Original Article

Relationship between Occlusal Force and Mandibular Condyle Morphology

Evaluated by Limited Cone-Beam Computed Tomography

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ABSTRACT

Objective: To clarify the relationship between occlusal force and mandibular condyle morphology using clinical data.

Materials and Methods: The subjects were 40 female patients with malocclusion. The mandibular condyle morphology was assessed by using limited cone-beam CT imaging. The maximum occlusal force was calculated by using pressure-sensitive films. Maxillofacial morphologies were analyzed by using data from lateral cephalograms.

Results: Correlation analysis showed that the occlusal force was correlated with the lateral and posterior radii of the condyles, and with the mandibular plane angle to the Frankfort horizontal plane (FH). Moreover, condylar length was significantly correlated with the occlusal plane angle to the FH, the mandibular plane angle to the FH, the ramus inclination, and the posterior facial height (S-Go). Low-occlusal-force patients tended to have smaller mandibular condyles. This size-related difference was more remarkable on the lateral and posterior side.

Conclusions: Occlusal force influences not only maxillofacial morphology but also mandibular condyle morphology. (*Angle Orthod.* 2009;79:1063–1069.)

KEY WORDS: Occlusal force; Mandibular condyle morphology; Limited cone-beam computed tomography

INTRODUCTION

Occlusal force is one of the important factors influencing maxillofacial development. Muscular dystrophy patients have muscle weakness and a peculiar facial structure termed ''long face,'' characterized by excessive lower vertical facial height and open bite.[1] Masticatory training for children with long face syndrome improves the occlusal force and stimulates mandibular growth.[2] On the other hand, individuals with a large volume of masticatory muscles have a so-called ''short face.'' The vertical maxillofacial dimension is thought to be closely related to occlusal force.[3–8]

The condylar cartilage acts as a regional adaptive growth site during mandibular growth.[9] Absence of the condyles affects the amount of mandibular growth.[10] Deviations in condylar growth can affect facial esthetics.[11] Mechanical compression induces chondrogenesis and condylar growth.[12] Masseteric resection in growing rats caused bradyauxesis of the mandibular condyles, indicating that occlusal force may also affect condylar growth.[13] Occlusal force, maxillofacial morphology, and mandibular condyle morphology seem to influence each other, but the relationship between occlusal force and mandibular condyle morphology has not been reported.

Recently, some studies were conducted on mandibular condyle morphology, using dry skulls and x-ray imaging. Condyles with a convex superior surface and oval form in the axial plane were frequently observed.[14] Moreover, condylar long axis length was

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found to be correlated with many jaw dimensions and, therefore, probably with masticatory functions as well, whereas the short axis length was not.[15] The condylar deformity characterized by internal derangement of the temporomandibular joints (TMJs) was evaluated, and radiographic erosion of the articular surface and osteophytes was found in arthrosis deformans of the TMJs.[16–18] An estimate of mandibular condyle morphology has been carried out only by categorizing morphology and measuring the long and short axes of the condyles.

In recent years, limited cone-beam computed tomography (CT; 3DX Multi-Image Micro CT, Morita Co Ltd, Tokyo, Japan) has enabled the three-dimensional evaluation of mandibular condyle morphology with higher spatial resolution,[19,20] and is highly reliable for morphologic measurements compared with helical CT. The aim of this study was to estimate mandibular condyle morphology in detail and investigate the clinical relationship between occlusal force and mandibular condyle morphology by using 3DX imaging.

MATERIALS AND METHODS

This retrospective study included 40 adult female patients with malocclusion who visited the Orthodontic Clinic of Tokyo Medical and Dental Hospital from August 2003 to February 2006 and for whom 3DX imaging of the TMJs was recommended before orthodontic treatment.

The number of subjects per malocclusion type was: Angle's Class I, 16 patients; Class II, 13 patients; and Class III, 11 patients. The mean age ($\pm$SD) was 24 years ($\pm$6.7 years). We chose adult cases to eliminate consideration of mandibular condyle growth.[21] Patients with a 3-mm or more midline shift of the mandible relative to the ideal facial midline were excluded.[22]

Measurement Methods

The maximum occlusal force was calculated by using one pressure-indicating film (Dental Prescale 50-H type R; Fuji Film Co Ltd, Tokyo, Japan) per clench. With this dental prescale system, the distribution and magnitude of the occlusal force over the entire dentition can be measured close to that of natural occlusion.[23] The subjects were seated with the head in the natural position. The films were immediately read with a scanning apparatus (Dental Occlusion Pressuregraph 703; Fuji), and the maximum occlusal force was evaluated. The occlusal force was recorded thrice for each subject, and the intermediate value was used for the statistical analysis.[24]

Lateral cephalograms were obtained for each subject in the centric occlusion position. The cephalometric landmarks are shown in Figure 1. Angular and linear measurements were made by tracing individual cephalograms.

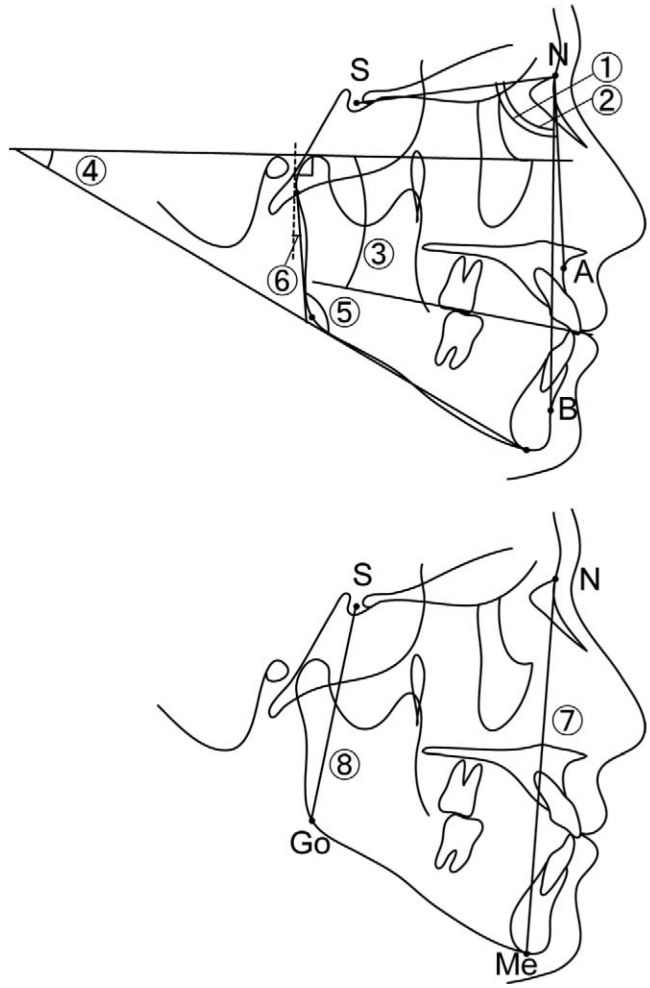

Figure 1. Cephalometric measurements. Conventional cephalometric landmarks are: S, sella; N, nasion; A, Point A; B, Point B; Me, menton; Go, gonion; 1, SNA (°); 2, SNB (°); 3, occlusal plane angle to the FHP (°); 4, MP angle to the FHP (°); 5, gonial angle (°); 6, ramus inclination (°); 7, N-Me (mm); and 8, S-Go (mm).

Mandibular condyle morphology was assessed by 3DX imaging. 3DX data were recorded with the patients sitting in the position in which the Frankfort horizontal plane (FH) is horizontal and the jaws are in centric occlusion. A single 360° scan collected projection data from a cylinder (height $=$ 30 mm; diameter $=$ 40 mm) for image reconstruction. The exposure factors were 80 kV, 7 mA, and 17 s. The imaging data were displayed on a PC monitor. Reconstructed slices were 1 mm thick. The condylar radii (the distance from the center of the long axis to the contours of the condyles) were measured by using analysis software (i-VIEW-3DX version 1.67; Morita). The average radius of the right and left condyles was used for the statistical analysis. Condylar morphology is classified from the superior and frontal views,[14,15] therefore, we mea-

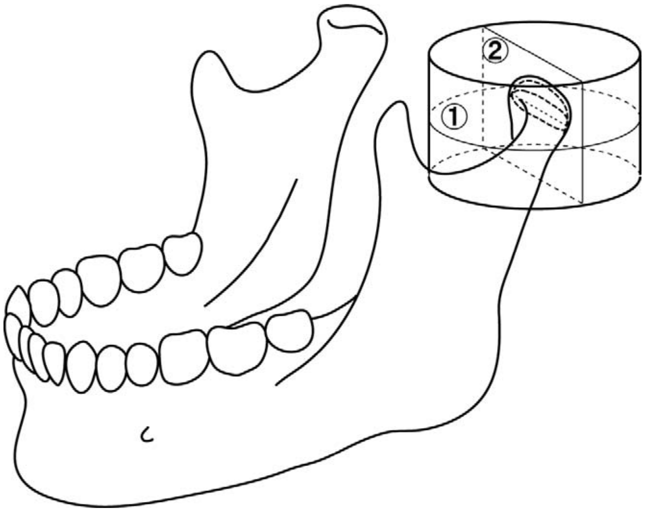

Figure 2. The standard planes for measurement. (1) Axial plane: the plane parallel to the FH and running along the midpoint of the medial and lateral poles of the mandibular condyle. (2) Frontal plane: the plane running along the long axis of the mandibular condyle vertical to the FH.

sured axial and frontal condylar images. The measurement details in the standard planes are:

- The axial and frontal planes were established from the 3DX image (Figure 2).

  Axial plane: The plane parallel to the FH and running along the midpoint of the medial and lateral poles of the mandibular condyle.

  Frontal plane: The plane running along the long axis of the mandibular condyle and vertical to the FH.

- Using the axial image, the long and short axes were identified (Figure 3).

  Long axis: The distance between the medial and lateral ends of the mandibular condyle.

  Short axis: The distance between the two lines drawn parallel to the long axis and tangential to the outer margin of the condyle.

  The condylar radius was measured at 30° intervals from the center of the long axis to understand the topographic characteristic contours of the mandibular condyle.

- Using the frontal image, the condylar radius was also assessed at 30° intervals from the center of the long axis (Figure 4).[25]

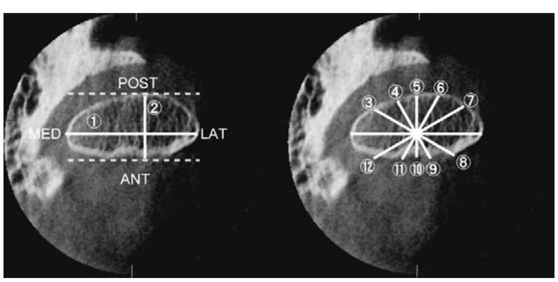

Figure 3. Parameters measured for the axial plane of the condyle. (1) Long axis (mm): distance between the medial and lateral ends of the mandibular condyle. (2) Short axis (mm): distance between the two lines drawn parallel to the long axis and tangential to the outer margin of the condyle. The radius (in mm) of the condyle was measured at 30° intervals from the center of the long axis: 3, radius at 30°; 4, radius at 60°; 5, radius at 90°; 6, radius at 120°; 7, radius at 150°; 8, radius at 210°; 9, radius at 240°; 10, radius at 270°; 11, radius at 300°; 12, radius at 330°.

One of the authors carried out all of the measurements. Further, at a 1-week interval, the same examiner measured all of the parameters in 10 subjects randomly chosen from the 40 patients. The systemic error was estimated using the paired *t*-test at $P < .05$. No significant differences were noted between the measurements in the first and second evaluations.

Statistical Analysis

The correlation coefficients among the condylar radii, occlusal force, and cephalometric measurements were calculated.

To compare the condylar morphology between high-occlusal-force and low-occlusal-force patients, two groups were selected from the subjects. Group I comprised the subjects with occlusal force values exceeding the mean + 1 SD, and group II comprised the subjects with occlusal force values below the mean − 1 SD. The mean value of the radius was calculated, and the average outline of the condyle was plotted for each group. Statistical comparisons were performed using a nonparametric test (Mann-Whitney *U*-test, $P <$ .05). The statistical analysis was performed with a

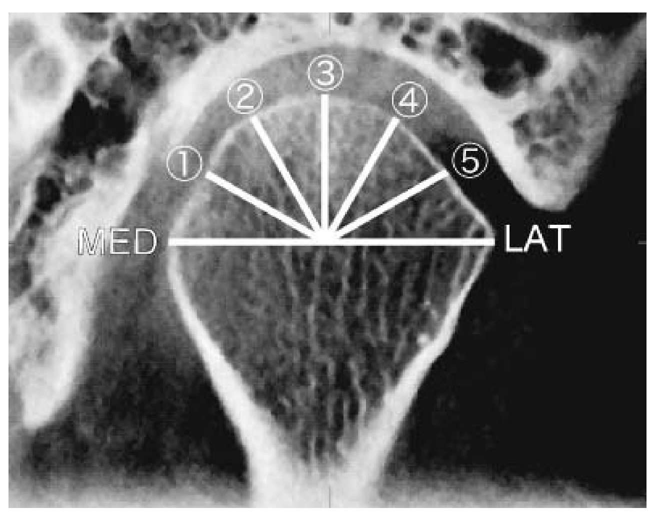

Figure 4. Parameters measured for the frontal plane of the condyle. The radius (in mm) of the condyle was measured at 30° intervals from the center of the long axis: 1, radius at 30°; 2, radius at 60°; 3, radius at 90°; 4, radius at 120°; 5, radius at 150°.

Table 1. Correlation Coefficients Between Condylar Radii and Occlusal Force

	Correlation Coefficient[a]	
Axial Plane		
Long axis	0.313	*
Short axis	0.252	NS
Radius at 30°	0.308	NS
Radius at 60°	0.376	*
Radius at 90°	0.349	*
Radius at 120°	0.417	**
Radius at 150°	0.386	*
Radius at 210°	0.491	**
Radius at 240°	0.051	NS
Radius at 270°	0.027	NS
Radius at 300°	0.015	NS
Radius at 330°	0.237	NS
Frontal Plane		
Radius at 30°	0.042	NS
Radius at 60°	−0.030	NS
Radius at 90°	0.014	NS
Radius at 120°	0.185	NS
Radius at 150°	0.433	**

[a] NS indicates not significant.
* $P < .05$; ** $P < .01$.

commercially available statistical package (SPSS for Windows release 10.0J, SPSS Japan Inc).

RESULTS

Correlation between Size of the Mandibular Condyle and Occlusal Force

The long axis length; the radii at 60°, 90°, 120°, 150°, and 210° in the axial plane; and the radius at 150° in the frontal plane were all significantly correlated with the occlusal force (Table 1).

Correlation between Occlusal Force and Maxillofacial Morphology

Occlusal force was correlated with the mandibular plane angle (MP-FH) (Table 2).

Table 2. Correlation Coefficients Between Cephalometric Measurements and Occlusal Force

	Correlation Coefficient[a]	
SNA	0.171	NS
SNB	0.150	NS
Occ-FH	−0.304	NS
MP-FH	−0.319	*
Gonial angle	−0.224	NS
Ramus inclination	0.088	NS
N-Me	−0.095	NS
S-Go	0.270	NS

[a] NS indicates not significant.
* $P < .05$.

Correlation between Size of the Mandibular Condyle and Maxillofacial Morphology

The long axis length and the radius at 150° in the axial plane were correlated with SNB. The long axis length and the radius at 150° in the frontal plane were correlated with the occlusal plane angle (Occ-FH). The long axis length; the radii at 30°, 60°, 120°, and 150° in the axial plane; and the radius at 150° in the frontal plane were all correlated with MP-FH. The long axis length; the radii at 60°, 150°, and 330° in the axial plane; and the radii at 120° and 150° in the frontal plane were correlated with the ramus inclination. The long axis length; radii at 30°, 60°, 90°, 120°, and 150° in the axial plane, and the radii at all angles in the frontal plane were correlated with the posterior facial height (S-Go). The gonial angle and the anterior facial height (N-Me) were not correlated with any of the condylar radii (Table 3).

Average Condylar Morphology With Regard to the Occlusal Force

The average occlusal force (±SD) was 587.5 N (±264.1 N). The condyles of group II patients (N = 6) were found to be smaller than that of group I patients (N = 6). A significant between-group difference was noted in the long axis length; the radii at 60°, 90°, 120°, and 150° in the axial plane; and the radius at 150° in the frontal plane (Tables 4 and 5; Figures 5 and 6).

DISCUSSION

A recent study showed that bilateral masseteric resection at the prepubertal stage in rats leads to impaired formation of the mandibular bone and condyle in adults.[13] A rat condyle transplanted into the subcutaneous dorsal site of a littermate changed in terms of shape, cellular kinetics, and collagen formation.[26] Condylar growth is regulated not only by genetic factors but also by functional factors. In this study, the condyles of individuals with high occlusal force were very well developed in terms of the long axis length; the radii at 60°, 90°, 120°, 150°, and 210° in the axial plane; and the radius at 150° in the frontal plane. These radii indicate the size of the lateral and posterior part of the condyle. The high-occlusal-force group tended to have condyles with larger, more rounded form at the lateral and posterior side than the low-occlusal-force group.

Previously, it was mentioned that compressive stress during clenching is localized at the lateral side of the mandibular condyle by the distribution of sulfated glycosaminoglycans in the surface layers of human TMJs.[27] On finite-element analysis of human TMJ, it was also reported that the largest stress is

Table 3. Correlation Coefficients Between Condylar Radii and Cephalometric Measurements

		SNA	SNB	Occ-FH	Gonial Angle	MP-FH	Ramus Inclination	S-Go	N-Me
Axial plane	Long axis	0.298	0.340*	−0.374*	−0.165	−0.509**	0.343*	0.360*	−0.172
	Short axis	0.085	0.177	0.094	0.174	−0.062	0.207	0.040	−0.105
	Radius at 30°	0.265	0.176	−0.180	−0.106	−0.455**	0.278	0.282*	−0.093
	Radius at 60°	0.217	0.226	−0.136	0.049	−0.339*	0.357*	0.325*	−0.084
	Radius at 90°	0.143	0.189	−0.028	0.005	−0.290	0.282	0.377*	−0.008
	Radius at 120°	0.204	0.205	−0.063	−0.056	−0.364*	0.281	0.332*	−0.056
	Radius at 150°	0.163	0.347*	−0.179	−0.047	−0.425*	0.460**	0.342*	−0.153
	Radius at 210°	0.113	0.075	−0.106	−0.140	−0.301	0.125	0.290	−0.115
	Radius at 240°	0.045	0.117	0.180	0.203	0.129	0.012	−0.018	−0.035
	Radius at 270°	0.102	0.205	0.157	0.194	0.072	0.081	0.040	−0.039
	Radius at 300°	0.090	0.180	0.157	0.223	0.094	0.110	−0.030	−0.036
	Radius at 330°	0.114	0.220	0.020	0.286	−0.063	0.365*	0.130	−0.030
Frontal plane	Radius at 30°	0.073	0.184	−0.089	−0.068	−0.268	0.169	0.356*	0.029
	Radius at 60°	−0.024	0.233	−0.120	0.127	−0.156	0.288	0.372*	0.090
	Radius at 90°	−0.006	0.266	−0.244	0.118	−0.210	0.338	0.328*	−0.026
	Radius at 120°	0.048	0.234	−0.291	0.075	−0.304	0.395*	0.360*	−0.126
	Radius at 150°	0.223	0.235	−0.313*	−0.152	−0.509**	0.346*	0.420**	−0.282

* $P < .05$; ** $P < .01$.

generated at the middle-to-lateral and superior-to-posterior areas of the condylar cartilage during jaw closure.[28] Mechanical compression induces chondrogenesis and condylar growth. Studies in which mandibular condyles were transplanted into a nonfunctional environment have shown that the progenitor cells of the proliferative zone differentiate into osteoblasts, and not chondroblasts in situ.[29,30] Under nonfunctional conditions, maturation and hypertrophy of the cartilage progress rapidly. Mature cartilage induces mesenchymal cells for the cessation of further cartilaginous growth.[13]

The sites of stress on the surface of the mandibular condyles during occlusion were as previously reported, coinciding with sites in the current study at which differences in mandibular condyle morphology were observed as a result of the intensity of occlusal force. The low-occlusal-force patients had weak pressure on the surface of the mandibular condyles during mastication; therefore, a marked difference from the high-occlusal-force patients appeared particularly in the lateral and posterior directions. Mandibular condyle growth was inhibited at these sites, and differences in morphology were apparent. In addition, growth of mandibular condyle cartilage occurred laterally and posteriorly, leading to differences at these sites.

Clinically, it has been observed that weaker masticatory muscular force during the growth periods results in a skeletal pattern in which the mandibular plane, occlusal plane, and gonial angles are large, and the ramus is short.[5,6] A previous biomechanical study

Table 4. Average Condylar Radii in the Axial Plane[a]

	High-Occlusal-Force Group I (N = 6)		Low-Occlusal-Force Group II (N = 6)		Mann-Whitney *U*-test
	Mean (mm)	SD	Mean (mm)	SD	
Long axis	18.31	1.25	15.95	1.60	*
Short axis	7.86	0.82	6.92	1.20	NS
Radius at 30°	6.72	0.63	5.98	0.51	NS
Radius at 60°	5.29	0.37	4.60	0.32	**
Radius at 90°	4.74	0.31	4.12	0.60	*
Radius at 120°	5.32	0.42	4.59	0.58	*
Radius at 150°	7.09	0.80	6.11	0.52	*
Radius at 210°	6.78	1.07	5.86	0.53	NS
Radius at 240°	4.00	0.97	3.91	0.60	NS
Radius at 270°	3.24	0.87	2.97	0.77	NS
Radius at 300°	3.94	0.78	3.80	1.12	NS
Radius at 330°	6.83	1.06	6.19	0.85	NS

[a] SD indicates standard deviation; NS, not significant.
* $P < .05$; ** $P < .01$.

Table 5. Average Condylar Radii in the Frontal Plane[a]

	High-Occlusal-Force Group I (N = 6)		Low-Occlusal-Force Group II (N = 6)		Mann-Whitney *U*-test
	Mean (mm)	SD	Mean (mm)	SD	
Radius at 30°	9.65	1.36	9.29	1.90	NS
Radius at 60°	7.97	1.30	8.11	1.48	NS
Radius at 90°	7.18	0.88	7.23	1.19	NS
Radius at 120°	7.39	1.20	6.90	1.24	NS
Radius at 150°	8.69	1.42	7.16	0.66	*

[a] SD indicates standard deviation; NS, not significant.
* $P < .05$.

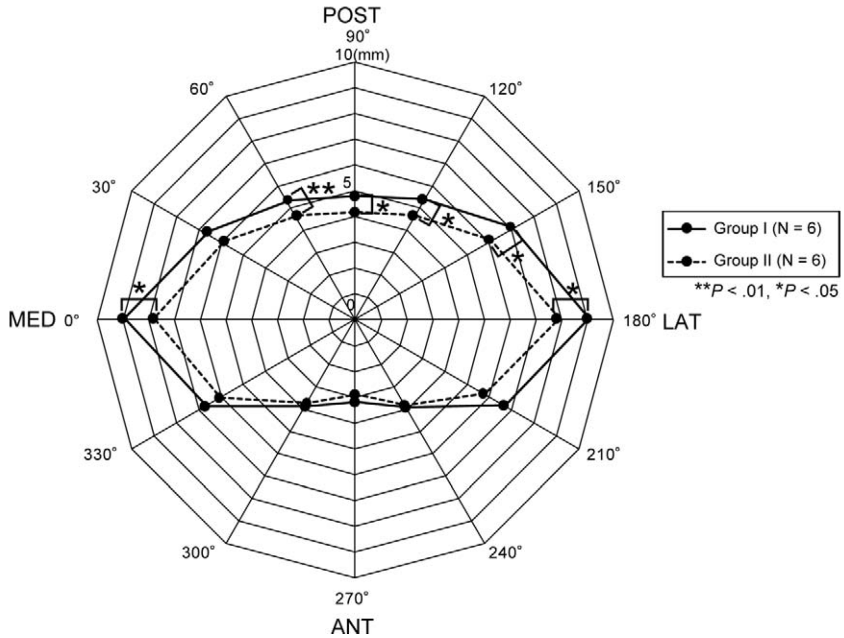

Figure 5. Average condylar morphology in the axial plane with regard to the occlusal force. Group I: high-occlusal-force patients; Group II: low-occlusal-force patients. * $P < .05$; ** $P < .01$.

showed that a mechanical disadvantage in the masseter may result from an increase in the gonial and mandibular plane angles.[7] Similarly, in the present study, a negative correlation was found between occlusal force and MP-FH; further, MP-FH, ramus inclination, and S-Go, which are considered to be related to occlusal force, were closely correlated with the long axis length and the lateral and posterior radii of the condyles. These results clarified the relationships among occlusal force, mandibular condyle morphology, and maxillofacial morphology.

SNB was correlated with the long axis length and the radius at 150° in the axial plane, but the correlation coefficient was small; SNA was not correlated with any radius of the condyle. It has been reported that condylar size does not differ between skeletal Class III and Class II patients.[31] Our results also indicated that the sagittal mandibular position is not closely related to condyle formation.

This study suggests that occlusal force influences not only maxillofacial morphology but also condylar morphology. Therefore, mandibular growth requires optimal compressive forces at the condylar and gonial regions: that is, desirable mandibular growth needs substantial occlusion during growth.

CONCLUSIONS

- Occlusal force is correlated with the long axis length and the lateral and posterior radii of the mandibular condyles.
- Occlusal force influences not only maxillofacial morphology but also mandibular condyle morphology.

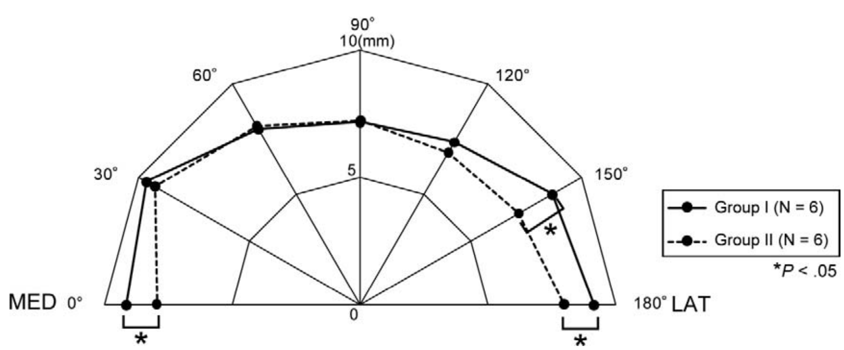

Figure 6. Average condylar morphology in the frontal plane with regard to the occlusal force. Group I: high-occlusal-force patients; Group II: low-occlusal-force patients. * $P < .05$.

REFERENCES

1. Kreiborg S, Jensen BL, Møller E, Björk A. Craniofacial growth in a case of congenital muscular dystrophy. *Am J Orthod.* 1978;74:207–215.
2. Ingervall B, Bitsanis E. A pilot study of the effect of masticatory muscle training on facial growth in long-face children. *Eur J Orthod.* 1987;9:15–23.
3. Weijs WA, Hillen B. Relationship between masticatory muscle cross-section and skull shape. *J Dent Res.* 1984;63: 1154–1157.
4. Gionhaku N, Lowe AA. Relationship between jaw muscle volume and craniofacial form. *J Dent Res.* 1989;68:805–809.
5. Sassouni V. A classification of skeletal facial types. *Am J Orthod.* 1969;55:109–123.
6. Ringqvist M. Isometric bite force and its relation to dimensions of facial skeleton. *Acta Odontol Scand.* 1973;31:35–42.
7. Throckmorton GS, Finn RA, Bell WH. Biomechanics of differences in lower facial height. *Am J Orthod.* 1980;77:410–420.
8. Proffit WR, Fields HW. Occlusal forces in normal- and long-face children. *J Dent Res.* 1983;62:571–574.
9. Scott JH. *Dentofacial Development and Growth.* 1st ed. London, England: Pergamon Press; 1967;165–173.
10. Tsolakis AI, Spyropoulos MN, Katsavrias E, Alexandridis K. Effects of altered mandibular function on mandibular growth after condylectomy. *Eur J Orthod.* 1997;19:9–19.
11. Pirttiniemi P, Peltomäki T, Müller L, Luder HU. Abnormal mandibular growth and the condylar cartilage. *Eur J Orthod.* 2009;31:1–11.
12. Kantoumaa T, Hall BK. On the importance of cAMP and Ca^{++} in mandibular condylar growth and adaptation. *Am J Orthod Dentofacial Orthop.* 1991;99:418–426.
13. Yonemitsu I, Muramoto T, Soma K. The influence of masseter activity on rat mandibular growth. *Arch Oral Biol.* 2007; 52:487–493.
14. Yale SH, Allison BD, Hauptfuehrer JD. An epidemiological assessment of mandibular condyle morphology. *Oral Surg Oral Med Oral Pathol.* 1996;21:169–177.
15. Wedel A, Carlsson GE, Sagne S. Temporomandibular joint morphology in a medieval skull material. *Swed Dent J.* 1978;2:177–187.
16. Toller PA. Osteoarthrosis of the mandibular condyle. *Br Dent J.* 1973;134:223–230.
17. Yamada K, Hanada K, Hayashi T, Ito J. Condylar bony change, disk displacement, and signs and symptoms of TMJ disorders in orthognathic surgery patients. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod.* 2001;91:603–610.
18. Christiansen EL, Thompson JR, Kopp S, Hasso AN, Hinshaw DB Jr. Radiographic signs of temporomandibular joint disease: an investigation utilizing X-ray computed tomography. *Dentomaxillofac Radiol.* 1985;14:83–92.
19. Kijima N, Honda K, Kuroki Y, Sakabe J, Ejima K, Nakajima I. Relationship between patient characteristics, mandibular head morphology and thickness of the roof of the glenoid fossa in symptomatic temporomandibular joints. *Dentomaxillofac Radiol.* 2007;36:277–281.
20. Honda K, Larheim TA, Maruhashi K, Matsumoto K, Iwai K. Osseous abnormalities of the mandibular condyle: diagnostic reliability of cone beam computed tomography compared with helical computed tomography based on an autopsy material. *Dentomaxillofac Radiol.* 2006;35:152–157.
21. Takenoshita Y. Development with age of the human mandibular condyle. Part I: Gross anatomy and inner architecture. *Dentomaxillofac Radiol.* 1982;11:5–15.
22. Akahane Y, Deguchi T. Morphology of the temporomandibular joint in skeletal Class III symmetrical and asymmetrical cases: a study by cephalometric laminography. *J Orthod.* 2001;28:119–127.
23. Harada K, Watanabe M, Ohkura K, Enomoto S. Measure of bite force and occlusal contact area before and after bilateral sagittal split ramus osteotomy of the mandible using a new pressure-sensitive device: a preliminary report. *J Oral Maxillofac Surg.* 2000;58:370–374.
24. Saito S, Tanaka N, Kurabayashi H, Shibasaki Y. Cross-sectional comparative analysis of occlusal contact areas and occlusal force before and after orthodontic treatment using pressure sensitive occlusal sheets for various types of malocclusion. *Orthod Waves Jpn Ed.* 2002;61:263–271.
25. Sato C, Muramoto T, Soma K. Functional lateral deviation of the mandible and its positional recovery on the rat condylar cartilage during the growth period. *Angle Orthod.* 2006;76:591–597.
26. Michiyasu O. An experimental study on the growth of the rat mandibular condyle by means of subcutaneous transplantation. *J Osaka Univ Dent Sch.* 1977;22:21–45.
27. Kopp S. Topographical distribution of sulfated glycosaminoglycans in the surface layers of the human temporomandibular joint. *J Oral Pathol.* 1978;7:283–294.
28. Koolstra JH, van Eijden TM. Combined finite-element and rigid-body analysis of human jaw joint dynamics. *J Biomech.* 2005;38:2431–2439.
29. Meikle MC. In vivo transplantation of the mandibular joint of the rat: an autoradiographic investigation into cellular changes at the condyle. *Arch Oral Biol.* 1973;18:1011–1020.
30. Meikle MC. The role of the condyle in the postnatal growth of the mandible. *Am J Orthod.* 1973;64:50–62.
31. Katsavrias EG, Halazonetis DJ. Condyle and fossa shape in class II and class III skeletal patterns: a morphometric tomographic study. *Am J Orthod.* 2006;129:470–478.