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Original Paper

An advanced method of individual jaw movement analysis

Eiichiro Minemura*[1], Yohei Takeuchi[1], Yoshihito Manome[2],
Hitoshi Kimura[3], Norio Inou[4] and Koutaro Maki[1]

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Abstract

The assessment of jaw movements is a common method of evaluating stomatognathic function. However, with conventional methods, detailed examination of the interrelationship between maxillofacial morphology, tooth morphology, and jaw movements is difficult. Therefore, we engineered a method of analyzing individual three-dimensional (3D) jaw movements along a time axis. This study included five adult patients with permanent dentition and no notable oral parafunctional habits who visited the orthodontic department of the Showa University Dental Hospital. We used a jaw movement analysis system to assess jaw movements during free mastication. We assessed the (1) movement trajectory of the main occluding area, (2) rate of change in the distance between the origin and the insertion of the masticatory muscles, and (3) contact patterns of the dentition. The results for (1) showed no interrelationships. For (2), the origin and insertion of the lateral pterygoid muscle exhibited characteristic changes. The analysis of the contact pattern between the upper and lower dentition showed the contact of the molars posterior to the first premolar when masticating on the balancing side. These results indicate that jaw movements occur in a way that is appropriate for the maxillofacial morphology when food is crushed during mastication. Additionally, the occlusal contact and condylar movement during mastication may be more affected on the balancing side than on the working side. Thus, the jaw movement analysis system used in this study was useful for movement analysis during functional activity.

Key words: mandibular movement, display system, masticating movement, molar movement trajectories, occlusal contact

Introduction

Stomatognathic function refers to mastication, swallowing, and phonation. Specifically, mastication is a part of the process of absorbing large amounts of energy into the body through food ingestion[1]. Masticatory movements are very important life activities and are learned and acquired naturally when transitioning from newborn to infancy[2]. A neurophysiological study revealed that the centers involved in controlling masticatory movements are programmed in the brainstem similar to that of walking and respiration[3]. These movements are also affected by peripheral information from the teeth, masticatory muscles, temporomandibular joint, and other sources[4–6]. Further, they undergo various changes depending on the properties of the food and bolus in the oral cavity. The morphogenesis of the maxillofacial region occurs mainly through cartilaginous growth. Accordingly, it is thought to be closely related to the development of stomatognathic functions associated with mechanical factors, such as mastication and occlusal status[7–10].

Conventionally, mastication has been evaluated by measuring jaw movements, electromyographic measurements, and assessment of masticatory ability. Among these, jaw movement measurements have

* Corresponding author
✉ Eiichiro Minemura
minemura-e@dent.showa-u.ac.jp

[1] Department of Orthodontics, School of Dentistry Showa University, 2-1-1 Kitasenzoku, Ohta-ku, Tokyo 145-8515, Japan.
[2] Nac Image Technology Inc.
[3] Department of Engineering Design, Tamagawa University & Academy
[4] Organization for fundamental Research, Institute of Innovative Research, Tokyo Institute of Technology

generally involved observing the trajectories of jaw movements projected onto a two-dimensional (2D) plane. However, a detailed examination of the relationships between maxillofacial and occlusal morphology and stomatognathic functions such as jaw movements using conventional methods is difficult. Therefore, engineering methods of analysis that can identify each muscle involved in jaw movements generated by complex contractions of the masticatory muscles along a time axis are needed. Moreover, studying movement trajectories and occlusal contact status of the upper and lower teeth on the same time axis is necessary.

Thus, this study aimed to devise a new method of examining in detail the interrelationships between maxillofacial morphology and stomatognathic functions during mastication, specifically regarding occlusal surface morphology and jaw movements. We used an analysis system that can make detailed observations of jaw movements in each patient[11–13] to assess jaw movement trajectories and occlusal contact status during mastication.

Materials and methods

The jaw movement analysis system used in this study requires cone-beam computed tomography (CBCT; Hitachi, CB MercuRay or KaVo, 3D eXam) images of the patients and computed tomography (CT; Comscan, ScanXmate-130SS940) of their plaster models. The 3D model is constructed by integrating these image data. Upper and lower jaw movement data were collected using an optical method with a high-speed CCD video camera (Library, Himawari SP200-W). The jaw movements of each participant were visualized through moving images based on these data (Figure 1). This allowed us to reproduce the maxillofacial morphology unique for each participant (resolution, 0.377 mm/pixel). This system made it possible to analyze movements in four

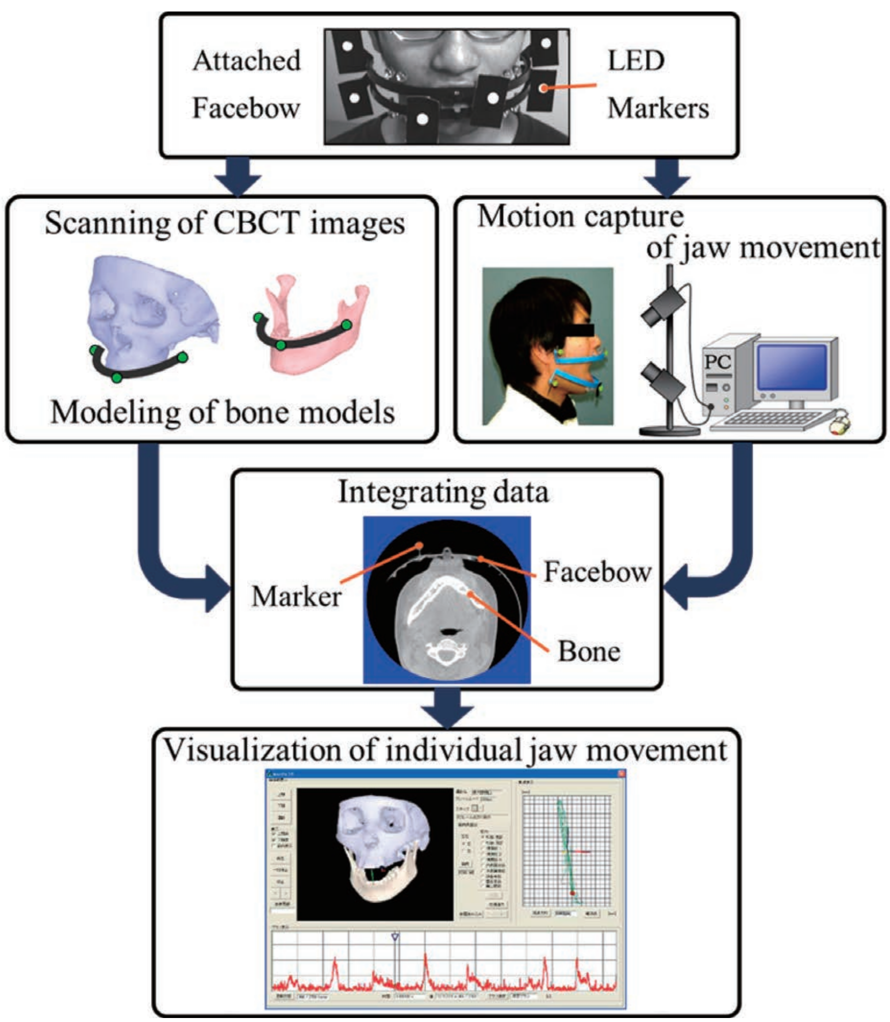

Fig. 1. Diagram of the three-dimensional display system. This shows the procedure up until the display of individuals' jaw movement. This was obtained from the coauthor's manuscripts[11–13].

Table 1. Outline of CCD video cameras used

Specifications of video cameras.	
Camera	Library Inc. "HIMAWARI" SP200-W × 2 units
Output data	Continuously 480 × 640 pixel Bitmap gray scale images
Sampling frequency	50 ～ 200 fps

This displays the details of the CCD cameras used to measure jaw movement.

Camera frame.	
Size of camera case	90 × 140 × 740
Angle between cameras	π / 3 rad
Distance between cameras	600 mm

This shows the details of the CCD camera frames used to measure jaw movement.

Table 2. Specifications of dental CBCT device and industrial CT device

	Dental CBCT device		Industrial CT device
manufacture	CB MercuRay	3DeXam	ScanXmate-130SS940
Image size	512 pixel × 512 pixel	576 pixel × 576 pixel	1,024 pixel × 1024 pixel
Image area	193 mm × 193 mm	170 mm × Φ230 mm	88 mm × 88 mm
Resolution of images	0.377 mm/pixel	0.400 mm/pixel	0.86 mm/pixel
Slice number	512	432	～ 1,024 (Adjusted to the thickness)
Slice thikness	0.377 mm	0.400 mm	0.086 mm

This displays details about the equipment used for CBCT and CT imaging.

dimensions, including time, on a 3D model with a resolution of 0.09 mm/pixel in the region of dentition. Tables 1, 2 show the specifications of the measuring equipment used in this system.

The 3D jaw model constructed with this method is a hybrid jaw model reproduced by integrating CT images. One type uses industrial CT images that show the shape of the dentition in high resolution. The other type uses CBCT images of the jaw morphology. This allows for simultaneous observations of the overall shape of the jaw and detailed shape of the crowns. Therefore, when integrating these models, accurate aligning of both CT images is important. The matching process used in this method has been shown to have an alignment accuracy of approximately 0.1 mm (Figure 2).

The study participants were patients with permanent dentition and no notable oral parafunctional habits who visited the orthodontic clinic of Showa University Dental Hospital. Patients with congenital diseases, jaw deformities causing severe facial asymmetry, and centric occlusion with an extremely small area of occlusal contact were excluded. Informed consent was obtained from all participants.

For observations that take into account the maxillofacial morphology, according to the classification of Sassouni[14], the system and methods devised in this study were evaluated in five adult participants (male, n = 1 ; female, n = 4), as shown in Figure 3.

A gum (Lotte, XYLITOL) was used as food in the jaw movement analysis because its movement trajectory is easy to observe. Free masticatory movements were measured for approximately 10 s. The three items described below were examined based on these measurements.

Observation of the movement trajectory at the main occluding area

The observation points for the trajectory of movements were determined by referencing previous reports on the main occluding areas[15–17]. The main occluding area was defined as "an area located in the first molar that has evolved to the center of functionality for grinding food during mastication." A simple examination using stopping is generally used for the assessment. Following this, we used a tablet-

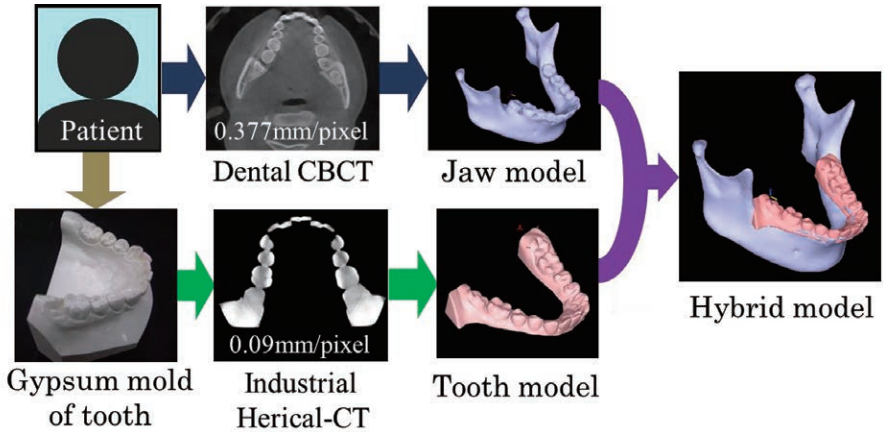

Fig. 2. Procedure of generating a hybrid model. This shows the steps for creating a three-dimensional jawbone model. This was obtained from the coauthor's manuscripts[11-13].

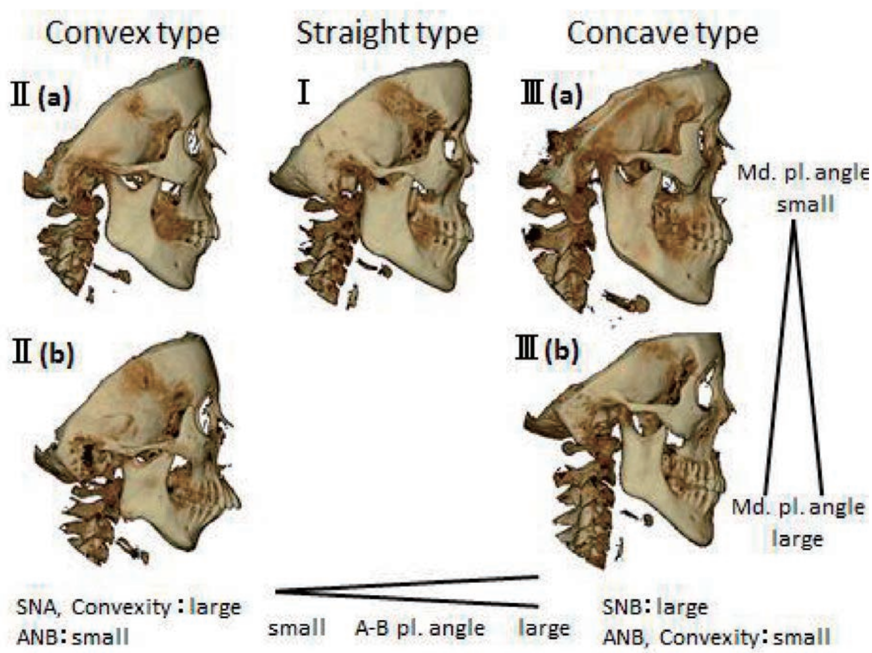

Fig. 3. Classification of maxillofacial morphology. SNA, SNB, ANB, A-B plane angle, and mandibular plane angle-cephalometric analyses were used as indicators for skeletal assessment during classification.

shaped gum that was divided into smaller pieces of about 4 × 4 mm when estimating the main occluding area. Using this, we visually observed the type of teeth and site where the gum was crushed during the initial mastication. Table 3 shows the main occluding area of each participant, which was estimated using this simple examination. After determining the observation points, the trajectory of movements was projected onto a cross-section that included its tangent line, and the state of contact with the occlusal surface of the maxillary teeth was observed.

Table 3. Main Occluding Area

maxillofacial morphology	Main Occluding Area
I	Lower left side first molar distal area
Ⅱ (a)	Lower right side first molar distal area
Ⅱ (b)	Lower right side first molar distal area
Ⅲ (a)	Lower right side first molar distal area
Ⅲ (b)	Lower right side first molar mesial area

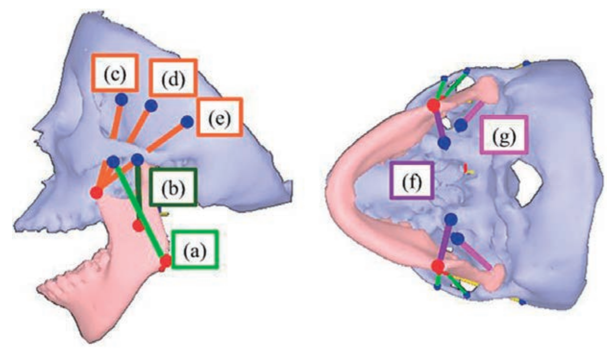

Fig. 4. Setting the points corresponding to the origin and insertion of the masticatory muscles. Points (a) to (g) were set arbitrarily.
(a) Superficial masseter muscle (SMM), (b) deep masseter muscle (DMM), (c) anterior temporal muscle (ATM), (d) middle temporal muscle (MTM), (e) posterior temporal muscle, (f) medial pterygoid muscle (MPM), and (g) lateral pterygoid muscle (LPM).

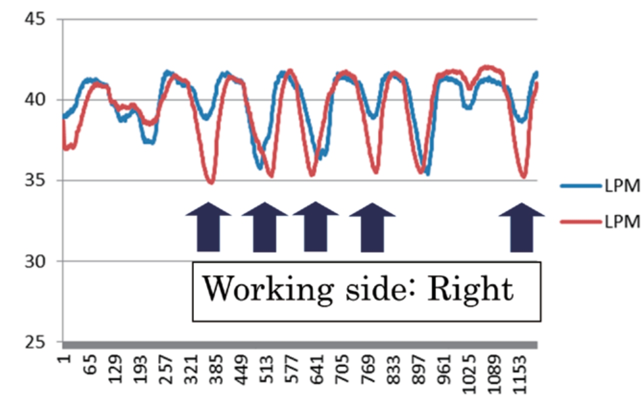

Fig. 5. Change in the length of the lateral pterygoid muscle. The vertical axis shows the distance (cm) between the origin and insertion, and the horizontal axis shows time (camera frame rate: 0.005 s/frame).

Measurement of the rate of change in the distance between the origin and the insertion of the masticatory muscles

Points corresponding to the origin and insertion of muscles were designated in the 3D models, and a program was used to measure the distance between the two points. The change in the distance between the two points was assessed by measuring the difference in the distance at rest and during chewing. Figure 4 shows the points that could be established, including the jaw opening and closing muscles. To establish the origin and insertion of the lateral pterygoid muscle (LPM), we used the pterygoid process of the sphenoid bone and the pterygoid fovea, which are the origin and insertion of the inferior head of the LPM that could be established on the models. The formula used for the ratio of the length change of the masticatory muscles is as follows:

$$\frac{(\text{Distance of rest}) - (\text{Distance during gum mastication})}{(\text{Distance of rest})} \times 100(\%)$$

Analysis of occlusal contact patterns

A program for detecting sites where the distance between voxel data for maxillary and mandibular dentition was within 0.1 mm was used to analyze the patterns of occlusal contact over time during gum mastication. This analysis requires determining whether the working side is the left or right side in each movement cycle. However, this system does not have a food-display function. Moreover, the condition of the motion measurement was free mastication. Therefore, from the movement observations alone, it was not possible to determine the working side for actual food chewing. Therefore, we focused on the change in the LPM length over time (Figure 5). This was obtained by plotting the chronological changes in the distance between the origin and insertion of the masticatory muscles as described above. The assessment was based on the anatomical characteristics of the participants, namely, the mandibular condyle moved a greater anteroposterior distance on the balancing side than on the opposite working side during unilateral gum chewing[18–21]. Therefore, the working side was determined to be the one with the smaller change in the distance for the LPM.

The time of appearance of the minimum value on this graph (Figure 5) was considered the time when there was the largest deviation of the lower jaw. The working and balancing sides were determined by comparing the changes in the distance between the origin and insertion of LPM on both sides at that time.

Results

movement trajectory of the main occluding area

Figure 6 shows the relationships between the movement trajectory of the main occluding area and the opposing maxillary tooth.

The movement trajectories of the main occluding areas when chewing gum exhibited different shapes of trajectories, 3D directions of the movement, and contact distances with the opposing tooth surface. However, no relationships were observed between maxillofacial morphology and either tooth occlusal surface morphology or jaw movements. In addition,

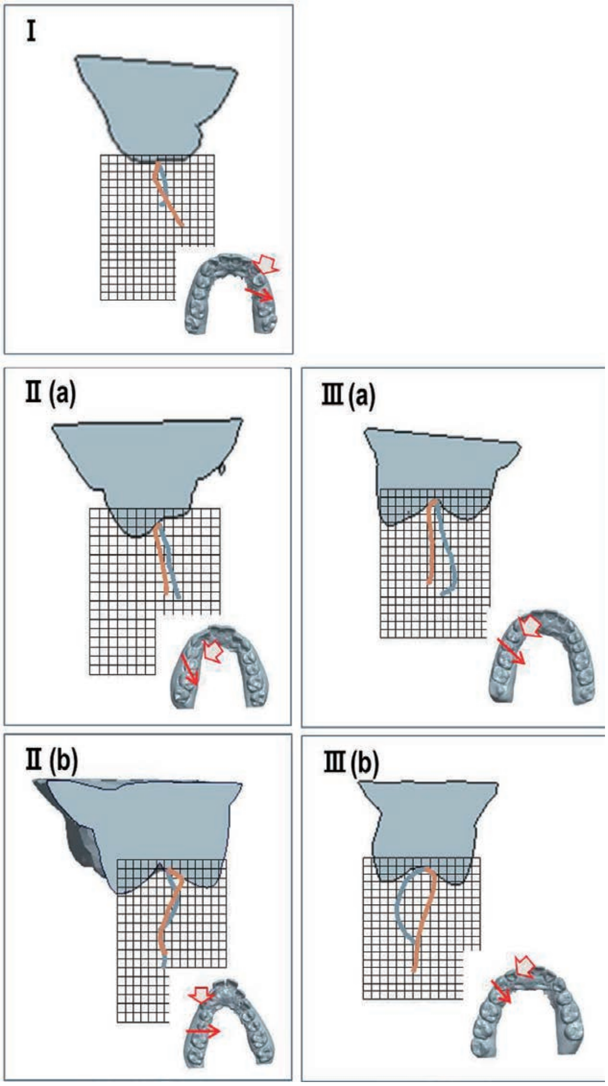

Fig. 6. Molar trajectory while masticating gum. In each figure, the cross-sectional shapes of the teeth were cut perpendicular to the paper surface in the direction indicated by the thin arrow on the maxillary dentition and observed from the direction of the thick arrow. The solid line indicates the trajectory of movement when the observation point is each subject's main occluding areas, as shown in Table 3. The red and blue parts of the trajectory indicate the mouth-opening and mouth-closing trajectories, respectively.

as shown in Table 3, the main occluding areas were used as the observation points in all patients.

Rate of the change in the distance between the origin and insertion of the masticatory muscles

Table 4 shows the rate of change in the distance between the origin and insertion of the masticatory muscles during upper–lower dentition contact for each participant while at rest and while chewing gum.

Compared with other types, types II (a) and II (b) exhibited significantly less change in the distance between the origin and insertion of the LPM. In addition, the bilateral anterior, middle, and posterior temporal muscles exhibited significantly higher values.

Occlusal contact patterns of the upper and lower dentition

Figure 7 shows the contact patterns for the teeth during gum mastication for each type of maxillofacial morphology. Although tooth types varied among participants, the occlusal contact was observed at the moment of grinding of food pieces during gum mastication in all participants for molars posterior to the balancing-side canine but at different times in relation to the working-side contact. These contacts were all to the lateral-incline surface of the palatal cusp or medial-incline surface of the buccal cusp. The contact sites were substantially consistent when the contact states between cycles were analyzed in each participant. In addition, there was an observed tendency for the contact sites and the contact range to increase on both working and balancing sides as gum mastication time progressed.

Discussion

movement trajectory of the main occluding area

Trajectories of motion at the observation points were different between each participant in the contact distance to the maxillary tooth surfaces of the

Table 4. Ratio of length change (%) between origin to insertion of masticatory muscles, SMM: Superficial masseter muscle, DMM: Deep masseter muscle, ATM: Anterior temporal muscle, MTM: Middle temporal muscle, PTM: Posterior temporal muscle, MPM: Medial pterygoid muscle, LPM: Lateral pterygoid muscle, R: Right side, L: Left side

	SMM (R/L)	DMM (R/L)	ATM (R/L)	MTM (R/L)	PTM (R/L)	MPM (R/L)	LPM (R/L)
I	0.6/0.4	0.8/0.6	1.0/1.0	1.1/1.2	0.9/0.9	0.7/0.6	−0.9/−0.6
II (a)	4.8/5.9	5.0/8.0	9.0/9.9	8.6/11.0	4.8/9.0	6.7/5.9	−2.9/−3.7
II (b)	0.8/−0.2	0.2/−0.1	2.4/1.8	2.9/2.2	2.3/2.6	0.3/1.0	−3.2/−1.0
III (a)	0.1/1.0	0.5/0.8	−0.6/−0.1	−0.6/−0.8	−0.6/−1.5	−1.7/1.4	−0.2/1.9
III (b)	1.2/2.1	1.4/4.0	1.3/2.6	1.1/2.3	0.5/1.0	1.3/2.8	−1.4/−0.3

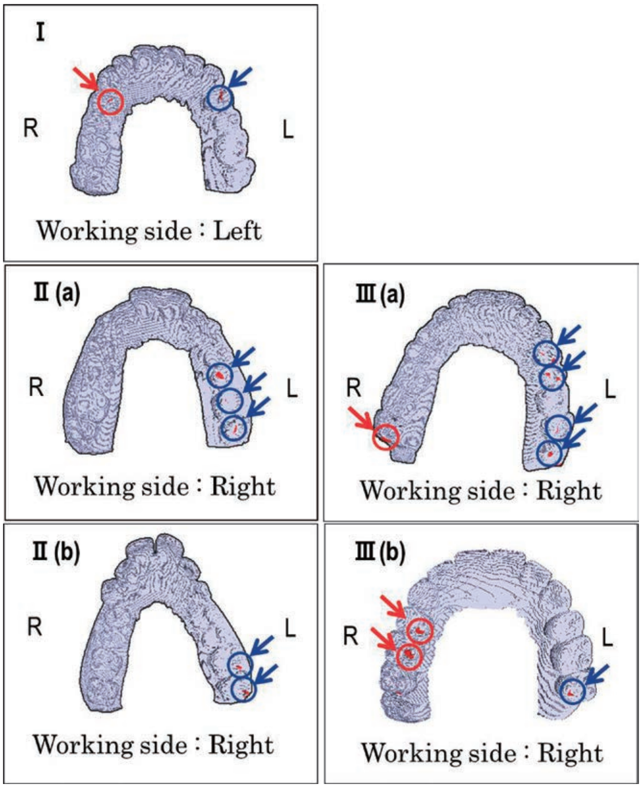

Fig. 7. Analysis of tooth contact. Portions where the distance between the voxel data in maxillary and mandibular dentition was within 0.1 mm were regarded as contact portions during the mouth-closing trajectory in one cycle of the second to fourth cycles after the start of mastication of a gum tablet. The working side is shown with red arrows and circles, and the balancing side is shown with blue arrows and circles.

antagonist teeth, direction of 3D deflection, and shape of the movement trajectory. However, an association was not observed between maxillofacial morphology and the dental occlusal form or jaw movement. We attribute this to the 3D characteristic of masticatory motion and occlusal contact changes over time simultaneously with its occurrence in multiple teeth. Therefore, evaluating the movement pathways at any single observation point was difficult. Although the main occluding areas employed as observation points for the five participants were different from the right to left, the type of tooth—mandibular first molar—was consistent for all five participants (Table 3). This result supports the existence of the main occluding areas[17], which have previously been noted in the literature.

Rates of change in the distance between the origin and insertion of the masticatory muscles

These rates of change were compared between maxillofacial morphological types. Compared with the other types, the convex type (skeletal type II (a) and II (b) exhibited lower rates of change in the distance between the origin and insertion of the LPM. This is premised on designating the pterygoid process as the LPM origin and insertion as an area equivalent to the pterygoid fossa, which means when crushing gum, the bilateral mandibular condyles are pushed more posteriorly than when at rest. A previous study on the relationship between maxillofacial morphology and the temporomandibular joint found that bilateral internal derangement and osteoarthritis were significantly more frequent in cases of maxillary prognathism accompanied by the inclination of the inferior mandibular plane and mandibular retraction, i.e., skeletal class II[22]. This suggests that temporomandibular joint lesions can affect maxillofacial morphology. However, our results suggest that jaw movements may affect the formation of temporomandibular joint lesions or maxillofacial morphology, or the possibility of mutual influence.

Contact pattern of the upper and lower dentition

We assumed that during the second to fourth chewing cycles, gum has some hardness and maintains its original shape to some degree. At this time, occlusal contact was observed on the balancing-side molars when crushing food particles. Further, the occlusal contact area and range increased over time on both the working and balancing sides. This phenomenon was confirmed in all cases regardless of the differences in maxillofacial morphology, and with some exceptions, the contact patterns were similar. This study performed assessments during chewing gum, although another study obtained similar findings on the occlusal contact of the balancing-side molars in an investigation of occlusal contact near the central occlusal position using articulating paper and other materials[23]. Since our results include an analysis of masticatory movements using food, we surmise that during food crushing, a gap for the food particles was created between the upper and lower jaws, which had greater effects on the balancing side. Further, regardless of the maxillofacial morphology, all participants exhibited occlusal contact in molars posterior to the first premolar on both the working and balancing sides and similarities in contact patterns.

This result is consistent with the findings of Satsuma *et al*.[24,25], who examined the condylar movement during clenching. They found that during maximum muscle activity of the working-side masseter muscle, the condyle was significantly superior on the balancing side than on the working side. They also pointed out the importance of a greater mechanical load on the balancing side condyle during clenching. Okubo *et al*.[26–29] demonstrated that when an occlusal force is exerted with food interposed, the occlusal contact generated on the balancing side creates mechanical stability, which they inferred was possibly rotating the mandible, with the working side as the fulcrum. From this, the occlusal contact and movement pattern on the balancing side when crushing food during mastication might influence the maxillofacial morphology. This signifies that dentition width and inclination of the cusp slope are important for individual diagnoses and that the ideal arch in orthodontic therapy should not only have form but also functionality. These results show that in patients with a certain degree of occlusal contact in central occlusion, mandibular movement suited to the maxillofacial morphology is performed to obtain appropriate occlusal contact of maxillary and mandibular teeth when food is being ground during mastication.

Jaw movement analysis system and related programs

The system used in this study reproduces a participant-specific 3D hybrid jaw model and reproduces the motion data acquired by optical methods in a 4D image. For the hybrid jaw model created by this method, the STL data of the dentition shape was created using industrial CT data by which evaluating the image accuracy is easy as in a previous study. However, the motion measurement using an optical method was used to obtain motion data. In this case, the upper and lower facebows with labeling points are fixed only in the teeth. When fixing the facebows for measurement, they are attached to the labial cervix of the lower anterior teeth to avoid affecting the occlusal contact between the upper and lower teeth as much as possible. Through this, the influence of the head position, skin, and facial muscles is minimized, and measurement of the jaw movement is achieved with less error. Furthermore, analyzing the expansion and contraction of masticatory muscles and occlusal contact state of the upper and lower dentition in the time axis is possible, but not with conventional methods. Moreover, the motion trajectory at any observation point in both the 2D and 3D spaces can be observed. This allows for detailed examination of biological functions, which was difficult with conventional methods. However, regarding motion analysis, as the jaw is considered a rigid body when analyzing jaw movements in a living body, we should consider the shaking of the teeth and jaw distortion and evaluate their effects as well.

The summary of the findings is as follows:

・When chewing food during mastication, the mandibular movements may be suited to the maxillofacial morphology, such that appropriate occlusal contact for crushing food occurs between the upper and lower teeth.

・The occlusal contact and condylar movement during mastication may be more affected on the balancing side than on the working side, which may be involved in the formation of maxillofacial morphology.

・Assessments with the jaw movement analysis system and related programs, as utilized in this study, are useful for analyzing the contact between the upper and lower dentition and analyzing mandibular movements during functional activities.

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Conflict of interest disclosure

This study was conducted with the approval of the ethics committee of the Showa University School of Dentistry (Approval No. 2010–006). In addition, the authors have no conflicts of interest to declare regarding this paper.

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