原 著 論 文

Relationship between frontal/lateral mandibular translations and masticatory movement based on evaluation of occlusal surface motion

Toshinori Okawa [1)], Susumu Abe [1)], Masanori Nakano [2)], Kenji Oka[3)], Eriko Horikawa[1)], Fumiaki Kawano [1, 3)]

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Abstract : **Objective:** This study aimed to clarify whether crown restorations with adjusted occlusal surfaces that were formed using frontal/lateral mandibular translations, functioned without interference during mastication.

Materials and Methods: In 10 adult volunteers who had healthy normal dentition, frontal and lateral border movement was measured during unilateral mastication and free mastication, using an ultrasound digital mandibular measuring system (ARCUS digma2). Additionally, precise impressions of the upper and lower dental arch were taken, and dental casts were made. These casts were measured using a CAD/CAM scanning system (ARCTICA). For the fabrication of crown restorations, the functionally generated path technique (FGP technique) was used on the monitor for the lower first and second molar. The movement of the opposite teeth on the occlusal surface during frontal and lateral border movement, during unilateral mastication, and during free mastication was considered the functional occlusal surface. The data of the functional occlusal surface generated by frontal/lateral mandibular translations and that of each of the masticatory functional occlusal surfaces were superimposed using three-dimensional data evaluation software (GOM). The difference between these surfaces was evaluated to determine the interference area, maximum interference difference, and average interference difference.

Results: Interference was present for all functional occlusal surfaces created by mastication as well as those determined by frontal/lateral mandibular translations. The average interference values, in order of free masticatory movement, habitual masticatory side, and non-habitual masticatory side, were as follows. Interference area: 167.5 ± 20.8 mm^2, 121.9 ± 28.5 mm^2, 144.6 ± 28.0 mm^2; maximum interference distance: 345.0 ± 43.1 µm, 189.0 ± 39.9 µm, 309.0 ± 46.8 µm; average interference distance: 130.0 ± 15.7 µm, 64.0 ± 10.6 µm, 130.0 ± 21.9 µm. Statistically significant differences were found for the maximum interference distance and average interference distance (both $p < 0.05$).

Conclusions: The functional occlusal surfaces for each form of mastication demonstrated interference with the functional surface of frontal/lateral mandibular translations. Thus, crown restorations of which the occlusal surfaces were adjusted and formed by frontal/lateral mandibular translations may interfere with mastication.

Introduction

The occlusion of applied crown restorations needs to allow chewing of food while causing no harm to the temporomandibular joint and periodontal tissue. Five requirements should be satisfied, which are the following. 1) Maxillomandibular relation at the intercuspal position; 2) stability of occlusal contacts at the intercuspal position; 3) directions of any excursion

1) Department of Comprehensive Dentistry, Tokushima University Graduate School
2) School of Oral Health Sciences, Faculty of Health and Welfare, Tokushima Bunri University
3) Department of Clinical Education and Oral Care, Tokushima University Hospital

with occlusal contacts from intercuspal position or to intercuspal position; 4) position of occlusal contacts that guide mandibular movements; 5) position, curvature, and smoothness of occlusal plane and dental arch[1)]. Crown restorations are usually fabricated in an indirect method. First, a wax-up of occlusion is made using the articulator, and next it is made by the cast method. Thereafter, occlusal adjustment of the crown restoration is performed by again using the articulator. Moreover, dentists adjust crown restorations in the mouth, because crown restorations that are produced using the indirect method are 200–300 μm higher than the exact occlusion[2)]. After occlusal adjustment, the crown restoration is cemented in place. At this time, dental technicians and dentists aim to attach suitable occlusal contacts to the restoration and adjust occlusion such that there is no occlusal interference at the intercuspal position and during mandibular translations. Previous reports have found that the intercuspal position is a fundamental mandibular position and that lateral mandibular translations approximate the terminal movement path during masticatory movement[3, 4)].

In various clinical techniques, crown restoration using the functionally generated path technique (FGP)[5)] or occlusal adjustment on the fully adjustable articulator recommended by Gnathology[6)] has been generally recognized as yielding suitable occlusion, which does not require occlusal adjustment in the oral cavity. These techniques aim to provide a perfect occlusal relationship at the intercuspal position and during lateral mandibular translations. On the other hand, a previous report showed that patients with crown restorations prepared using the FGP technique had a negative experience and developed fatigue during mastication, even though the sensation at the intercuspal position was not unpleasant[7)]. Moreover, dentists adjust occlusion of restorations at the intercuspal position and for mandibular transitions, and confirmed that the patients' jaws move smoothly during frontal and lateral mandibular translations. Nevertheless, these patients sometimes report experiencing various occlusal difficulties at later visits, with patients complaining of fatigue during mastication, and of chipping of the molar porcelain fused to the metal crown. In addition, even though patients were used nocturnal occlusal sprint, these things were happening. Thus, occlusal relationships during mastication have been speculated to be one of the reasons for these difficulties. Given this background, the following clinical question is raised: what occlusal adjustment, utilizing mandibular translations, can allow production and placement of a crown restoration with good chewing ability and without chipping?

Nishigawa et al. reported that they could fabricate occlusal surfaces on crown restorations by recreating a FGP, using a custom-developed six-degree articulator and jaw-tracking device, and succeed to cement this in the patient without having to make occlusal adjustments in the oral cavity[8)]. Moreover, Suzuki et al. reported that the closed sliding phase (phase Ⅳ) of masticatory movement translated to the posterior path of the lateral border movements, while the open sliding phase (phase Ⅴ) of masticatory movement translated to the anterior path of the lateral border movements[9)]. If the mandibular movement path differed, the occlusal contacts might be altered. Difficulty in chewing or easy chipping of the superstructure may be related to differences in occlusal relationships present during masticatory movement as compared to mandibular rotations. There have been some previous reports on the occlusal relationship during mastication[10-14)]; however, no quantitative comparison of occlusal contacts between both types of mandibular movements has been reported.

Dental computer-aided design (CAD)/computer-aided manufacturing (CAM) technology has shown high dimensional accuracy and good appropriateness for tooth abutments due to advances in computing techniques[15, 16)]. In Japan, dental clinical treatment has adapted to the use of CAD/CAM in recent years[17-26)]. Moreover, this technology makes it possible to display the dynamic occlusal contacts on the screen[27)] and to evaluate the three-dimensional data of occlusal surfaces quantitatively.

In this study, the FGP technique was used to fabricate occlusal surfaces using a commercial CAD system was conducted. The study aimed to investigate the differences in occlusal surfaces generated by mastication in comparison with those generated during frontal and lateral mandibular translations, in a quantitative manner, in order to address the above-mentioned clinical question.

Materials and Methods

1. Study population

Ten adult volunteers (five male and five female, aged 26.2 ± 3.3 years and 26.6 ± 1.5 years, respectively) were recruited. All participants had healthy normal dentition except for the third molar. They did not have crown restorations, except for tiny inner restorations on some teeth. No occlusal interference was observed at the intercuspal position. Examination for any limitation of mandibular movement, recurrent facial pain, and tenderness or fatigue of the temporomandibular joint and/or masticatory muscles was subjectively and objectively negative.

This study was approved by the Ethics Committee of Tokushima University Hospital (No. 2657). All participants provided written informed consent for this study.

2. Identification of habitual masticatory side

All participants were interviewed to clarify on which side they usually masticated. They were also asked to bite temporary sealing material (TEMPORARY STOPPING, GC Corporation, Tokyo, Japan) three times for any tooth position in order to identify the main occluding area[28]. The results of this trial were compared with the interview results to ensure a match.

3. Measurement of jaw movement

An ultrasound digital mandibular measuring system (ARCUS® digma2, KaVo Dental GmbH, Biberach, Germany) was used to measure jaw movement, with a sampling frequency of 50 Hz.

For collection of jaw movement data, the upper and lower preliminary impressions were taken using irreversible hydrocolloid impression material (AROMA FINE PLUS, GC Corporation, Tokyo, Japan), and diagnostic casts were made using hard plaster (Zō STONE, SHIMOMURA GYPSUM CO., LTD, Saitama, Japan). Modeling plastic compound (MODELING COMPOUND, GC Corporation, Tokyo, Japan) was placed on the upper bite-fork of the ARCUS digma2; the compound was softened and a dent or impression in the upper occlusal surface was made by using an upper diagnostic cast. Next, self-curing acrylic resin (TRAY RESIN Ⅱ, SHOFU INC., Kyoto, Japan) was placed on the lower attachment of the specialized ARCUS digma2, and a dent or impression on the buccal surface of the tooth was made for the lower diagnostic cast. This was done without contact with the upper tooth and without mandibular translation.

The sensor of the ARCUS digma2 was set in parallel with the Camper's plane. The upper bite-fork was attached to the transmitter of the ARCUS digma2, and the upper dental arch was recorded against the upper sensor. Next, the prepared lower attachment was affixed to the transmitter of the ARCUS digma2, and adjusted without preventing jaw movement. This attachment was then adhered to the lower tooth, using cyanoacrylate-based adhesive (Aron Alpha® EXTRA®, TOAGOSEI, Tokyo, Japan), and the lower dental position was recorded against the upper dental arch at the intercuspal position.

The "Articulator mode" in the jaw movement measurement system was used. First, frontal border movement, left lateral border movement, and right lateral border movement were recorded in order as frontal/lateral mandibular translations. Next, one sheet of gum (Fit's, LOTTE Co., Ltd., Tokyo, Japan), as a test food, was sufficiently softened and placed on the center of tongue. Recording was started at the intercuspal position, and five strokes of left- and right-sided mastication was performed, followed by ten strokes of free mastication. Mastication speed was not dictated.

4. Three-dimensional measurement of dental model

Individual trays were made using a diagnostic cast and self-curing acrylic resin. A precise impression of the

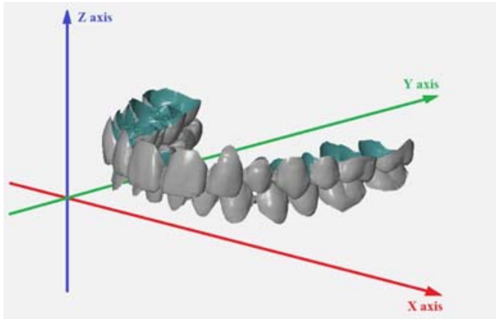

Figure 1. Setting of the coordinate system

occlusal surface of the upper and lower dental arch was taken using the individual trays and silicone impression material (Imprint™ Ⅱ, 3M, St. Paul, MN, USA), and a precise dental cast was made, for shape measurement, using ultra-hard plaster (NEW FUJIROCK, GC Corporation, Tokyo, Japan). The precise dental cast was also set in the articulator (Protar 5, KaVo Dental GmbH, Biberach, Germany) utilizing the upper bite-fork and bite-fork supporter.

A clinically applicable CAD/CAM scanning system (ARCTICA Auto Scan, KaVo Dental GmbH, Biberach, Germany) was used for three-dimensional measurement of the dental model. The scanning method followed the instructions supplied in the manual of this system, and CAD software (KaVo multi CAD, KaVo Dental GmbH, Biberach, Germany: multi CAD) belonging to this CAD/CAM scanning system was used as operation software.

The coordinate system in the monitor was based on the occlusal plane constructed by the X-axis (frontal view) and Y-axis (sagittal view). The Z-axis was the normal direction of the occlusal plane, with the positive direction being the upper side of the occlusal plane (Figure 1).

5. Data analysis

5-1) Analysis of target jaw movement

This study performed four analyses of jaw movements. 1. Frontal, left, and right lateral border movement, as frontal/lateral mandibular translations. 2. Five strokes of gum mastication on the habitual chewing side. 3. Five strokes of gum mastication on the non-habitual chewing side. 4. Ten strokes of free gum mastication.

5-2) Functional occlusal surface

To fabricate the crown restoration, the FGP technique was used on the CAD system for the lower first and second molar (Figure 2-a). Half of the height of the crown of each of these molars was removed by multi-CAD (Figure 2-b). A block with sufficient volume to be marked by opposite occlusal surface movement was

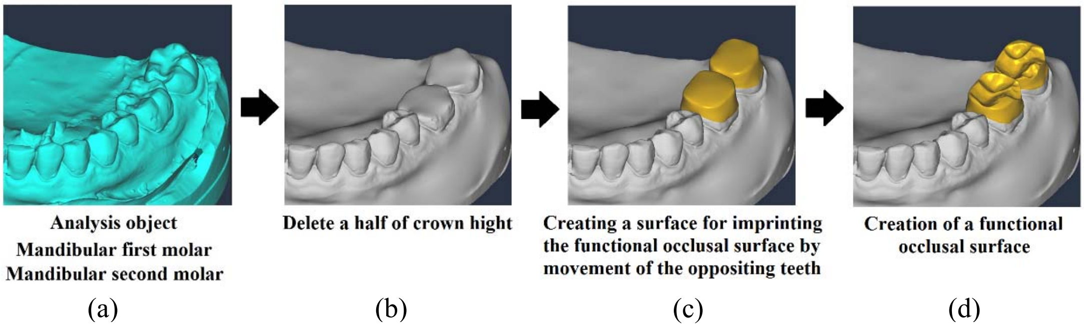

Figure 2. Flowchart showing the analysis method

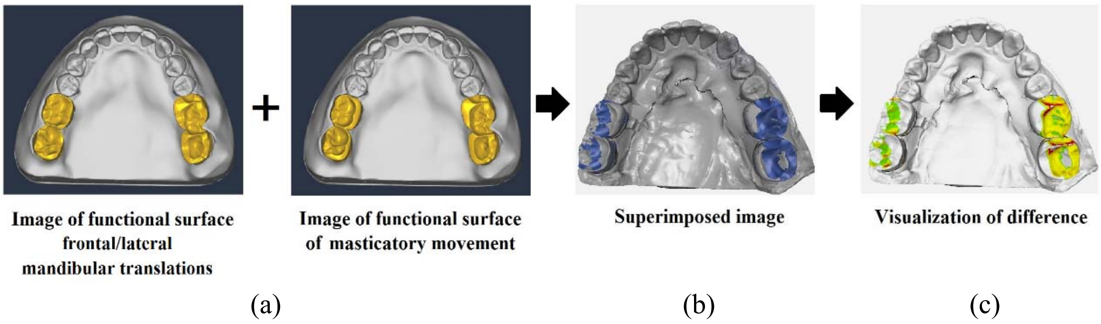

Figure 3. Superimposition of the functional surface of frontal and lateral border movement and of free masticatory movement

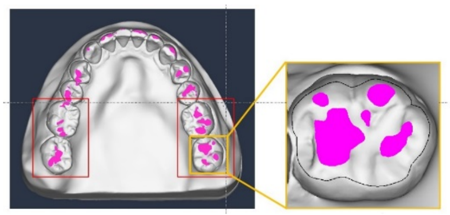

Figure 4. Visualization of the occlusal contact area and analysis target area

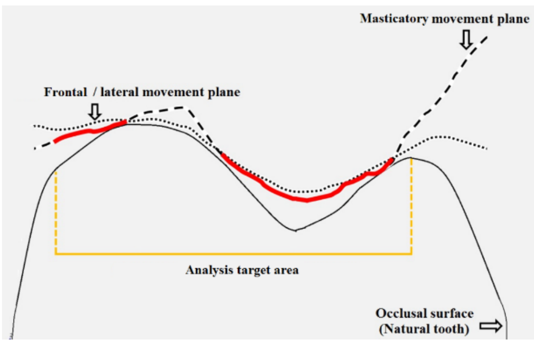

Figure 5. Image demonstrating the interference region

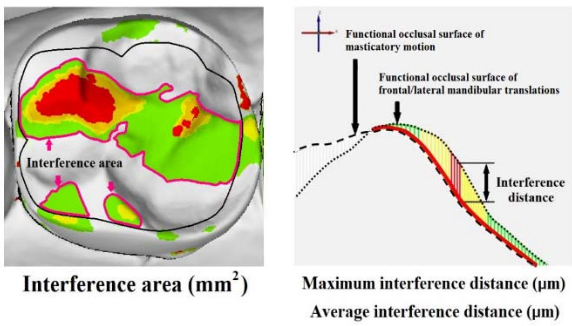

Figure 6. Images of interference area and distance

fabricated on this removed half of the crown (Figure 2-c). The movement of the opposite teeth on the occlusal surface was marked on the FGP table (block) during each jaw movement; we termed this the functional occlusal surface (Figure 2-d).

Utilizing these methods, four types of functional occlusal surfaces were fabricated by frontal/lateral mandibular translations, gum mastication on the habitual or non-habitual side, and free gum mastication.

5-3) Superposition of the functional occlusal surface and analysis target area

Superimposition of the functional occlusal surface was performed using three-dimensional data evaluation software (GOM Inspect, GOM, Braunschweig, Germany). The baseline was the functional occlusal surface that was fabricated from frontal/lateral mandibular translations (Figure 3-a).

It was difficult to identify the region around the functional occlusal surface that would be marked by the opposite teeth. Therefore, < 300 μm was set as the reference value for occlusal contacts, which included close range contacts, in this study (Figure 4).

5-4) Identification of the interference region

The interference region was defined as the region for which the value of the functional occlusal area for mastication on the Z-axis was less than the value for frontal/lateral mandibular translations, after superimposing the two functional data sets (Figure 3-b, 3-c, Figure 5).

5-5) Evaluation of interference region

The interference region was quantitatively evaluated using three parameters: the interference area, maximum interference distance, and average interference distance for each form of mastication (free mastication, habitual mastication, and non-habitual mastication) (Figure 6).

#. Interference area: The total interference area of the left/right first molar and second molar of each subject was calculated, and thereafter, the average interference area of ten subjects was calculated.

#. Maximum interference distance: The longest distance from the interference region within the analyzed target area for each participant was represented, and the values of all participants were averaged.

#. Average interference distance: The average interference region was calculated for each participant, and the values of all participants were averaged.

5-6) Statistical analysis

The three parameters, i.e., the interference area, maximum interference distance, and average interference distance, were compared between the three types of jaw movements (free mastication, habitual mastication, and non-habitual mastication) using the Kruskal–Wallis test, followed by the Steel–Dwass test. Statistical significance was set at $p < 0.05$ using EZR (Jichi Medical University Saitama Medical Center, Saitama, Japan) [29].

Results

1. Identification of habitual masticatory side

The habitual masticatory side, determined by interviewing each participant, coincided with the side on which they chewed the tip of temporary sealing material in all participants. Moreover, when the 10 strokes of free masticatory movement were divided into the chewing sides, the habitual masticatory side was used 5.9 ± 0.6 times, and the non-habitual masticatory side 4.1 ± 0.6 times.

2. Difference between functional occlusal surfaces of mandibular translation and of masticatory movements

Differences between the functional occlusal surfaces of masticatory movement and frontal/lateral mandibular translations were calculated for each parameter (interference area, maximum interference distance, and average interference distance; Table 1).

Chewing on the habitual masticatory side produced a smaller interference area than chewing on the non-habitual masticatory side, as well as that yielded by free masticatory movement (21.7 mm^2, 44.6 mm^2; respectively). Chewing on the habitual masticatory side resulted in a smaller maximum interference distance than chewing on the non-habitual masticatory side and that produced by free masticatory movement (120 μm and 156 μm, respectively). Chewing on the habitual masticatory side yielded a smaller average interference distance than by chewing on the non-habitual masticatory side and by free masticatory movement (66 μm and 66 μm, respectively).

3. Comparison between masticatory sides

The Kruskal–Wallis test did not reveal a statistically significant difference in the interference area between the three forms of mastication ($p = 0.47$). However, there were significant differences between the three forms of mastication in terms of the maximum interference distance and average interference distance ($p = 0.04$, $p = 0.01$; respectively). Then, multi-comparisons were performed for two parameters using the Steel–Dwass test. For the maximum interference distance, chewing on the habitual masticatory side yielded a significantly smaller distance than did free masticatory movement ($p = 0.04$). Moreover, for the average interference distance, chewing on the habitual masticatory side produced significantly smaller distances than did chewing on the non-habitual masticatory side and free masticatory movement ($p = 0.04$, $p = 0.01$; respectively).

Table 1. Interference area, maximum interference distance, and average interference distance for each type of masticatory movement (n = 10)

	A Free mastication	B Habitual side	C Non-habitual side	One-way ANOVA	Post-hoc test (Steel-Dwass test) A vs B	A vs C	B vs C
Interference area	167.5±20.8mm²	122.9±28.5mm²	144.6±28.0mm²	0.47	0.32	0.63	0.73
Maximum Interference distance	**345.0±43.1μm**	**189.0±39.9μm**	309.0±46.8μm	**0.04 ***	**0.04 ***	0.88	0.14
Average Interference distance	**130.0±15.7μm**	**64.0±10.6μm**	**130.0±21.9μm**	**0.01 ***	**0.01 ***	0.97	**0.04 ***

*** : $p < 0.05$**

Discussion

1. Research method

1-1) Quantitative evaluation by the virtual FGP technique

This study aimed to address the clinical question about whether masticatory movement caused an occlusal interference due to a close occlusal relationship in comparison with the mandibular translations, because patients reported problems, including "difficult chewing" or "chipping of porcelain fused to metal crown", even though a complete occlusal relationship had been established upon fitting of the crown restoration by utilizing mandibular translations. The occlusal relationship during both mandibular translations and masticatory movements was quantitatively evaluated in order to resolve this clinical question. In the beginning of evaluation of dynamic occlusal contacts, those were only reports on occlusal contacts during mandibular translations[30-32]. It was concluded that it was not always easy to evaluate the occlusal relationship during masticatory movement by comparing the intercuspal position or by assessing mandibular translations. Subsequently, a six-degree digital jaw-tracking device was developed[33], and a method was devised that combined the digital data of mandibular movement and three-dimensional measurement data of the dental arch[34]. Various studies have reported evaluations of the occlusal relationship during masticatory movement using this method[12-14]. Moreover, it was easy to evaluate and analyze the occlusal relationship quantitatively by making use of current advances in dental CAD/CAM technology[27].

In the clinic, the FGP technique, which generates the occlusal surface by using mandibular translations on the articulator, was devised[5] and was expected to allow fabrication of crown restorations that harmonized with the stomatognathic system. However, this method was not able to recreate the masticatory movement on the articulator. On the other hand, it was possible to design an occlusal surface for crown restorations using the intercuspal position, mandibular translations, and masticatory movement by making use of current dental CAD/CAM technology.

The present study aimed to fabricate a lower first molar crown restoration utilizing the FGP technique on the CAD system. The functional occlusal surface was defined as the movement trajectory of the oppsite tooth on the virtual FGP table. The data of the functional occlusal surface generated by frontal/lateral mandibular translations and that of each of functional occlusal surfaces generated by various forms of mastication were superimposed, and the degree of overlap between these surfaces was then determined quantitatively. This allowed an evaluation of how crown restorations fabricated by the conventional, indirect method or by using the FGP technique, with occlusal adjustment based on intercuspal position or frontal/lateral mandibular translations, interfered with mastication.

1-2) Measurement accuracy

It was necessary to investigate various errors before the functional occlusal surface was quantitatively evaluated. First, the three-dimensional shape of the dental arch was constructed by scanning an upper and lower dental cast using ARCTICA. Second, the ARCUS digma2 was used as a jaw-tracking device. Both these data sets were input to the graphic terminal of a CAD system. The various errors that were caused by the dimensional changes from taking impressions or making the dental cast model[35] and the errors of CAD machine (official error: maximum 10 μm) and of the jaw-tracking device (official error: ± 100 μm)[36] were considered. Moreover, since the dental arch and tooth were treated as rigid bodies, tooth mobility [37, 38] and jaw deformation[39] during dynamic movement needed to be considered. However, these errors were present to an equal extent in both the functional occlusal surface created by mandibular translation and that created by masticatory movements. Therefore, since the amount of interference determined by superimposing the surfaces generated by both types of movements was the true value, after offsetting errors, our method of evaluation method was highly reliable, and had a high measurement accuracy for comparing the two functional occlusal surfaces.

1-3) Analysis range

The functional occlusal surface created by masticatory movements did not have a clear border line between the area traced by the opposite tooth and the non-traced area. This study defined both occlusal contact regions and nearby occlusal regions as the occlusal contact area, and determined that the cusp slope with the area (X-Y-plane) that included the occlusal vertical distance (Z-axis) was equal or less than 300 μm.

2. Results

2-1) Number of mastication strokes in habitual or non-habitual masticatory side for free masticatory movement

For analysis of free masticatory movement using gum, the number of mastication strokes on the habitual masticatory side was large, but the number of strokes on the non-habitual masticatory side was also quite large. This result was considered due to the effect of softening the gum, but participants chewed similarly on both sides.

In a previous study, the relationship between foods and masticatory laterality[40] and the relationship between oral manipulative skill and masticatory functions[41] have been reported, but no differences between the habitual and non-habitual side in terms of different foods has not been reported. A future study should investigate the difference between each masticatory side for different foods.

2-2) Differences between the functional occlusal surface created by mandibular translations and masticatory movements

By investigating the interference area, maximum interference distance, and average interference distance in this study, we showed the difference in the movement tracked on the occlusal surface on the lower molars between mandibular translations and masticatory movement. This result agreed with those of Suzuki et al., which showed a difference between the mandibular movement path and the masticatory movement path[9].

The maximum interference distance exceeded 300 μm for free masticatory movement, using gum, and was about 200 μm for gum masticatory movement on the habitual masticatory side. The average interference distance exceeded 50 μm for each of the masticatory movements. To determine the influence of high interference of crown restorations, Tanaka et al. showed that interference of more than 60 μm had an impact on the masticatory system[42], Kato et al. showed that interference of more than 60 μm changed masticatory movement[43], and Ikeda et al. showed that interference of more than 10 μm had an impact on the sensation threshold of dental pulp[44]. Since our study showed a larger interference than these previous studies, this study suggested that occlusal adjustment or fabricated crown restoration based only on mandibular translations was not sufficient to remove the interference during masticatory movement. Therefore, we consider that we have successfully addressed the clinical question about “difficult chewing” or “chipping super-structure of implant without cushioning of periodontal membrane”.

2-3) Difference in the interference amount between the habitual and non-habitual masticatory side

Numerous previous studies have reported the relationship or difference between the characteristics of the habitual and non-habitual masticatory sides. Three previous studies have reported that masticatory muscle activity and masticatory efficiency were higher, and the number of strokes was greater, on the habitual masticatory side than on the non-habitual masticatory side[45-47]. Therefore, the habitual masticatory side is considered to have high mastication frequency and stable mastication.

On the contrary, for the non-habitual masticatory side, Nimura et al. reported that the movement path and stability of movement rhythm were less than for the habitual masticatory side[48]. These are thought to be related to the results obtained in the present study, in which interference with the occlusal surface was greater on the non-habitual masticatory side than on the habitual masticatory side.

3. Future prospects

CAD/CAM crown restorations are increasingly used, and their frequency of clinical implementation will continue to grow in future. Yamase et al. reported that one of the factors for broken resin material was interference during occlusion, based on follow-up examination of CAD/CAM crown restorations[49]. However, the relationship between breakage of CAD/CAM crown material and occlusion has not been clarified at present. Moreover, Ikawa et al. showed the usefulness of fabricating CAD/CAM crown restorations using functional mandibular movement and a virtual articulator[50], but studies or clinical applications that included fabrication of crown restoration with masticatory movement have not been reported to date. Therefore, it is necessary to perform a more detailed analysis of occlusal facets, the time sequence of masticatory movement, and clinical research using CAD/CAM crown restorations adjusted according to masticatory movement in future.

Conclusions

Ten adult volunteers who had healthy normal dentition underwent measurement of mandibular translation and gum mastication movements, using a CAD system. The movement of the opposite teeth on the occlusal surface during mandibular translations and gum mastication were visualized using a digital FGP method, and we considered a method for quantitative investigation of the difference between frontal/lateral mandibular translations and mastication. Our analysis yielded the following results:

1. We devised a method for analyzing the relationship between the movement of the teeth opposite the occlusal surface during mandibular translation and mastication movements.
2. This movement path during mandibular translations and mastication differed, and when the occlusal surface was generated using the FGP method or a CAD/CAM system on the basis of frontal/lateral mandibular translations, the occlusal surface demonstrated regions of interference during mastication.
3. Interference on the non-habitual mastication side was greater than that on the habitual mastication side.
4. The newly devised method is useful for quantitatively evaluating interference after crown restorations.

Conflicts of Interest

There are no conflicts of interest to be disclosed.

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