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Three-dimensional Motion Analysis of Lip and Mandibular Movements during Mastication

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Abstract: Many aspects of the coordination of lip and mandibular movements in the process of eating have not yet been clarified. This time, aiming to objectively evaluate lip and mandibular movements when chewing, the movements of the corners of the mouth and the mandible during mastication were measured three-dimensionally and analyzed. The subjects were 20 healthy women with individual normal occlusion. The test food was a commercially-available biscuit with a weight of 1 g. With six measuring points set for the lips and pogonion, the movements at those measuring points were captured with two CCD cameras during mastication, and the resulting images were analyzed with a three-dimensional motion analysis system. The analysis result showed that X- and Z-axis movements occurred on the working-side corner of the mouth, with Z-axis movements preceding X-axis movements, while on the balancing-side corner of the mouth, X- and Z-axis movements occurred simultaneously. Data on the amount, time taken, and speed of movements measured at each anatomical landmark showed that the working-side corner of the mouth moved a greater distance at a faster pace and, therefore, in less time than that of the balancing-side corner of the mouth. This is conceivably due to the aforementioned differences in X- and Z-axis movements of the working-side and balancing-side corners of the mouth. Further comparisons and studies with expansion of the subjects to include children will be necessary.

Key words: three-dimensional motion analysis, mastication, lip movement.

The functions of ingesting, chewing, and swallowing food involve the use of various organs, including the mandible and tongue. The lips play a particularly important role in sensing food and remaining closed during subsequent mastication and deglutition. Considerable research has been conducted on the functional dynamics of tongue and mandibular activities during mastication.^{1~8)} Literature has also been published on motion analysis of labial activity, such as a study analyzing functional lip dynamics during chewing in healthy children and adults, as well as in cerebral palsy

children with masticatory dysfunction,⁹⁾ in addition to a study investigating the dynamic relationship between the lips and tongue during swallowing of solid foods in adults using CCD cameras and a diagnostic ultrasound device¹⁰⁾ and a study on lip and mandibular movements during mastication in adults.^{11~13)} However, to the best of our knowledge, there are virtually no published reports examining coordination of lip and mandibular movements during mastication. Subjective extraoral assessment of chewing and swallowing functions is difficult, because tongue movements are an inherently

intraoral activity. Conversely, external observation of the lips, especially the corners of mouth and mandible is relatively simple. The oral cavity contains various muscles,¹⁴⁾ many of which are located around the corners of the mouth. The complex movement of these muscles means that three-dimensional (3D) analysis is essential to evaluate them objectively. Therefore, in the present study, 3D measurement and analysis of lip and mandibular coordination were conducted during mastication. This study also sought to demonstrate movements of the lips and corner of mouth, as well as the mandible, by simple external observation in order to apply the findings to dysphagia habilitation.

Materials and Methods

1. Subjects

The subjects were 20 healthy women, aged 26 to 29 years (average age, 28.3 ± 0.8 years), with individual normal occlusion and no discernible stomatognathic system abnormalities. The subjects provided their informed consent to participate in the study after receiving an explanation about the methods and potential safety risks. This study was conducted with the approval of the ethics review board of Showa University School of Dentistry (approval no. 2010-030).

2. Experimental equipment

The measuring system used in this research was that of Sekita et al.¹³⁾ and Takahashi et al.¹⁵⁾ Video images captured with 2 CCD cameras (VGA 60 Hz; Algo Application, Tokyo, Japan) were saved onto a personal computer (Panasonic, Tokyo, Japan) and then analyzed using dedicated software (Move-tr/3DR type; Algo Application) (Fig. 1). The 2 CCD cameras were set up at an optical axis of 60° at 110 cm from the subject so that their imaging axes were as parallel to the floor as possible, and minor adjustments were made to match the subject's facial position. A calibration grid was then filmed to provide reference points for capturing lip movement.

3. Anatomical landmarks

The designated measurement points were located at

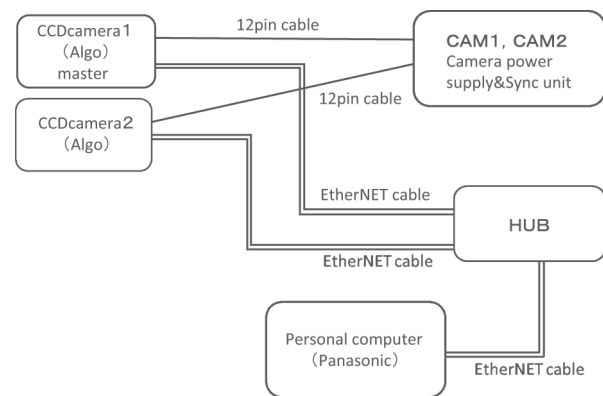
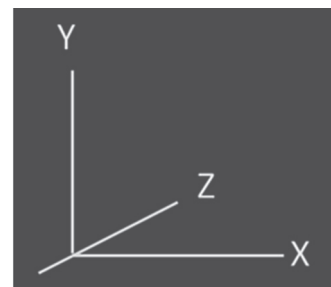
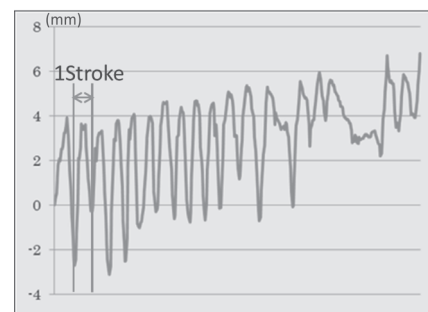


Fig. 1 The block diagram of the 3-D Auto Tracking System.



(1) A coordinate axes.



(2) The definition of stroke.

Fig. 4 A coordinate axes and the definitions of stroke in this research. (1) A coordinate axes. X-axis: Horizontal. Y-axis: vertical. Z-axis: anteroposterior. (2) The definition of stroke. A single stroke was defined as the interval between the first and subsequent minimum values via a maximum value.

the following 7 anatomical landmarks: (1) right corner of the mouth; (2) left corner of the mouth; (3) labrale superius; (4) labrale inferius; (5) pogonion; (6) the tip of the nose; and a (7) fixed point external to the face. Markers with a diameter of 5 mm were attached to each of these anatomical landmarks (Fig. 2).

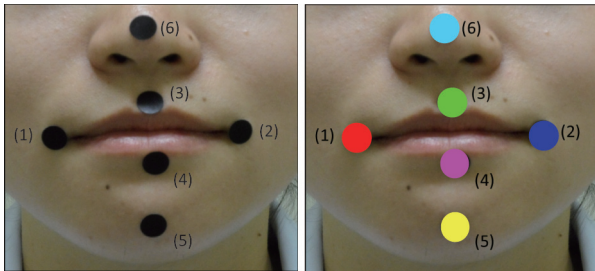


Fig. 2 Measuring points for during mastication. (1) the right corner of mouth (red). (2) the left corner of mouth (blue). (3) the superior labial tubercle (green). (4) the inferior labial tubercle (pink). (5) pogonion (yellow). (6) the tip of nose (skyblue)



Fig. 3 The arrangement plan of the cameras.

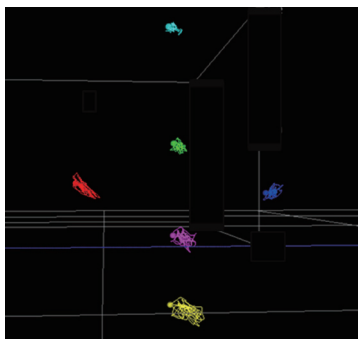


Fig. 5 The trace of the point during mastication.

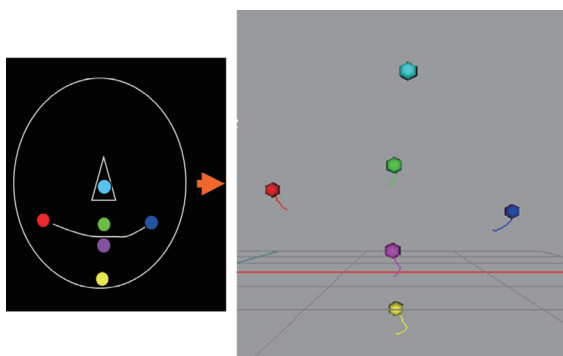
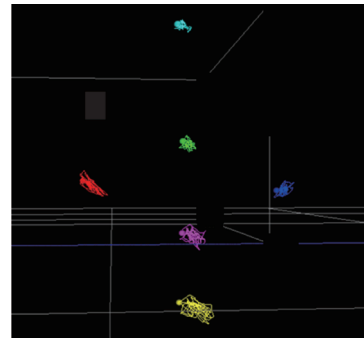
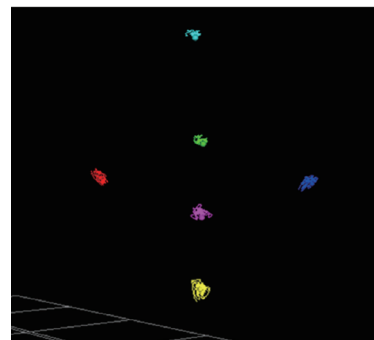


Fig. 7 The movement of corner of mouth of XY direction. Simultaneous lateral movement of the working-side (red) and balancing-side (blue) corner of mouth.



(1) The movement of pattern 1



(2) The movement of pattern 2

Fig. 6 The pogonion movements of pattern1 and pattern 2. (1) The movement of pattern 1. (2) The movement of pattern 2. The pogonion movement of pattern 1. The movement of side direction was independent action. The pogonion movement of pattern 2. The movement of lengthwise direction was independent action.

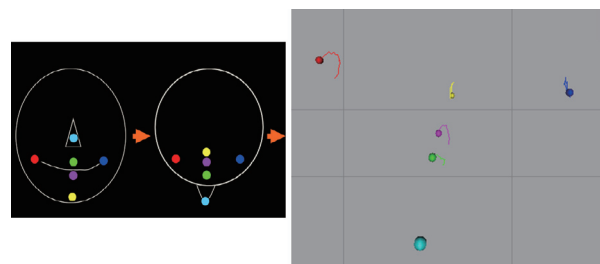


Fig. 8 The movement of corner of mouth of XZ direction. Z-axis movements preceding X-axis movements on the working-side corner of mouth (red), X- and Z-axis movements occurred simultaneously on the balancing-side corner of mouth (blue).

4. Measurement

Subjects were instructed to sit down low in a folding chair with their back pressed against the chair back, feet on the floor and thighs in contact with the chair surface. Based on the method proposed by Takahashi et al.,¹⁵⁾ the

subject's head was secured using a headrest, and a band was placed around the forehead so that the Frankfort plane was largely parallel to the floor (Fig. 3). Subjects were given sufficient opportunity to practice maintaining the correct measurement position, during which time their habitual chewing side was determined. The test food was a commercially-available biscuit (20 mm×10 mm×1 mm) with a weight of 1 g, which was fed to each subject with a flat metal spoon with assistance a total of 5 times. Lip and mandibular movements from ingesting until swallowing were then recorded using the 2 CCD cameras.

5. Analysis

The acquired calibration grid was used to create 3D calibration data that was then applied to a 3D coordinate system. The 6 designated anatomical landmarks were detected with 3D tracking, and 3D data were created using dedicated software. The images recorded at each landmark were then extracted at 50-ms intervals and analyzed from immediately after food ingestion until immediately before swallowing. The distance between the labrale superius and labrale inferius landmarks was measured while the subject remained still in order to identify the recorded image corresponding to the moment immediately after ingestion. The image recorded immediately after ingestion in which the distance between landmarks labrale superius and labrale inferius was closest to the distance between these same landmarks when the subject was at rest was used as the reference image for immediately after ingestion. Moreover, the recorded image in which the distance between the right corner of the mouth and the left corner of the mouth was greatest was used as the reference image for immediately before swallowing, because this is where muscular tension of the commissures starts to become active during swallowing.

6. Analytical variables

Horizontal and vertical movements were plotted on the X- and Y-axis, while anteroposterior movements were plotted on the Z-axis (Fig. 4). On the graph plotting Y-axis movements, a single stroke was defined as the

interval between the first and subsequent minimum values via a maximum value (Fig. 4).

The following 8 variables 1)–8) were subjected to analysis during mastication.

- 1) Average number of strokes and time taken (each subject)
- 2) X- and Y-axis movements of the pogonion
- 3) X- and Y-axis movements of the working-side corner of the mouth and pogonion
- 4) X- and Y-axis movements of the working-side and balancing-side corners of the mouth
- 5) X- and Z-axis movements of the working-side and balancing-side corners of the mouth
- 6) Relationship between the amount of movement of the working-side and balancing-side corners of the mouth and pogonion
- 7) Relationship between time taken and speed of the working-side and balancing-side corners of the mouth and pogonion
- 8) Relationship between amount of movement of the working-side corner of the mouth and pogonion by movement pattern

Student's *t*-test was used to compare the average amount of movement, time taken, and speed of the working-side and balancing-side corners of the mouth and pogonion.

Results

Examples of respective landmark movements extracted at 50-ms intervals are shown in Fig. 5. The tracking results were examined to determine whether a relationship existed between the X-, Y-, and Z-axis movements.

1. Average number of strokes and time taken

The average number of strokes and time taken from immediately after ingestion until immediately before swallowing were 13.52 ± 2.85 strokes and 17.65 ± 3.57 seconds, respectively.

2. X- and Y-axis movements of the pogonion

Predominantly horizontal pogonion movement was classified as 'pattern 1', while predominantly vertical

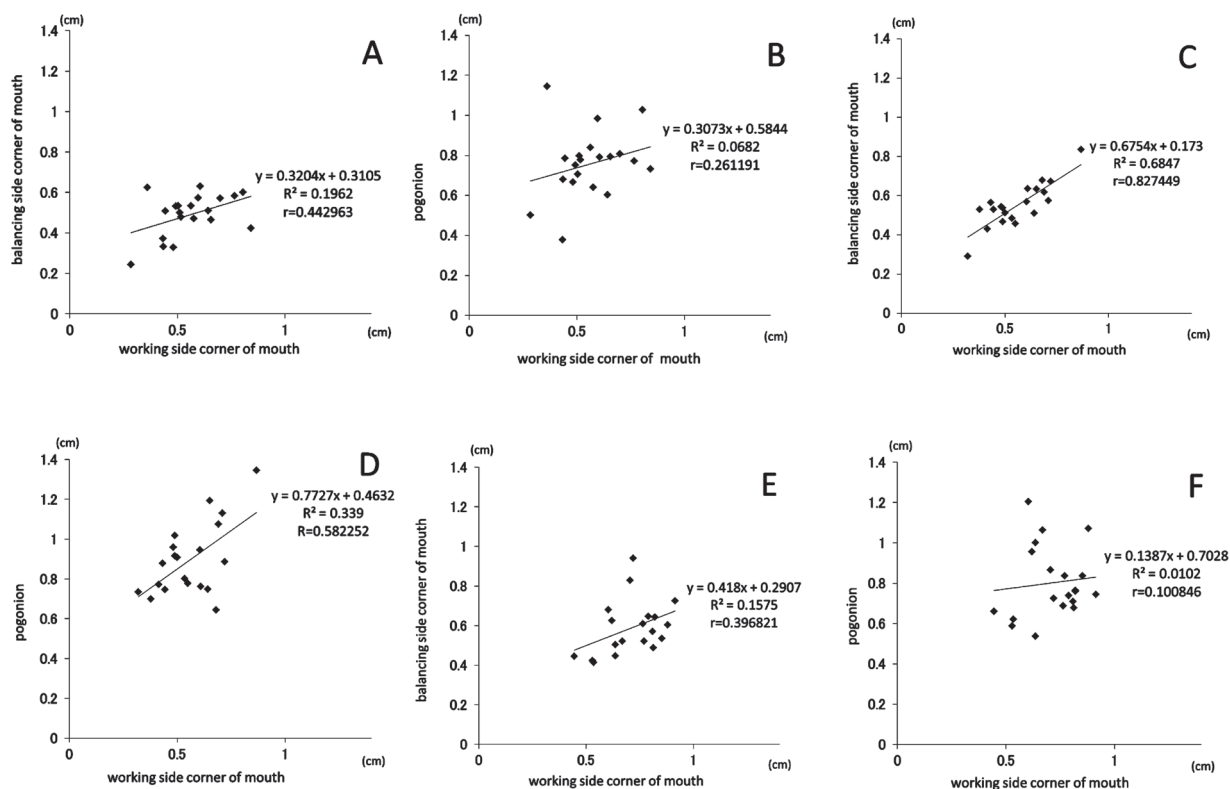


Fig. 9 The total movement of corner of mouths and pogonion. A. The total movement of X direction of the corner of mouth. B. The total movement of X direction of working side corner of mouth and pogonion. C. The total movement of Y direction of the corner of mouth. D. The total movement of Y direction of the working side corner of mouth and pogonion. E. The total movement of Z direction of the corner of mouth. F. The total movement of Z direction of the working side corner of mouth and pogonion.

pogonion movement was classified as 'pattern 2'. Pattern 1 movements were observed in 14 of the 20 subjects, and pattern 2 movements were seen in the remaining 6 subjects (Fig. 6).

3. X- and Y-axis movements of the working-side corner of the mouth and pogonion

All subjects showed movement of the working-side corner of the mouth towards the working-side, with 84.26% of all subjects' measurement strokes being associated with pogonion movement (Fig. 7).

4. X- and Y-axis movements of the working-side and balancing-side corners of the mouth

Simultaneous lateral movement of the working-side and balancing-side corners of the mouth was seen in 89.28% of all subjects' measurement strokes (Fig. 7).

5. X- and Z-axis movements of the working-side and balancing-side corners of the mouth

All subjects showed X- and Z-axis movements of

the working-side corner of the mouth, with Z-axis movements preceding X-axis movements in 86.59% of all subjects' strokes. On the balancing-side corner of the mouth, X- and Z-axis movements occurred simultaneously, and only 1.75% of all strokes involved Z-axis movement followed by X-axis movement (Fig. 8).

6. Relationship between the amount of movement of the working-side and balancing-side corners of the mouth and the working-side corner of the mouth and pogonion

Strokes constituting the most total movement were examined at the working-side corner of the mouth for the X-axis and at the balancing-side corner of the mouth and the pogonion for the Y-axis. The results are shown in Fig. 9. Y-axis correlations were observed between the working-side and balancing-side corners of the mouth ($P < 0.0001$) and between the working-side corner of the mouth and pogonion ($P < 0.001$). Moreover, significantly

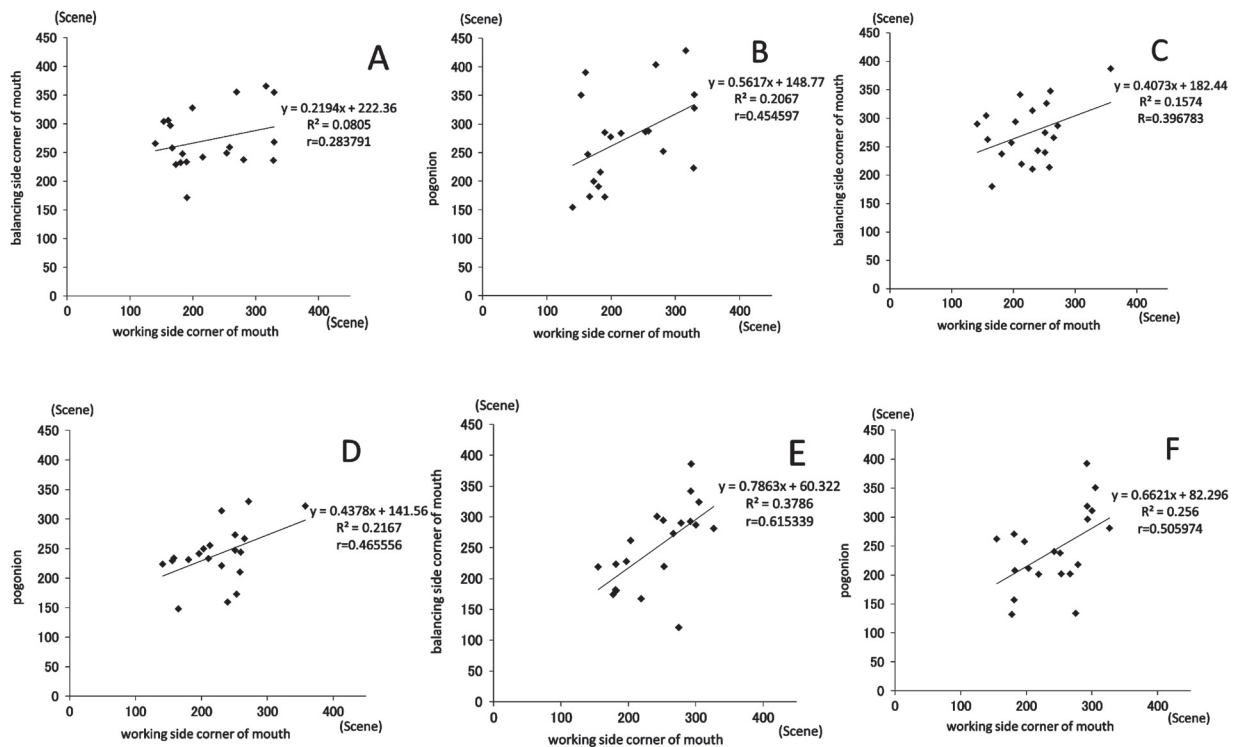


Fig. 10 The time required corner of mouths and pogonion. A. The time required of X direction of the corner of mouth. B. The time required of X direction of the working side corner of mouth and pogonion. C. The time required of Y direction of the angle of mouth. D. The time required of Y direction of working side corner of mouth and pogonion. E. The time required of Z direction of the corner of mouth. F. The time required of Z direction of working side corner of mouth and pogonion.

greater movement occurred at the pogonion compared to the balancing-side on the X-axis, and at the working-side versus the balancing-side on the Z-axis.

7. Relationship between the time taken and the speed of the working-side and balancing-side corners of the mouth and between the working-side angle of the mouth and pogonion

Stroke times constituting the most total movement were examined at the working-side corner of the mouth for the X-axis and at the balancing-side corner of the mouth and pogonion for the Y-axis. The results are presented in Fig. 10. Z-axis correlations were observed between the working-side and balancing-side corners of the mouth ($P < 0.01$), and significant X-, Y-, and Z-axis correlations were seen between the working-side corner of the mouth and pogonion ($P < 0.05$). Moreover, balancing-side and pogonion movements were significantly greater than working-side movements along both the X- and Y-axis.

Movement speed at each anatomical landmark was determined based on the amount of movement and time taken, the results of which are shown in Fig. 11. Specifically, working-side movements were significantly faster than balancing-side movements on the X-, Y-, and Z-axis. Meanwhile, pogonion movements were significantly faster than working-side movements on the Y- and Z-axis.

8. Relationship between the amount of movement of the working-side angle of the mouth and pogonion by movement pattern

The relationship between the amount of movement at each landmark was assessed according to the 2 patterns described in part 2 of the Results section. Grinding-type movements were classified as pattern 1, and chopping-type movements were classified as pattern 2. The results are shown in Table 1. On the Y-axis, pattern 2 movement tended to be greater at the working-side and balancing-side corners of the mouth, as well as the pogonion. On

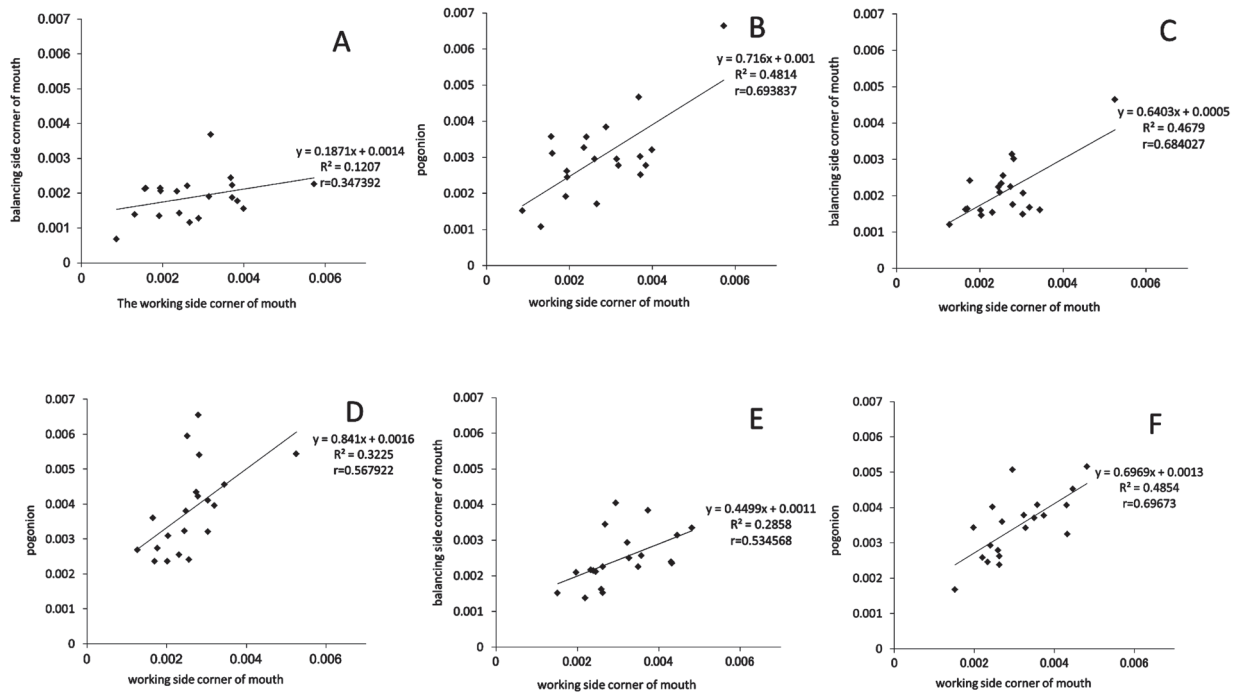


Fig. 11 The speed of corner of mouths and pogonion. A. The speed of X direction of the corner of mouth. B. The speed of X direction of the working side corner of mouth and pogonion. C. The speed of Y direction of the corner of mouth. D. The speed of Y direction of the working side corner of mouth and pogonion. E. The speed of Z direction of corner of mouth. F. The speed of Z direction of the working side corner of mouth and pogonion.

Table 1 Average of speed of X, Y, Z direction of angle of mouth and pogonion.

		X direction		Y direction		Z direction	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Pattern 1 (Grinding type) n=14	the working side corner of mouth	0.54	0.12	0.53	0.12	0.7	0.12
	the balancing side corner of mouth	0.49	0.09	0.52	0.09	0.62	0.15
	pogonion	0.79	0.14	0.84	0.12	0.83	0.18
Pattern 2 (Grinding type) n=6	the working side corner of mouth	0.6	0.19	0.62	0.16	0.74	0.15
	the balancing side corner of mouth	0.49	0.13	0.61	0.12	0.53	0.08
	pogonion	0.7	0.22	0.99	0.25	0.75	0.17

n=20

the Z-axis, pattern 1 movement was more predominant at the balancing-side corner of the mouth and pogonion than its pattern 2 counterpart.

Discussion

In a study analyzing the role of the lips in swallowing, Ayano et al.¹⁶⁾ reported that muscular traction of the left and right corners of the mouth can be observed in weaning children at around the same time that they develop the ability to perform a vertical compressing motion with the tongue. When this tongue compression involves active movement of the corners of the mouth

as part of the swallowing process, the muscles around the corners of the mouth (i.e., the levator, depressor, and buccinator muscles) all actively contribute to the function of eating. Several studies have already examined facial movements,^{17~19)} jaw movement during mastication,^{20~23)} and lip movement including muscular traction of the corners of the mouth,^{15,24,25)} but, to the best of our knowledge, there have not been any reports on external 3D motion analysis using external anatomic landmarks. The present study therefore undertook 3D observation and analysis of lip and mandibular coordination during food ingestion.

The resulting study findings demonstrated the movements of the lips, corners of the mouth, and mandible, which are all relatively simple to evaluate externally during mastication. If these results could be used as a guide during external assessment of intraoral activity, which is difficult to inspect externally in dysphagia patients, they may even be applicable to dysphagia rehabilitation.

In a study assessing changes in lip width during deglutition, Ishida et al.¹⁰⁾ reported that swallowing caused muscle traction at the corner of the mouth. This suggests that lip movement can be used to estimate tongue activity. During weaning, children typically develop the preliminary skills of placing food into the mouth and then compressing and crushing food with the tongue. By the age of 3 years, the child has normally developed upper and lower deciduous molar teeth and has acquired masticatory function. These developmental processes are very important in acquiring the ability to ingest food, and a detailed understanding of the associated movements is also useful in the rehabilitation of children with dysphagia. The present study was a pilot study of adults conducted with the aim of investigating lip and mandibular coordination in children and disabled individuals in the future.

1. Study methods

When conducting research of this nature, it is essential to specify the shape and physical characteristics of the test food and to maintain sanitation and hygiene. In light of the above-mentioned aim to target children in future research, the test food and its weight were specified to enable safe consumption by children. While reports vary, the average weight of food that a child can generally ingest in a single mouthful is approximately 5 g.²⁶⁾ Gum has often been used in previous research on mastication,^{27~29)} and the present study selected a cookie as the test food in order to observe a range of movements from ingestion to swallowing, and because it is familiar to children.

The upper and lower lips and the left and right corners of the mouth were selected as the 4 anatomical landmarks

based on previous literature.^{9,15)} In terms of mandibular movement, Hirano²⁷⁾ demonstrated that the mouth opening measured at the pogonion was a valid substitute for the mandible. In light of these findings, the pogonion was also selected as an anatomical landmark indicating mandibular movement in the present study.

The term “working side” is typically used to denote the habitual chewing side on which most tooth contact occurs during mastication.³⁰⁾ Previous research has shown that distribution of the working side between the left and right sides is almost equal in randomly-selected male and female adults, and that it is not correlated to occlusal problems or hand dominance.³⁰⁾ This finding appears to be valid given that the right to left ratio of habitual chewing in the present study was almost equal at 12:8.

Meanwhile, a study by Sekita et al.¹³⁾ found that, when performing measurements using 2 CCD cameras at optical axes of 30°, 35°, 60°, and 90°, the 60° setting produced the smallest margin of error. An optical axis of 60° was therefore adopted when recording with 2 CCD cameras in the present study. Since Takahashi et al.¹⁵⁾ reported that the use of a headrest, as well as a band around the subject’s forehead, provided sufficient fixation during measurement, the same equipment was used when recording subjects in the present study.

2. Interpretation of the results

1) Average number of strokes and time taken

In a study by Goto et al.,³¹⁾ the average time from commencement of chewing to completion of initial swallowing of an 8-g barium cookie was 17.80±3.26 s. Ouchi et al.³²⁾ reported a similar average chewing time using the same type of cookie, at 15.35±2.92 s. In the present study, the average time taken to chew and swallow a 1 g cookie was 17.65±3.57 s, which is more or less comparable to that of the 2 prior studies. The similarity of these results despite the relatively small size of the test biscuit at 1 g suggests that, as long as the amount is appropriate for an adult to consume in a single mouthful, the time taken for chewing and swallowing is not overly influenced by slight variations in the amount.

2) X- and Y-axis movements of the pogonion

Mandibular movement during mastication can generally be divided into the following 2 main patterns, namely “chopping”, which indicates a biting action characterized by vertical movement of the mandible with little lateral displacement, and “grinding”, which refers to a grating action characterized by considerable lateral displacement. Adopting the classification described by Goto et al.,³¹⁾ the present study used the frontal trajectory data of the pogonion obtained from analysis to categorize major lateral movement of the pogonion as pattern 1 and major vertical movement as pattern 2. During external observation of the pogonion, pattern 1 was presumed to be a grinding movement of the mandible, and pattern 2 was considered to be a simple vertical movement of the mandible.

The lips are surrounded by a series of muscles centered around the corners of the mouth, such as the buccinator muscle, which supports the buccal mucosa and interacts with the mandible to prevent masticated food from falling into the oral vestibule.^{33,34)} In the present study, it is this intraoral motion that was believed to be responsible for the apparently similar movement of the working-side corner of the mouth and pogonion towards the working side. Mastication generates intense internal and external movements in the working-side cheek and upper cheek that often pull the balancing-side commissure towards the working side.⁹⁾ A study by Mukai et al.⁹⁾ argued that detailed objective 3D analysis of the commissures is essential due to the abundance of muscles and complex (internal/external, vertical, and horizontal) movements. In the present study, 3D analysis of the balancing side corner of the mouth revealed movement towards the balancing side contrary to that of the working-side corner of mouth and pogonion. This movement was attributed to the presence of the orbicularis oris muscle surrounding the lips. Most of the musculature comprising the orbicularis oris pulls the corner of the mouth in a posterolateral direction, giving the rima oris its generally straight appearance. It is this likely movement of the buccinator and orbicularis oris that caused the corner of the mouth to

be pulled outwards in the present study. Furthermore, the biscuit used as the test food was hard, but only slightly agglutinate, adherent, and elastic, allowing it to disperse throughout the mouth on chewing. Therefore, some of the biscuit spread to the balancing side, which may have caused the subjects to masticate on the balancing side as well as the working side.

3) X- and Z-axis movements of the working-side and balancing-side corners of the mouth

The above-mentioned study by Hirano²⁷⁾ investigated the average trajectory of lip movement during gum chewing. The trajectory of the working-side corner of the mouth was pulled inwards in the open mouth state due to contraction of the orbicularis oris, pulled outwards in the closed-mouth state due to contraction of the buccinator, and was also affected by movement of the mandible. Meanwhile, the trajectory of the balancing-side corner of the mouth moved inwards and was subsequently drawn back and downwards when the subject's mouth started to open due to the loss of support from the dentition, thereby resulting in movement in a postero-medial-inferior direction. The trajectory of the corners of the mouth from immediately after ingestion until immediately before swallowing the cookie was similar to the above-mentioned average trajectory of lip movement during gum chewing. Moreover, the working-side corner of the mouth moved in the direction of the Z-axis before moving towards the X-axis in the closed-mouth state, because it was initially drawn back before moving outwards. As mentioned above, mandibular movements associated with chewing the food and buccal movements to keep the food between the teeth reflected the movements of the working-side corner of the mouth.

4) Relationship between amount of movement of the working side and balancing side angle of the mouth and of the working side angle of the mouth and pogonion

Previous studies have indicated that buccal muscle activity during mastication is characterized by significantly higher buccinator and masseter activity on the chewing side than on the non-chewing side.³⁵⁾ While the

present study did not reveal significant differences in X- and Y-axis movements, the amount of movement was far greater on the working-side than on the balancing-side. Movement of the corner of the mouth is influenced not only by movement of the mandible but also of the muscles surrounding the lips. In this study, these surrounding muscles may have affected the movement of the corner of the mouth to such an extent that the amount of movement of the working-side corner of the mouth was more substantial than that on the balancing-side.

Data on the amount, time taken, and speed of movements measured at each anatomical landmark showed that the working-side corner of the mouth moved a greater distance at a faster pace and therefore in less time than that of the balancing-side corner of mouth. This is conceivably due to the aforementioned differences in X- and Z-axis movements of the working-side and balancing-side corners of the mouth. The working-side corner of the mouth moved in the direction of the Z-axis before moving towards the X-axis in the closed-mouth state. This outcome was attributed to the grinding of food on the working-side, wherein the relative reduction in time taken was the result of a considerable amount of movement at a fast speed in order to achieve efficient mastication. The distance and speed of movement along the Z-axis was also significantly greater on the working-side corner of the mouth than on the balancing-side corner of the mouth for precisely the same reason.

Meanwhile, previous research has indicated that movement of the pogonion was not significantly larger than that of the incisal point, but it did tend to have greater lateral displacement,³⁶⁾ suggesting that mandibular movements translate to movements on the skin's surface, which in turn generate a substantial amount of movement at the pogonion.

A study by Iwanami et al.³⁷⁾ addressed the differences between mandibular movement patterns I and III, and the findings of the present study demonstrated that pogonion movement along the Y-axis tended to be greater for the chopping type than for the grinding type, although not significantly so. The chopping pattern is characterized

by greater movement of the pogonion along the Y-axis than along the X-axis, so the study results concur with the hypothesis that chopping movements should exceed grinding movements. It is also consistent with the finding of a previous study that the extent of mouth opening at the mandibular incisor point was greater for the chopping type.³⁷⁾ The pogonion and working-side corner of the mouth interact, as demonstrated in part 4 of the Results section. Consequently, Y-axis movement of the working-side corner of the mouth is also predominantly of the chopping type.

Conversely, compared to Y-axis movement, X-axis movement of the working-side corner of the mouth was deemed to be predominantly of the grinding type, which is itself characterized more by movement along the X-axis. While the results were not significant, pogonion movement tended to be higher for the grinding pattern. On the other hand, working-side corner of the mouth movement was greater for the chopping type, although not significantly so. It was presumed that, when mandibular movements were reflected by the working-side corner of the mouth, the result would be the same as for the pogonion, but, in fact, the chopping pattern was prevalent, an outcome believed to have been due to the effect of movement of the muscles around the lips. On the chewing side, the muscles around the lips work to prevent masticated food from falling into the oral vestibule, and the cheek keeps the food between the dentition. Based on this series of movements, the working side corner of the mouth is influenced by the muscles around the lips to the extent where the corner of the mouth may move inwards. Comparison of the chopping and grinding patterns showed that Y-axis movement was greater for the chopping pattern, thereby suggesting that the amount of X-axis movement tended to be larger for the chopping pattern than for the grinding pattern, because the chopping pattern requires movement of the peri-oral facial muscles and support of the cheeks to keep food between the dentition.

In the future, we intend to expand the scope of this study to include children.

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