Archives of Oral Biology 81 (2017) 198–205

Contents lists available at ScienceDirect

Archives of Oral Biology

journal homepage: www.elsevier.com/locate/archoralbio

Original research

Differences between the chewing and non-chewing sides of the mandibular first molars and condyles in the closing phase during chewing in normal subjects

Hiroshi Tomonari[a], Sangho Kwon[b], Takaharu Kuninori[b], Shouichi Miyawaki[b,*]

[a] Department of Orthodontics, Kagoshima University Medical and Dental Hospital, 8-35-1, Sakuragaoka, Kagoshima, Japan
[b] Department of Orthodontics, Kagoshima University Graduate School of Medical and Dental Sciences, 8-35-1, Sakuragaoka, Kagoshima, Japan

ARTICLE INFO

Keywords:
Mandibular first molar
Condyle
Mastication
Masticatory path

ABSTRACT

Objective: This study aimed to assess differences between the closing paths of the chewing and non-chewing sides of mandibular first molars and condyles during natural mastication, using standardized model food in healthy subjects.
Design: Thirty-two healthy young adults (age: 19–25 years; 22 men, 10 women) with normal occlusion and function chewed on standardized gummy jelly. Using an optoelectric jaw-tracking system with six degrees of freedom, we recorded the path of the mandibular first molars and condyles on both sides for 10 strokes during unilateral chewing. Variables were compared between the chewing side and the non-chewing side of first molars and condyles on frontal, sagittal, and horizontal views during the early-, middle- and late-closing phases.
Results: On superior/inferior displacements, the chewing side first molar and condyle were positioned superior to those on the non-chewing side during the early- and middle-closing phases. Conversely, the first molar and condyle on the non-chewing side were positioned significantly superior to those on the chewing side during the late-closing phase. On anterior/posterior displacements, the chewing side mandibular first molar and condyle were positioned significantly posterior to those on the non-chewing side throughout all closing phases.
Conclusion: Our results showed the differences between the mandibular first molars and condyles on both sides with respect to masticatory path during natural chewing of a model food. These differences can be useful for informing initial diagnostic tests for impaired masticatory function in the clinical environment.

1. Introduction

Mastication results from the interaction of an intrinsic, rhythmical neural pattern and sensory feedback generated by the interaction of the masticatory system with food (Lund, 1991; Lund and Kolta, 2006). The generation of a smooth masticatory movement of the mandible is important for health, to break down food particles into small pieces (Wang & Mehta, 2013; Wilding & Lewin, 1994; van der Bilt, 2011). During this processing of food, muscle activity is used to exert force and to control the direction of mandibular closure precisely (Pr & schel & Raum, 2001; Slagter, Bosman, van der Glas, & van der Bilt, 1993). The masticatory path during mandibular closure has been differentiated into two phases based on the activities of the mandibular closing muscles (Lund, 1991). The fast-closing phase, which has the lowest level of closing muscle electromyography activity, occurs directly after the start of jaw closure until the teeth come into contact with the food bolus. The resistance of the food slows down the lower jaw, and the jaw closure muscles become more active to overcome the resistance of the food; this is called the slow-closing phase. At the final mandibular closure, the so-called occlusal phase, there is approximately isometric contraction of the closure muscles, and numerous studies have shown that the pattern of the masticatory path is influenced by the individual pattern of occlusal guidance (Belser & Hannam, 1985; Hannam, De Cou, Scott, & Wood, 1977; Rilo, Fernández-Formoso, Mora, Cadarso-Suárez, & Santana, 2009; Witter, Woda, Bronkhorst, & Creugers, 2013).

It is assumed that the first molar region plays an important role in masticatory function, because the number of occlusal contacts as well as the magnitude of bite forces acting on them are greater for first molar teeth than for pre-molar or anterior teeth (Hidaka, Iwasaki, Saito, & Morimoto, 1999; Hattori et al., 2009). Previous studies have attempted to clarify the masticatory mechanism on the first molar and

* Corresponding author at: Department of Orthodontics, Field of Developmental Medicine, Health Research Course, Graduate School of Medical and Dental Sciences, Kagoshima University 8-35-1, Sakuragaoka, Kagoshima, Japan.
E-mail address: miyawaki@dent.kagoshima-u.ac.jp (S. Miyawaki).

http://dx.doi.org/10.1016/j.archoralbio.2017.05.006
Received 31 May 2016; Received in revised form 1 May 2017; Accepted 14 May 2017

condylar points. In natural chewing, it has been reported that the path of the lower central incisor point differs from that of the mandibular first molar at final closure (Dejak, Młotkowski, & Romanowicz, 2003; Gibbs & Lundeen, 1982; Gibbs, Lundeen, Mahan, & Fujimoto, 1981; Hayasaki et al., 2003; Miyawaki et al., 2001). The chewing side first molar moves slightly anteriorly (mean: 0.3 mm; range, 0–0.54 mm) in the final closing path (Gibbs et al., 1981). Furthermore, a previous study has reported that the condyle underwent a large upward movement on the non-chewing side during controlled submaximal clenching using unilateral occlusal stops (Okano, Baba, & Ohyama, 2005). In addition, it has been revealed that the condyle–fossa distance on the non-chewing side was smaller than that for the opening phase of a chewing cycle, as determined by measuring the variation of the minimum condyle–fossa distance (Palla, Gallo, & G & ssi, 2003). These reports suggested that the mandibular jaw tilts due to a slight elevation of the non-chewing side mandibular arch during the final stage of mandibular closure. However, the differences between the functional and non-functional sides in the paths of the mandibular first molar and condyle throughout mandibular closure during natural chewing are not known.

The aim of this study was to assess the differences between the closing paths of the chewing and non-chewing side mandibular first molars and condyles during natural mastication using standardized model food. For this purpose, we examined the masticatory paths, by directly observing the mandibular first molars and condyles on both sides in the frontal, sagittal, and horizontal view during unilateral chewing with normal occlusion.

2. Materials and methods

2.1. Subjects

The study protocol was reviewed and approved by the Ethics Committee at our hospital (#25-116). The study was conducted in full accordance with ethical principles, including those of the World Medical Association Declaration of Helsinki. It is advisable to give ethical approval upfront. All subjects provided their written, informed consent after receiving an explanation of the study's goals and structure.

Thirty-two healthy young adults (mean age: 22.7 years; range: 19–25 years; 22 men, 10 women) with normal occlusion and function were selected for this study. We examined the participants' clinical information and clinical signs and symptoms of temporomandibular disorders (TMDs), (i.e., temporomandibular joint [TMJ] sounds, tiredness/stiffness, pain, limitations in opening the mouth (< 5.0 mm), and TMJ locking or impaired opening) by clinical examination and questionnaires based on the Research Diagnostic Criteria for TMD Axis I (Dworkin & LeResche, 1992). The study inclusion criteria included: (1) a complete Angle Class I canine and molar relationship, (2) normal overjet and overbite, (3) fully emerged permanent dentition (excluding third molars), (4) no signs or symptoms of TMD, (5) little crowding and rigid intercuspation, and (6) no current or recent dental or orthodontic treatment.

2.2. Test foodstuffs

Standardized 5-g gummy jelly (Meiji Seika Kaisha Confectionery R & D Labs, Saitama, Japan) (Kitashima, Tomonari, Kuninori, Uehara, & Miyawaki, 2015; Miyawaki et al., 2005; Tomonari et al., 2014b) was specially prepared for the present study. The shape of the gummy jelly was similar to that of a truncated cone (5-g gummy jelly: height, 11 mm; top diameter, 12 mm; base diameter, 22 mm). The truncated cone shape was chosen because of its high stability, which ensured that a consistent height could be maintained when positioning the food on the occlusal surface and during chewing. Other relevant characteristics of the food used in the present study were as follows:

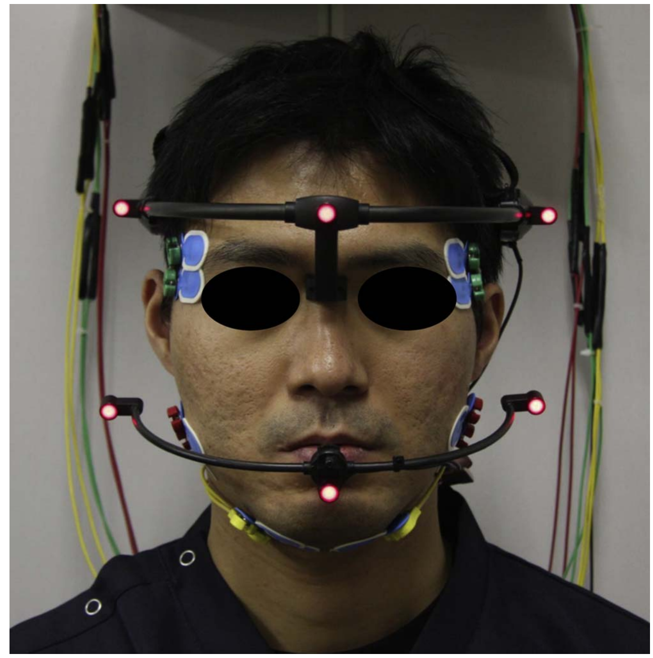

Fig 1. Subject is wearing a head frame and a face bow fixed to the end of a dental clutch at the CO position.

color (yellow), taste (orange), hardness (30.5 kg), cohesiveness (0.89 TU), and strain (21.9 TU). The mechanical characteristics of the test gummy jelly were measured using a texturometer (GTX-2, Zenken Company Ltd., Tokyo, Japan), as previously described (Miyawaki, Ohkochi, Kawakami, & Sugimura, 2001b).

2.3. System for recording masticatory path

2.3.1. Jaw movement

For all participants, we examined the lower central incisor, mandibular first molar, and TMJ paths on both sides, during open − close jaw movement using an optoelectric jaw-tracking system with six degrees of freedom (Kitashima et al., 2015; Miyawaki, Tanimoto, Kawakami, Sugimura, & Takano-Yamamoto, 2001a; Tomonari, Ikemori, Kubota, Uehara, & Miyawaki, 2014a). The system consisted of a head frame, a face bow, a pointer, light-emitting diodes (LEDs), CCD cameras, an amplifier, and a personal computer (Gnathohexagraph system Ver. 1.31; OnoSocki Ltd, Kanagawa, Japan) (Fig. 1). The sampling frequency was 89.3 Hz. The accuracy of the optical recording system was assessed using the method described by Tokiwa (Tokiwa 2001). They established 1530 three-dimensional reference points inside a 140 (X-axis) by 160 (Y-axis) by 50 mm (Z-axis) cuboid at 10-mm intervals using a full view of the XYZ stage-type calibrator. These reference points were located with LEDs and measured by the Gnathohexagraph system. Finally, the mean differences and standard deviation of the reference points and measurement points was calculated. The results of the accuracy tests for the equipment showed that the three-dimensional accuracy in terms of mean difference was 0.12 mm (standard deviation [SD] $\pm$ 0.06 mm). The head frame and face bow, each with three LEDs, were attached securely to the head and the dental clutch, which was bonded to the labial surface of the lower incisors. The clutch was bent to ensure that the movement of the mandible and lip was inhibited as little as possible. Using a pointer with two LEDs, the three-dimensional positions of the porion on both sides and the left infra-orbital point (Frankfort plane as the horizontal reference plane) were recorded by the jaw-tracking system. The lower central incisor point and the mandibular first molars' mesio-buccal cusps on the right and left sides were also recorded using this pointer. Subsequently, the bilateral condylar points were identified on the skin

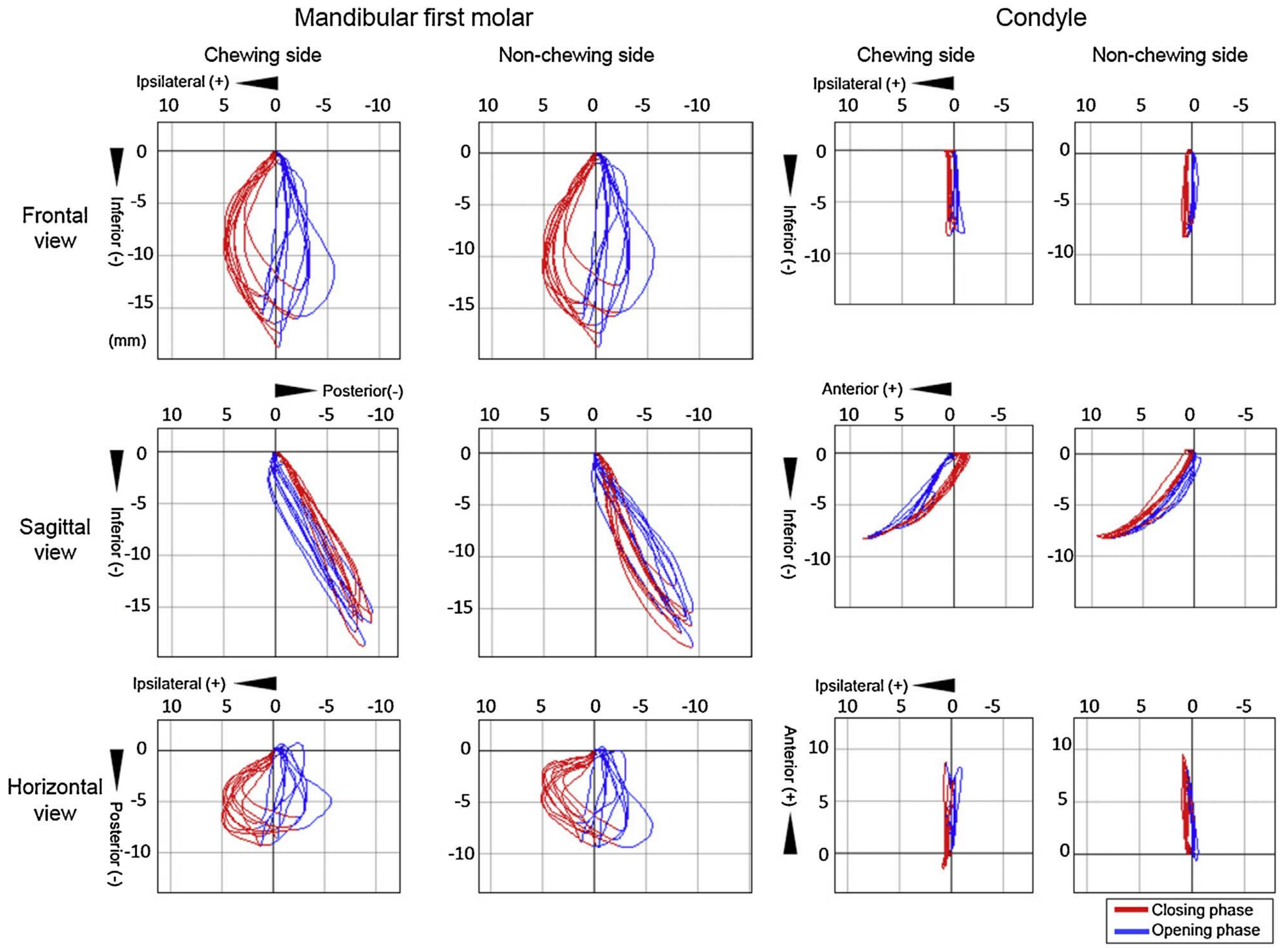

Fig. 2. Ten chewing cycles of the mandibular first molar and condyle on the chewing and non-chewing sides during unilateral mastication of gummy jelly, on frontal, sagittal, and horizontal views in one subject.

Table 1
Comparison of the displacement of the mandibular first molar between the chewing and non-chewing sides during the early-, middle-, and late-closing phases.

	Chewing side first molar		Non-chewing side first molar		Difference			
	Mean	SE	Mean	SE	Mean	95% confidence interval		P-value
Anterio/Posterior								
Maximum gap	−6.7	0.4	−5.9	0.4	−0.8	−1.2	−0.5	0.000
Early-closing phase 1	−6.0	0.4	−4.5	0.4	−1.5	−1.9	−1.2	0.000
Early-closing phase 2	−3.8	0.3	−2.1	0.3	−1.7	−1.9	−1.4	0.000
Middle-closing phase 1	−1.6	0.2	−0.5	0.2	−1.1	−1.2	−0.9	0.000
Middle-closing phase 2	−1.0	0.1	−0.6	0.1	−0.4	−0.5	−0.3	0.000
Late-closing phase 1	−0.9	0.1	−0.7	0.1	−0.2	−0.2	−0.1	0.000
Late-closing phase 2	−0.7	0.1	−0.6	0.1	−0.1	−0.2	0.0	0.000
Superior/Inferior								
Maximum gap	−13.7	0.5	−14.2	0.5	0.5	0.2	0.7	0.000
Early-closing phase 1	−11.8	0.4	−12.8	0.4	1.0	0.8	1.2	0.000
Early-closing phase 2	−7.4	0.3	−8.9	0.3	1.5	1.3	1.7	0.000
Middle-closing phase 1	−3.4	0.2	−4.6	0.2	1.2	1.0	1.3	0.000
Middle-closing phase 2	−1.8	0.1	−2.1	0.2	0.3	0.2	0.4	0.000
Late-closing phase 1	−1.3	0.1	−1.2	0.1	−0.1	−0.2	0.0	0.039
Late-closing phase 2	−1.2	0.1	−1.0	0.1	−0.2	−0.3	−0.1	0.000
Ipsilateral/Contralateral								
Maximum gap	1.4	0.3	1.5	0.3	−0.1	−0.1	0.0	0.514
Early-closing phase 1	3.2	0.3	3.2	0.3	0.0	−0.1	0.0	0.100
Early-closing phase 2	4.1	0.2	4.1	0.2	0.0	−0.1	0.0	0.364
Middle-closing phase 1	3.0	0.2	3.0	0.2	0.0	−0.1	0.0	0.594
Middle-closing phase 2	1.4	0.1	1.4	0.1	0.0	0.0	0.0	0.500
Late-closing phase 1	0.6	0.1	0.6	0.1	0.0	0.0	0.0	0.488
Late-closing phase 2	0.2	0.1	0.2	0.1	0.0	0.0	0.0	0.017

P-value: paired *t*-test or the Wilcoxon rank sum test

Table 2
Comparison of the displacement of the condyle between the chewing and non-chewing sides during the early-, middle-, and late closing phases.

	Chewing side condyle		Non-chewing side condyle		Difference			
	Mean	SE	Mean	SE	Mean	95% confidence interval		P-value
Anterio/Posterior								
Maximum gap	2.1	0.5	4.7	0.5	−2.6	−3.6	−1.4	0.000
Early-closing phase 1	0.8	0.3	5.9	0.5	−5.1	−6.0	−4.1	0.000
Early-closing phase 2	−0.4	0.2	5.2	0.4	−5.6	−6.4	−4.8	0.000
Middle-closing phase 1	−0.5	0.1	3.1	0.2	−3.6	−4.1	−3.0	0.000
Middle-closing phase 2	−0.1	0.1	1.3	0.1	−1.4	−1.7	−1.0	0.000
Late-closing phase 1	0.0	0.1	0.7	0.1	−0.7	−0.9	−0.4	0.000
Late-closing phase 2	0.1	0.1	0.4	0.1	−0.3	−0.5	−0.1	0.002
Superior/Inferior								
Maximum gap	−5.9	0.3	−7.5	0.4	1.6	1.0	2.3	0.000
Early-closing phase 1	−4.0	0.3	−7.6	0.4	3.6	2.9	4.3	0.000
Early-closing phase 2	−1.4	0.2	−6.5	0.3	5.1	4.5	5.8	0.000
Middle-closing phase 1	0.0	0.1	−4.0	0.3	4.0	3.4	4.5	0.000
Middle-closing phase 2	−0.1	0.1	−1.3	0.2	1.2	0.7	1.7	0.000
Late-closing phase 1	−0.4	0.1	−0.1	0.2	−0.3	−0.8	0.1	0.101
Late-closing phase 2	−0.6	0.1	0.1	0.1	−0.7	−1.0	−0.3	0.000
Ipsilateral/Contralateral								
Maximum gap	0.2	0.1	0.3	0.2	−0.1	−0.2	0.0	0.011
Early-closing phase 1	0.4	0.2	0.6	0.2	−0.2	−0.3	−0.1	0.001
Early-closing phase 2	0.5	0.1	0.7	0.1	−0.2	−0.4	−0.1	0.000
Middle-closing phase 1	0.5	0.1	0.6	0.1	−0.1	−0.2	0.0	0.005
Middle-closing phase 2	0.5	0.1	0.6	0.1	−0.1	−0.1	0.0	0.147
Late-closing phase 1	0.5	0.1	0.5	0.1	0.0	0.0	0.0	0.476
Late-closing phase 2	0.4	0.1	0.4	0.1	0.0	0.0	0.0	0.255

P-value: paired *t*-test or the Wilcoxon rank sum test.

by palpation of the lateral pole when a minor open − close movement was performed and was then recorded using the pointer. We calculated the location of reference points on condyle 20 mm medial from the skin (Gibbs & Lundeen, 1982) and used it to define the condylar points on the right and left sides of each subject using the Gnasthohexagraph system (Hayashi and Iijima, 1987; Miyawaki et al., 2005). This three-dimensional coordinate system was defined using the Frankfort plane as the x–y plane and the line between the left and right porions as the y-axis. Therefore, the x-, y-, and z-axes represented the anterior–posterior, lateral, and inferior–superior directions, respectively. Finally, we determined the three-dimensional positions of the bilateral mandibular first molars and bilateral condylar points relative to the Frankfort plane (as the horizontal reference plane). Each participant was seated on a chair in an upright but comfortable position, with the head naturally oriented. During recording, they were asked to fix their eyes on a red point on the CCD camera. To determine the preferred chewing side (PCS), the subject was instructed to chew a piece of gum. During 30 s of free chewing, the numbers of strokes on the right and left were counted. This process was repeated three times, and the dominant side was defined as the PCS (Kitashima et al., 2015; Kuninori et al., 2014).

After the PCS had been determined, a gummy jelly was placed on the tongue of each subject, with the maximum intercuspation. Each subject performed unilateral chewing of the gummy jelly, on the PCS, twice. The complete masticatory sequence was recorded, from the first cycle to the final swallowing action. Because the first session was an exercise in which the subject first experienced chewing under experimental conditions and perceived the properties of the test food, the second session was used for analysis of masticatory paths.

2.3.2. Data analysis

For the analysis of the masticatory path data during unilateral mastication, 10 representative cycles were selected using custom software (University of Kagoshima, Kagoshima, Japan) (Kitashima et al., 2015; Kuninori et al., 2014; Tomonari et al., 2014a) (Fig. 2). As the properties of the test food changed throughout mastication, the masticatory paths were analyzed in the cycles performed during the initial stage of mastication. Exclusion criteria for the cycle included at least one of the following characteristics: (1) maximum opening < 5.0 mm, (2) minimum closing > 3.0 mm, or (3) cycle duration < 300 ms. For the analysis of chewing cycles, firstly, the average of 10 chewing cycles was divided into the opening phase and the closing phase, on the basis of the vertical displacement of the lower central incisor as seen in the frontal view. The opening phase is the section from the most superior position until the most inferior position of the masticatory cycle. The closing phase is the section from the most inferior position to the most superior position of the masticatory cycle. Secondly, the closing phase was divided into three phases of equally spaced duration in the closing phase: early-closing phase, middle-closing phase, and late-closing phase. Finally, seven points of the mandibular molars and condyles, at equally spaced intervals throughout the three closing phases (early-closing phase: 3 points, middle-closing phase: 2 points, and late-closing phase: 2 points) were compared between the chewing side and the non-chewing side.

2.4. Statistical analysis

In *a priori* power analyses, we performed a sample size calculation (Faul, Erdfelder, Lang, & Buchner, 2007) using data derived from a pilot study, with five normal subjects. Based on the parameters of interest, the difference between the chewing and non-chewing sides was 0.12 (SD, 0.04) at late-closing phase 2. Assuming a significance level of 0.05 and a power of 80%, with an effect size f of 0.57, the sample size calculation indicated that 26 subjects were required. In the present study, the 32 normal subjects exceeded the aforementioned required numbers. To examine differences between masticatory paths on the functional and non-functional sides, variables were compared between the chewing side and the non-chewing side for the first molar and condyle in terms of anterior/posterior and ipsilateral/contralateral displacement in each of the three phases. On the basis of the data distribution, the paired *t* test or the Wilcoxon rank-sum test was used to compare the masticatory path variables between the chewing and non-chewing sides. A *P* value < 0.01 was considered statistically signifi-

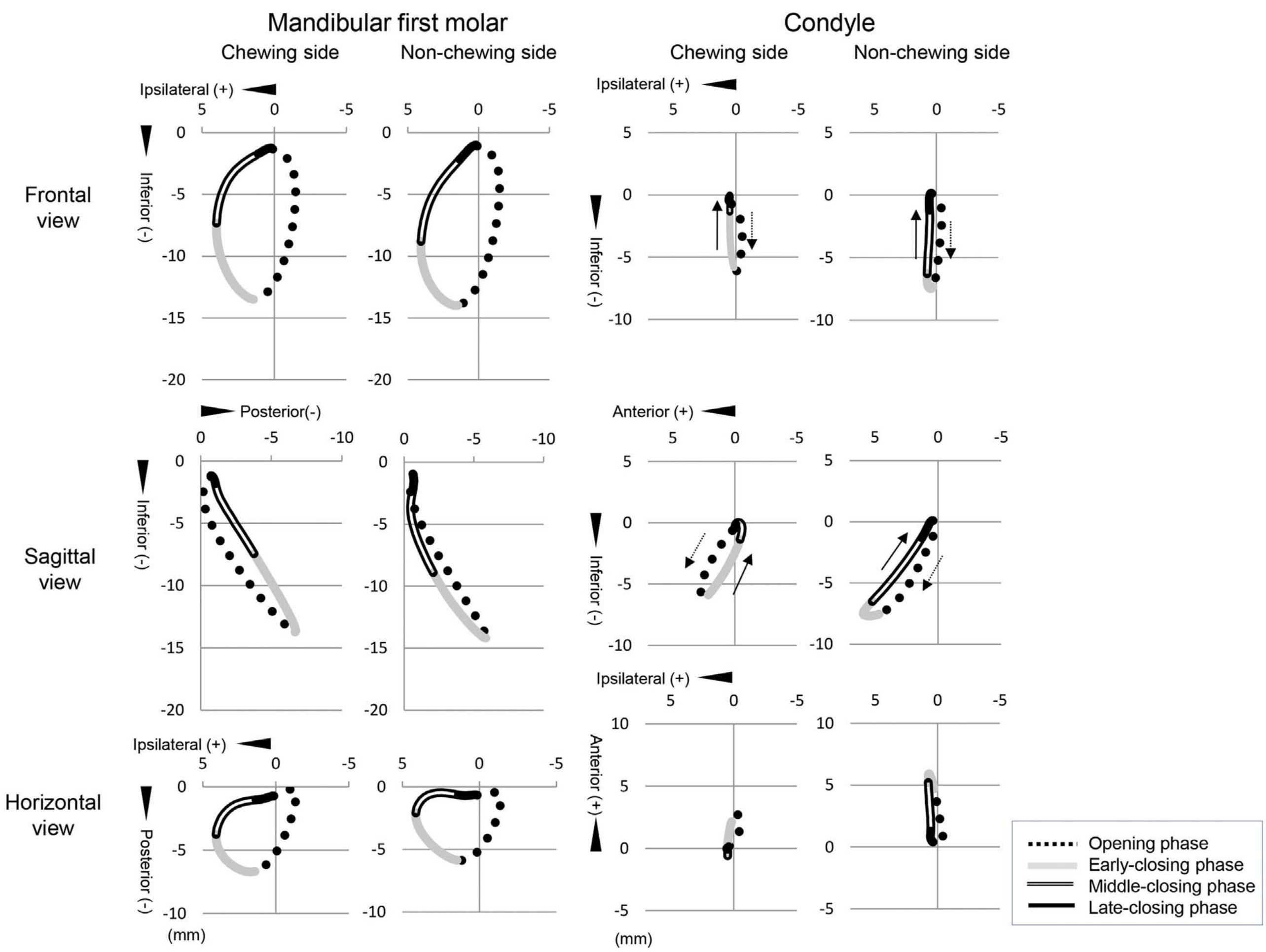

Fig. 3. Mean path of the mandibular first molar and condyle on the chewing and non-chewing sides during unilateral mastication of gummy jelly, in frontal, sagittal, and horizontal views in 32 subjects.

cant. Statistical analyses were performed using SPSS version 20 for Windows (SPSS for Windows; SPSS Japan, Tokyo, Japan).

3. Results

Tables 1 and 2 show the means and statistical significance of differences of the path of the mandibular first molar and condyle between the chewing and non-chewing sides during the early-, middle-, and late-closing phases in the anterior/posterior, superior/inferior, and ipsilateral/contralateral directions (Figs. 3 and 4). In superior/inferior displacements, the chewing side first molar was positioned superior to the first molar on the non-chewing side during the early- and middle-closing phases (mean difference: from 0.3 to 1.5 mm). Conversely, the non-chewing side first molar was positioned significantly superior to that on the chewing side during the late-closing phase (mean difference: −0.2 mm).

Similar to the path of the first molar, the chewing side condyle was positioned superior to that on the non-chewing side during the early- and middle-closing phases (mean difference: from 1.2 to 5.1 mm), and, conversely, the non-chewing side condyle was subsequently positioned significantly superior to that on the chewing side during the late-closing phase (mean difference: −0.7 mm).

In anterior/posterior displacements, the mandibular first molar on the chewing side was positioned significantly posterior to that on the non-chewing side throughout all closing phases, including the early-, middle-, and late-closing phase (mean difference: from −0.1 to −1.7 mm). Similar to the path of the first molar, the chewing side condyle was positioned significantly posterior to that on the non-chewing side throughout all closing phases (mean difference: from −0.3 to −5.6 mm).

In ipsilateral/contralateral displacement, the chewing side condyle was positioned more ipsilateral than on the non-chewing side during the early- and middle-closing phases (mean difference: from −0.1 to −0.2 mm), although there was no difference between the chewing side and non-chewing side paths of the mandibular first molars throughout the masticatory sequence.

4. Discussion

Previous investigations have attempted to clarify the masticatory mechanism based on incisor and condylar points, despite the fact that food crushing and tearing occur on the masticatory surfaces of the molars. Stresses and strains can be observed on the masticatory surface of the first molar during masticatory mandibular closure and can affect maxillo-mandibular formation (Korioth, 1990). For this reason, we attempted to identify differences between functional and non-functional paths of the mandibular first molar and condyle.

In this study, we showed that, during the early- and middle-closing phases, the chewing side first molar was positioned superior to that on the non-chewing side, and subsequently the non-chewing side first molar was conversely positioned superior to that on the chewing side during the late-closing phase. The difference in bilateral condylar paths between the chewing and non-chewing sides was observed to be similar to that of the first molar.

These inverse transpositions of the first molar and condyle between chewing and non-chewing sides from the middle-closing to the late-

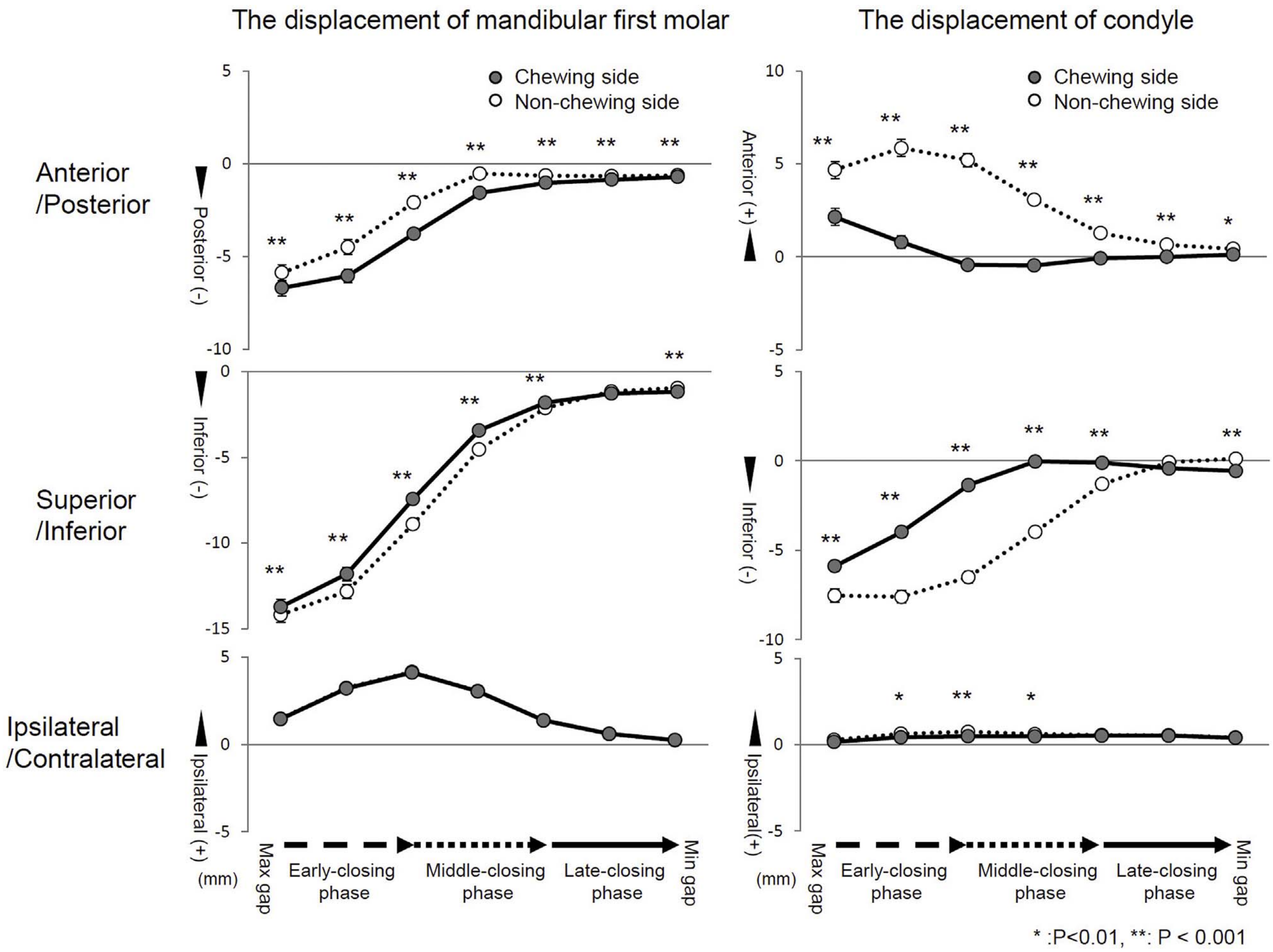

Fig. 4. Comparison of the displacement of the mandibular first molar and condyle between the chewing and non-chewing sides during the early-, middle-, and late-closing phases in the anterior/posterior, superior/inferior, and ipsilateral/contralateral directions. The seven points of the mandibular incisor and condyle are at equally spaced intervals throughout the three closing phases. The maximum gap reflects the most inferior position of the masticatory cycle, and the minimum gap reflects the most superior position of the masticatory cycle.

closing phase comprise a unique path of the mandible during masticatory mandibular closure. The upper and lower first molars on the functional side break down the food particles forcefully and smoothly, and efficiently mix the food with saliva to form a food bolus. Superior displacements of the chewing side molar during the early- and middle-closing phases can be considered a feed-forward control of rhythmic jaw movement that is not induced by peripheral organs (mainly periodontal receptor and muscle spindles) (Abbink, van der Bilt, Bosman, & van der Glas, 1997). The non-chewing side occlusal contacts have the potential to impair the smooth masticatory movement and can cause changes in jaw muscle activities (Nishigawa, Nakano, & Bando, 1997), although normal subjects often show contact on the non-chewing side during mastication (Anderson, 1976; Mohamed, Christensen, & Harrison, 1983). A previous study has suggested that human motor control applies a strategy primarily based on proprioception of the interocclusal distance to limit the impact of non-chewing side tooth contacts during unilateral chewing (Pr & schel, Jamal, & Morneburg, 2008; Pr & schel & Morneburg, 2002). The superior position of the chewing side first molar during the early- and middle-closing phases is thought to avoid occlusal contact of the non-chewing side, which could impair the smooth gliding movement.

In the late-closing phase, the superior displacement of the non-chewing side first molar is considered to cause resistance of food between the upper and lower molars on the functional side. In terms of this approximately isometric contraction of closure muscles, previous studies have investigated condylar movements on both sides under experimental, well-controlled submaximal clenching. (Baba, Yugami, Yaka, & Ai, 2001; Okano et al., 2005; Seedorf, Weitendorf, Scholz, Kirsch, & Heydecke, 2009). These studies demonstrated a slight elevation of the non-chewing side condyle. In addition, it has been reported that the decrease of the minimum condyle–fossa distance on closing is generally larger on the non-chewing side than on the chewing side (Palla et al., 2003). Our results, showing the superior positions of the mandibular first molar and condyle on the non-chewing side, as compared to those on the chewing side, are consistent with these previous reports. On the other hand, one of the questions often raised in dentistry is whether the chewing side TMJ is loaded during chewing. It has been reported that the condyle–fossa distance on the chewing side was slightly but statistically significantly smaller on closing than on opening; that is, it is loaded during the closing phase of chewing (Palla et al., 2003). In contrast, other reports showed that the chewing side condyle describes a closing path inferior to that of the opening path, which has been interpreted as proof that the chewing side condyle is distracted (Gibbs, Messerman, Reswick, & Derda, 1971). Our finding of an inferior excursion of the chewing side condyle, with slightly anterior displacement from the terminal position, is similar to that latter observation; that is, it is unloaded during the late-closing phase. In our experiment, occlusal contacts on the non-functional side were assumed to be absent, because the minimum gap remained about 1.2 mm, due to food resistance. The gummy jelly used in this study has been classified as belonging to the hardest food group according to a study that ranked conventional every-day foods based on 10 levels of hardness (Yanagisawa, Tamura, Teramoto, & Akasaka, 1989). The downward path of the chewing side condyle in this study may have been influenced by mandibular jaw tilting around a sagittal axis, which might have caused slight elevation of the mandibular first molar and condyle on the non-chewing side. The properties of food may contribute to loading of the TMJ during chewing.

The chewing side first molar has been reported to close on a lateral aspect, with small anterior components of movement during final closure; it can be assumed that this small movement is determined by occlusal contacts (Gibbs et al., 1981). Our results showed that the chewing side first molar is positioned posterior to the non-chewing side first molar throughout mandibular closure. These first molar masticatory paths derive from large anterior movements of the non-chewing side condyle, because few anterior/posterior movements were observed for the chewing side condyle, as also seen in a previous study (Palla et al., 2003). Jaw closing muscle contraction results in multiple occlusal contacts, directly or indirectly through food, when upper and lower teeth make contact. Using pressure-sensitive films to obtain information on all parameters, such as magnitude, direction, and point of application, the resultant bite-force has been shown to be slightly anteriorly inclined, from the perpendicular direction to the mandibular occlusal plane, during forceful intercuspal clenching (Hattori et al., 2009). The anterior path of the first molar from a posterior position may facilitate forceful and stable mastication.

A limitation of our study is that the pattern of the masticatory path was closely related to the individual pattern of occlusal guidance during the occlusal phase (Belser et al., 1985; Hannam et al., 1977 Hannam et al., 1977; Woda, Vigneron, & Kay, 1979), and it has been suggested that the masticatory path of closure before the occlusal phase is affected by muscles (Sato et al., 2007), TMJ form (Ogawa, Koyano, & Suetsugu, 1996), and by the inclination of the occlusal plane (Sato et al., 2007). These factors may also influence the masticatory paths of the first molars and condyles during mandibular closure.

In conclusion, we revealed that the masticatory path of the mandibular first molar, which performs the actual crushing and shearing of the food bolus on the chewing side, is quite different from that of the first molar on the non-chewing side throughout mandibular closure. The chewing side first molar is positioned superior to that on the non-chewing side from the beginning of mandibular closure to food contact, while the non-chewing side first molar, conversely, is positioned superior during the final closure, due to the resistance offered by the food. These inverse transpositions of first molar throughout mandibular closure also occurred in the bilateral condyles. Our results describe the differences between the mandibular first molars and condyles on both the chewing and non-chewing sides with respect to the masticatory path during natural chewing of a model food. These differences can be useful for informing initial diagnostic tests of impaired masticatory function in a clinical environment.

Conflict of interests

All authors declare that they have no potential conflict of interests with respect to the research, authorship, and/or publication of this article.

Funding sources

This study was partially supported by JSPS KAKENHI (23593036, 26463099, 17K11945, 15715758, 15H05051 and 15K11351).

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