompanied by an increased SN-MP angle and increased gonial angle,[24)] and that short-faced subjects have reduced vertical facial growth associated with a reduced facial height and reduced SN-MP angle.[25)] In addition, SN-MP angle is widely used as a reference to distinguish facial patterns.[14, 26～28)] SN-MP angles ranging from 30° to 41° are considered to be within the normal range for Japanese subjects.[14, 29)] Subjects with an SN-MP angle greater than 41° were considered to be members of the high-angle group, while subjects with an SN-MP angle less than 30° were classified into the low-angle group. The 14 subjects comprised 7 patients in the high-angle group (1 male and 6 females) and 7 patients in the low-angle group (5 males and 2 females). In addition to these 14 subjects, we also investigated two other high-angle subjects with open-bite malocclusion. It is possible that the muscular force system of open-bite subjects may be different from that of other non-openbite subjects. Therefore, the findings on the open-bite subjects did not undergo statistical analysis and were included for discussion only.

All subjects had complete dentition except for the third molars. Subjects who have image findings of the temporomandibular disorders (TMD), systemic diseases such as abnormal bone metabolism, severe malocclusion

Table 1 Classification of the subjects according to the vertical facial types.

	Vertical facial type		
	High-angle group (non-open bite cases) (SN-MP angle>41°)	Low-angle group (SN-MP angle<30°)	Total
Numbers	*n*=7, 1 male, 6 females	*n*=7, 5 males, 2 females	*n*=14, 6 males, 8 females
Age (mean±SD)	25.8±5.1	22.3±4.7	24.1±5.0

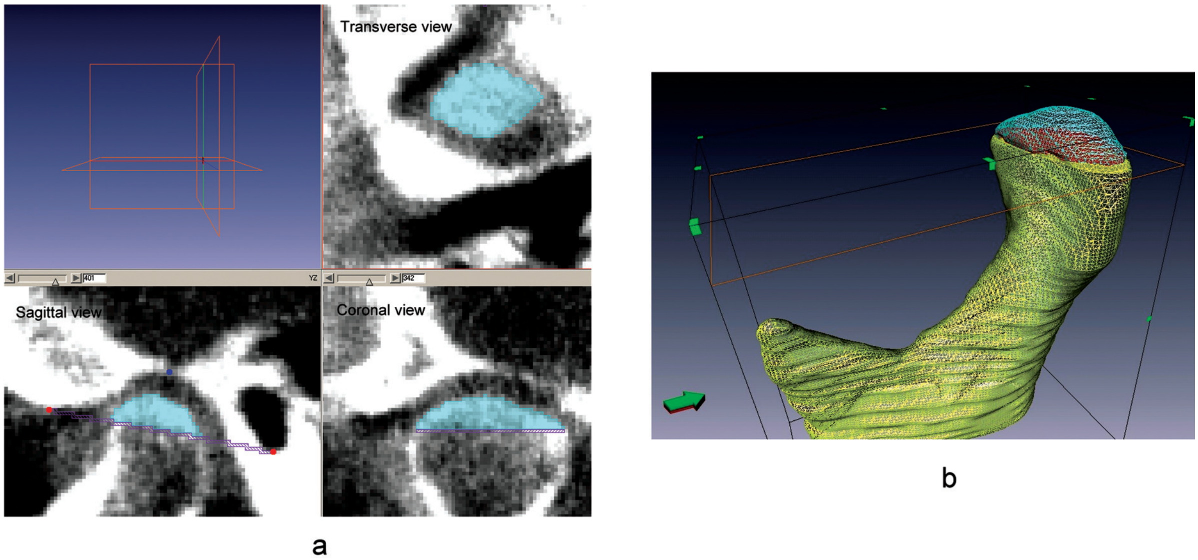

Fig. 1 a: The portion of the condylar head inside the fossa (marked as the blue area) was chosen superior to the reference plane (the purple line in coronal view) formed by the most inferior points of the articular tubercle and the auditory meatus (the red points in sagittal view) slice by slice. b: Reconstruction: The areas that were chosen in all slices were further processed using the Amira computer-aided 3-D surface reconstruction procedure by triangulation in order to fabricate a 3D contour of the condylar head, which allowed the surface area and volume of the condylar head to be measured.

(anterior open-bite, cross-bite), oral diseases (caries, loss of teeth, periodontitis), or prostheses were excluded. Subjects who had a history of orthodontic treatment, skeletal asymmetry or dental asymmetry were also excluded.

Maximal occlusal force measurement

A pressure-indicating film (Dental Prescale 50-H type R; Fuji Film Co., Ltd., Tokyo, Japan) was used to measure the maximal occlusal force at the intercuspal position during clenching.[30] The magnitude of the occlusal forces, the occlusal contact area and occlusal stress were then measured. Subjects were first positioned so that the Frankfort horizontal plane was parallel to the floor. The Films were then placed into the mouth and patients were instructed to clench their teeth with maximum possible force for 3 seconds. The films were read by a scanner (Occluzer®FPD-705; Fuji Film Co., Tokyo, Japan), then the size of the occlusal forces, the occlusal contact area, and occlusal stress were calculated. Subjects might not exactly bite in the intercuspal position with the maximum force at the first time, so that bite recording procedure was repeated three times, and the highest results were considered to be the maximum force of each subject.

Measurement of the surface area and volume of condyles

Each subject was instructed to bite in the intercuspal position, and the Cone-beam computed tomographic (CBCT) image of each subject was taken by a CBCT scanner (CB MercuryRay®, Hitachi Medical Co., Tokyo, Japan) at 60 kV and 10 mA. The slice thickness was 0.371 mm and a total of 512 images were obtained. The raw data set was converted into DICOM format and transformed into the required data format for the software (Amira®, Ver. 3.1.1; Mercury Computer Systems SAS, France). The results were analyzed by the same software.

Initially, we checked the sagittal slices of the CBCT images of each condyle, and the slice containing the most superior point of the fossa was identified; this is shown as a blue point in Fig. 1a. Two reference points were identified in this slice, namely the most inferior points of the articular tubercle and the auditory meatus, which are shown as red points in Fig. 1a. Next, a reference line connecting the two red points was drawn.[31~33] A reference plane was then created to be perpendicular to the sagittal plane from the reference line. The anatomic contour of the condylar head was then reconstructed. What was needed for the present study was the portion of condylar head above the reference plane. Therefore, we chose an appropriate threshold value and then chose the portion of condylar head above the reference plane slice by slice. Then we integrated all of these slices to reconstruct the portion of the condylar head that had been chosen by the software, Amira (Fig. 1b). Finally, we established the condylar surface and calculated the surface area and volume by the same software. In these circumstances, it is possible that an error might have arisen when we decided the outline of the condylar head. Therefore, this procedure was repeated three times, and the average values were used as the condylar surface area and volume; this was done to diminish any possible errors.

Statistical analysis

Mean values of the SN-MP angle, occlusal forces, the occlusal contact area, the condylar surface area, and the condylar volume for the two groups were compared by t-test analysis (Table 2). The significance level of the mean value was set at either $p<0.01$ or $p<0.05$. Single regression analysis was used to estimate the correlation of between occlusal forces and occlusal contact area, between condylar surface area and condylar volume, and between occlusal forces and condylar surface area (Figs. 2, 3).

Results

Comparison of the occlusal conditions between the high- and low-angle groups

A significant difference in values for the occlusal forces and occlusal contact area were found between the high- and low-angle groups ($p<0.01$), but no significant difference in occlusal stress was found between the two groups ($n=14$; Table 2). In the regression analysis, occlusal forces and occlusal contact area showed a positive correlation ($n=14$, $R^2=0.9695$; Fig. 2a).

Comparison of condylar surface area and volume between the high- and low-angle groups

Significant differences in condylar surface area and condylar volume between the high- and low-angle subjects were found ($n=14$, $p<0.01$; $p<0.05$ respectively; Table 2). Regression analysis showed that condylar surface area and condylar volume were positively correlated ($n=14$, $R^2=0.9479$; Fig. 2b).

Relationship between condylar surface area and occlusal forces

There was a positive correlation between occlusal forces and condylar surface area ($n=14$, $R^2=0.708$; Fig. 2c). There were also positive correlations between occlusal forces and condylar surface area among low-

Table 2 Measurements of the subjects according to the vertical facial types.

	SN-MP angle (Degree)		Occlusal force (Newton)		Occlusal contact area (mm^2)		Occlusal stress (Newton/mm^2)	
Low-angle group *n*=7	25.72±3.07	*	1291.0±442.76	*	33.03±14.63	*	40.31±3.66	n.s.
High-angle group *n*=7	42.33±1.40		547.29±229.39		12.84±5.95		43.37±2.56	

	Condylar surface area (cm^2)		Condylar Volume (cm^3)		Surface area/Volume (1/cm)	
Low-angle group *n*=7	2.51±0.31	*	0.46±0.08	**	5.50±0.34	n.s.
High-angle group *n*=7	1.92±0.33		0.32±010		6.14±0.91	
Open-bite group *n*=2	2.98±0.001		0.70±0.005		4.26±0.03	

*$p<0.01$; **$p<0.05$; n.s.: not signaificant.

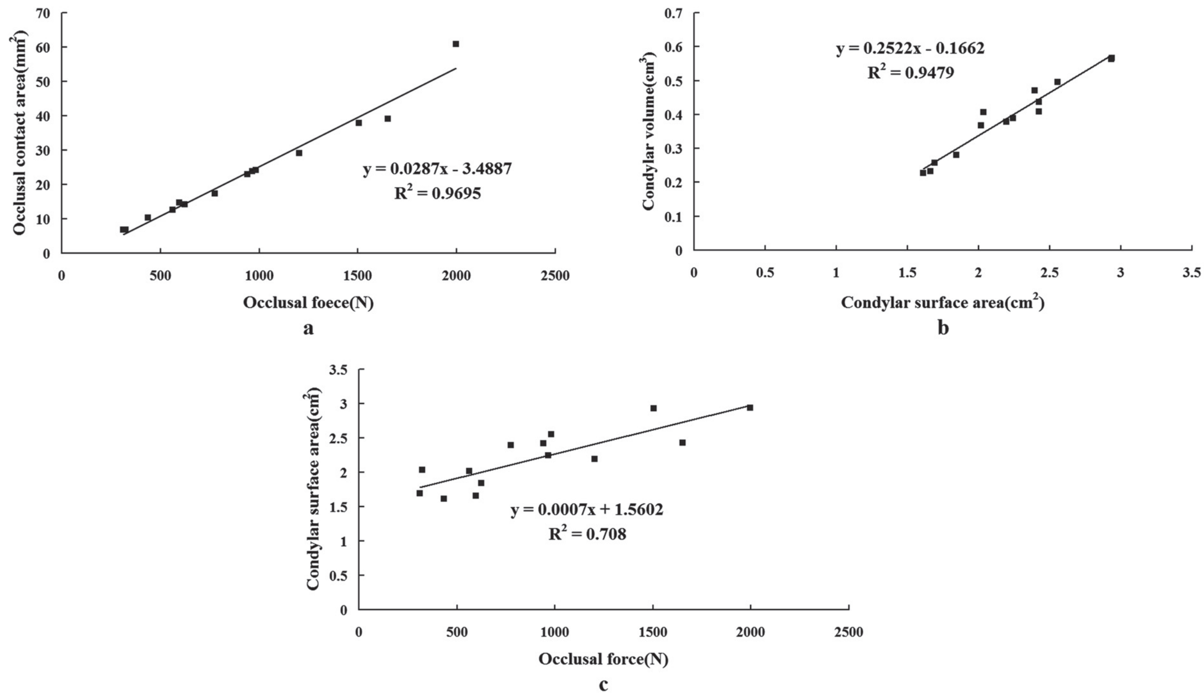

Fig. 2 a: A strong positive correlation was found between occlusal forces and occlusal contact area (*n*=14). b: A strong positive correlation was found between condylar surface area and volume (*n*=14). c: A strong positive correlation was found between occlusal forces and condylar surface area in all cases (*n*=14).

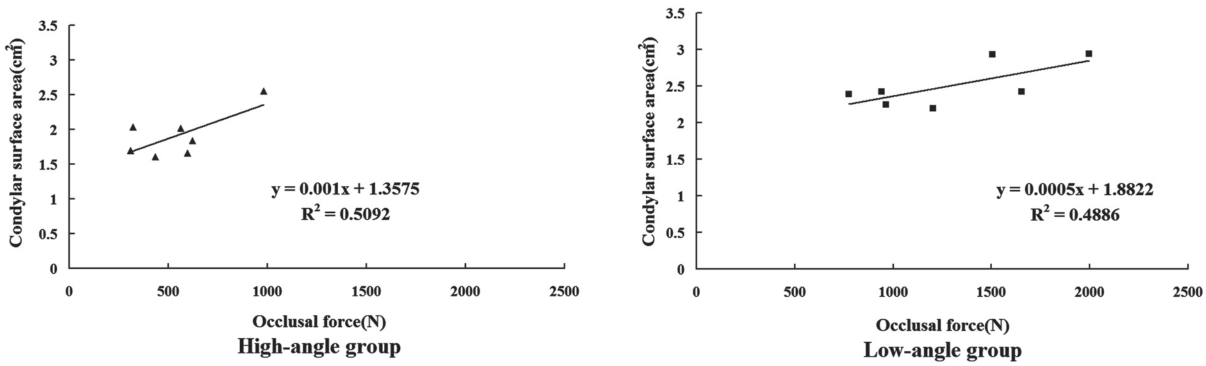

Fig. 3 A positive correlation between occlusal forces and condylar surface area was found in the high-angle group (*n*=7, ▲) and the low-angle group (*n*=7, ■). Furthermore, the slope of the regression equation for the high angle group was larger than that for the low-angle group.

angle subjects (*n*=7, R^2=0.4886; Fig. 3) and among high-angle subjects (*n*=7, R^2=0.5092; Fig. 3). The slope of the equation in high-angle group (0.001) was found to be larger than that in the low-angle group (0.0005) (Fig. 3).

The surface area to volume ratio (SA/V ratio)

The mean SA/V ratios in the low-angle group and in the high-angle group were 5.5 and 6.1, respectively (Table 2). Although the mean ratios were not significantly different between the two groups, the ratio was slightly larger in the high-angle group than in the low-angle group.

Discussion

The relationship between vertical facial types and electromyography (EMG) activity of the masticatory muscles has been confirmed by many studies. EMG activity of the masticatory muscles is weaker in high-angle subjects.[14, 17, 19] Some studies have also shown that there are lower occlusal forces in high-angle subjects.[17, 18] Therefore, it is not surprising to find that there is a significant relationship between vertical facial types and occlusal forces in our study (p<0.01), with low-angle subjects having stronger occlusal forces and high-angle subjects having weaker occlusal forces. We also found that occlusal contact area was smaller in the high-angle group and that average occlusal stresses were similar between both groups. Although Hidaka et al. have shown that an increased occlusal contact area is associated with the intensity of clenching and that there is constant average bite pressure at different clenching intensities,[30] few studies have investigated the relationship between occlusal stress and vertical facial types. This may be considered a special mechanism by which the stomatognathic system maintains an acceptable level of occlusal stress and masticatory efficiency without hurting the periodontal ligament during mastication. Briefly, occlusal stress may be controlled by the mechanoreceptors of the periodontal ligament and condyle via the central nervous system.

Healthy development of the TMJ depends on the distribution of stress within the articular tissues. An appropriate load is essential for the growth and differentiation of chondrocytes. It has been proved that an excessive[5, 6] or an insufficient load will induce deformation of the articular cartilage and cause degradation of the cartilage matrices. Articular tissue is able to change morphology when the load changes during mastication in the growth period. According to the equation: Stress=Load/Area, condyles may change morphology in order to increase surface area and relieve the excessive load during growth. Our study shows that low-angle subjects have a larger condylar surface area than high-angle subjects.

A number of previous studies have shown that short-faced subjects have a more oblique orientation of the joint reaction force[34, 35] and that this oblique direction of the joint reaction force may stimulate bone apposition in the posterior slope of eminence during growth, leading to a steeper inclination of the eminence and a deeper fossa. Ingervall and Kantomaa showed that low-angle subjects have deeper fossae and a steeper inclination of eminences [36, 37] while high-angle subjects have shallower and flatter fossae. It is possible that the portion of the condyle that enters the fossa in low-angle subjects is larger than that in high-angle subjects. In this study, we confirmed our hypothesis that the surface area and volume of the condyle is larger in low-angle subjects than in high-angle subjects.

A positive correlation between occlusal forces and condylar surface area was found in all subjects (R^2=0.708). As the occlusal force becomes stronger, the condylar surface area becomes larger. A positive correlation between occlusal force and condylar surface area was also found in both groups (R^2=0.4886 in the low-angle group and R^2=0.5092 in the high-angle group). In addition, the slope of the regression equation obtained in the high-angle subjects was larger than that obtained in low-angle subjects.

The different slopes of the two groups indicate that as occlusal force increases, the change in condylar surface area among the high-angle subjects is larger than among the low-angle subjects. This supports the idea that condylar growth may be influenced more in the high-angle group than in the low-angle group when occlusal force is changed.

The SA/V ratio is a measure of the corresponding surface area per unit volume. Sagittal cross-sections of the TMJ in Fig. 4 illustrate the different sagittal cross-sectional shapes of a half spherical condyle and a half ellipsoidal condyle. The two red lines show that these two half-circumferences have the same lengths and indicate that these two types of condyles have the same condylar surface area (the length × the slice width=surface area). It was well known that a sphere has the largest area compared to any other shapes with the same circumference. This means that a circular condyle has the largest volume and thus the smallest SA/V ratio relative to any other shape of condyle with the same surface area.

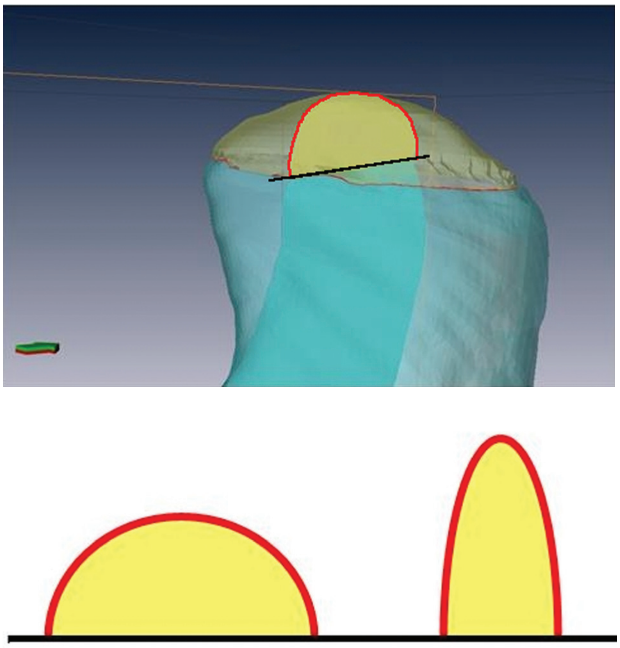

Fig. 4 The sagittal slices of the yellow portion of the TMJ were examined. The lower pictures show the different sectional shapes of a half spherical condyle and a half ellipsoidal one. The red lines show that the two arcs have the same length, indicating that these two types of condyles have the same surface area (the length× the slice width=surface area). A sphere has the largest area compared to any other shape with the same circumferences, which means that a circular condyle has the largest volume and thus the smallest SA/V ratio compared to other shapes.

The findings of the present study show that the low-angle group has a slightly smaller SA/V ratio than the high-angle group, indicating that the condyles of the low-angle group may have a more circular shape than those of the high-angle group. Similar findings have been reported previously, whereby high occlusal force subjects tended to have condyles that are larger and more rounded in the lateral and posterior areas, which is where the high levels of stress occur.[23, 38)] Thus we propose that the stronger bite force of the low-angle group is converted into greater stress at the TMJ, resulting in a more circular shape of the condyle. However, the results of the present study did not find a significant difference in the SA/V ratio between the two groups, but this is probably because the subject numbers were not large enough.

Another interesting finding of the present study was that the two open-bite subjects had larger condylar surface areas than the other high-angle subjects. One possible explanation for this is the presence of abnormal digastric muscle activity during chewing and swallowing.[39)] Abnormal hyperactivity of the digastric muscles may lead to a clockwise rotation of the mandible with a rotation center at the molar contact point during chewing or swallowing.[40)] The simultaneous use of two different muscle activities (the masticatory muscles and the digastric muscles) during mastication is likely to generate greater pressure at the condyle.

Condyles have the ability to adapt and this may be part of the mechanism by which the TMJ is able to control stress, specifically by increasing the surface area of the condyles to relieve any excessive load to a certain degree. If the excessive load exceeds the threshold at which the cartilage is able to resist, condylar resorption may arise to eliminate the load at the TMJ. If longitudinal data using CBCT, EMG and Magnetic resonance imaging (MRI) are obtained and are well coordinated, it is possible that more information about the mechanism will become available.

TMJ load is a reaction force that is influenced by the downward-acting bite force and the upward-acting masticatory muscle force.[12,13)] Since the directions and intensities of the masticatory muscle forces and the occlusal forces in the high-angle group are different from those in the low-angle group, the stress that occurs at the TMJ also differs between the two groups. Therefore, occlusal force is not only related to the craniofacial morphology but also the mechanical environment of the TMJ. We found that there were significant differences in condylar surface area and condylar volume between the high- and low-angle groups. We also found a positive correlation between occlusal forces and condylar surface area. Our findings indicate that subjects with different craniofacial patterns present with different occlusal forces and condylar surface areas and that the morphogenesis of the condyle is related to the occlusal forces. In conclusion, occlusal force is one of important factors that affect the mechanical environment of the TMJ. Furthermore, the quantitative evaluation of their relations will make precious planning method in orthodontics.

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