Title

Lip-closing pressure during food intake from a spoon in normal children

Short running Title

Lip pressure in self-feeding children

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Conflict of interest

The authors declare that they have no conflicts of interest.

Author contributions

All authors contributed to the study conception and design. Material preparation and data collection and analysis were performed by Y. Sasakawa, Y. Nakamura, T. Nakajima, S. Tsukuno, and M. Hozawa. The first draft of the manuscript was written by Y. Nakamura and critical revision of the manuscript was provided by I. Saitoh, T. Hayashi, and H. Hayasaki. All authors commented on previous versions of the manuscript and approved the final manuscript.

Abstract

Background: Understanding the refinement of self-feeding skills is useful for the assessment of oral functional development in children.

Objectives: To determine normative data on lip closing during food intake in the development of independent spoon feeding in normal children, we tested the hypothesis that lip-closing pressure and spoon operation differ depending on food type.

Methods: Fifteen normal children (eight boys, seven girls; mean age: 6.5 years) were asked to eat test foods (2, 3, and 5 g of yogurt and cream cheese) freely with a spoon. Lip-closing pressures and kinematic data on spoon operation were recorded simultaneously with a strain gauge transducer embedded in the spoon and Vicon motion analysis, respectively.

Results: In the most common lip-pressure pattern, only positive pressure was generated. In the second most common pattern, negative pressure occurred first, followed by positive pressure; this pattern was seen infrequently. Positive pressure ($P < 0.001$), pressure duration ($P < 0.001$), and spoon intraoral time ($P < 0.05$) during intake of cream cheese (an adhesive food) were significantly greater than those during intake of yogurt (a non-adhesive food). Pressure onset occurred at the beginning of the spoon-withdrawal period or at the turning point from spoon insertion to withdrawal, depending on the food.

Conclusions: Lip-closing force and spoon operation varied depending on food type in preschool and early elementary school children. Our findings suggest the need to consider the importance of food diversity and to pay attention to the spoon-withdrawal period when assessing the development and maturation of lip function.

Keywords: Lip, pressure, child development, feeding behavior, food intake, oral function

1. Background

Eating requires appropriate movement of the oral structures, including the jaw, lips, and tongue. Normal developmental acquisition of eating skills in infants is described in terms of milestones.[1] The first step is sucking from the breast or bottle, the second is eating from a spoon, the third is chewing solid food, and the fourth is eating independently (self-feeding).[2] The four major feeding milestones are generally mastered by 2 years of age, although refinements in oral motor control, skill, and social manners will continue beyond the first 2 years.[3] Although most studies have not evaluated older children, those of Gisel and colleagues examined aspects of the chewing cycle,[4] tongue movements,[5] and oral form discrimination[6] in children through 8 years of age. The results indicated that eating skills mature in children between 2 and 8 years of age and the authors provided a preliminary developmental curve for eating behaviors. Additionally, they reported that eating skills matured at different rates for different food textures. The mouth continues to change in shape and size with tooth replacement, and different food tastes and textures provide different oral sensorimotor experiences. These changes and experiences might contribute to the refinement of eating skills after late infancy.

Lip function plays an important role in almost all feeding stages, including food intake, chewing, and swallowing.[2,7] The lips open to accept food, close to contain food within the oral cavity and prevent leakage, and may retrieve food from outside the oral cavity. Lip movement during oral feeding can be visually observed. Several studies on the visual observation of lip movement during feeding have reported developmental progression of lip closure during bolus removal from a spoon or retention of a bolus within the oral cavity.[8-11] Most of these studies have focused on spoon-feeding with parental assistance. By 2 years of age, all children achieve lip closure for both removal and retention in at least 80% of trials for all food consistencies. Acquisition of lip closure in spoon-feeding is influenced by food texture and length of feeding experience. Although most studies have not been quantitative assessments, Chigira et al. used a pressure sensor to quantitatively evaluate the closing pressure of the mid-lip during assisted spoon-feeding.[12] They found that the mean lip-closing pressure on the spoon steadily increased from 5 months to 3 years of age and increased only slightly between 3 and 5 years of age in normal children. That study involved passive spoon-feeding. No previous studies have evaluated lip-closing pressure during self-feeding in children. In the present study, we quantitatively evaluated lip-closing pressure and spoon operation during self-feeding with a spoon to investigate how the development of lip-closing function affects the establishment of self-feeding.

The objective of this study was to obtain normative data on lip closing during food intake in normal children during the maturation steps toward independent spoon-feeding by testing the hypothesis that lip-closing pressure and spoon operation will differ depending on food adhesiveness and quantity in normal children. Additionally, we discuss the developmental changes in lip-closing function during food intake compared with data from normal adults in earlier studies.

2. Methods

2.1 Participants

Fifteen normal children (eight boys, seven girls) aged 4.9 to 9.8 years (mean: 6.5 years) were recruited on a voluntary basis; informed consent was obtained from the children and their parents. All children had primary dentition or early mixed dentition with eruption of the first permanent molar or incisor. None of the participants had any morphological or functional defects, abnormalities of the teeth or occlusion, or history of eating problems, including food allergy. All participants were right-handed.

The Ethics Committee of Niigata University approved the study (no. 2019-0047). The study was performed in accordance with the Declaration of Helsinki and the Ethical Guidelines for Medical and Health Research Involving Human Subjects (Public Notice of the Ministry of Education, Culture, Sports, Science and Technology and the Ministry of Health, Labour and Welfare of Japan, 2014).

2.2 Measurement system and procedure

We used the measurement system described in our previous study.[13] The following is a brief explanation of the measurement system. The system consisted of a pressure sensor for measuring lip-closing pressure and an optical 3D motion capture system, described below, for analysis of oral kinematics and spoon operation. We measured the interface pressure on the spoon generated by lip closure during food intake from the spoon. The system was composed of a waterproof miniature pressure sensor (diameter: 5 mm, thickness: 1.2 mm; PSS-AE; KYOWA, Tokyo, Japan), which employed a strain gauge transducer and was embedded in the surface of a stainless steel spoon (head width: 29 mm, length: 32 mm, depth 5.4 mm, total length: 170 mm, weight: 30 g; Light-spoon S; AOYOSHI, Niigata, Japan) (Figure 1A, B). Pressure signals were passed through an interface board (PowerLab; ADInstruments, Colorado Springs, CO, USA) at a sampling frequency of 1,000 Hz. Data analysis was performed with the PowerLab software package (LabChart 8; ADInstruments).

We used the Vicon motion analysis system (Vicon Motion Systems, Oxford, UK) to collect 3D kinematic data at a frequency of 100 Hz. For each participant, we attached 11 light-reflective markers to the face, 11 to the upper body, and 4 to the spoon. We tracked the motions of the markers (Figure 1C) with 10 charge-coupled device cameras. Five of the facial markers were attached to the right and left rims, right and left temples, and bridge of an eyeglass frame to configure the reference coordinate system. Four markers for recording spoon movement were attached to the rear portion of the spoon, as shown in Figure 1B.

We performed recordings between 15:00 and 17:00 in the afternoon, before dinner. Participants were asked to sit upright in a child-sized chair. They were given the weighed test food on a spoon held in their right hand and were asked to face forward with their mouth closed until a command for intake was given. Test foods were 2, 3, and 5 g of yogurt (Bulgaria yogurt LB81; Meiji Co., Ltd., Tokyo, Japan), the same quantities of cream cheese (Kiri; Bel Japon K.K., Tokyo, Japan), and 2 ml of water as a reference. The test foods were taken out of the refrigerator 30 minutes before testing and used at room temperature (20–22℃). According to previous texture profile analysis, the hardness, adhesiveness, and cohesiveness of the yogurt used in this study are 312 ± 14 N/m^2, 75.0 ± 6.2 J/m^3, and 0.84 ± 0.01, respectively, at 20 ± 2℃.[14] The hardness, adhesiveness, and cohesiveness of a cream cheese similar to that used in this study are $61.2 \pm 5.3 \times 10^3$ N/m^2, $21.7 \pm 2.5 \times 10^3$ J/m^3, and 0.25 ± 0.008, respectively, at 18℃.[15] Each test food was placed onto the spoon center, touching the sensor. We told each participant in advance to eat the test food in one bite and asked them to perform free intake of the test food after receiving a start command. The recording session began when the participant was stationary while holding the spoon before the start command and ended when the participant completed the swallow. Two timed recordings were performed for each condition of test food, and mean values were analyzed. The order of measurement of the different foods and quantities was randomized. We performed recordings after several trials with the spoon without test food to allow participants to adapt to the measuring environment.

2.3 Data analysis

We measured maximum positive and negative pressures and calculated integrated values of positive and negative pressures. As temporal parameters, the active pressure duration and the time between entry and exit of the spoon from the oral cavity (spoon intraoral time) were calculated. The calculation methods were as follows, in accordance with our previous study.[13] When pressure values during a trial exceeded ± 2 SDs of the baseline at rest for 3 s, the pressure was considered active. Test results in some participants did not show negative pressure in the recording. In such cases, we considered the negative pressure of the participants to be zero. Conversely, when only negative pressure was detected, we considered the positive pressure to be zero. The average positive and negative pressures were calculated as the average of the maximum values for positive and negative pressures of the 15 participants. Positive and negative pressure times were defined as the duration between onset and offset of pressure for each, and the total pressure time was the sum of the two (Figure 2A). For the spoon intraoral time, we determined the theoretical point of the spoon edge from the spoon marker set and calculated the time when the theoretical point passed through the superior lip plane, which was perpendicular to the reference coordinate plane of the head and contained the superior lip marker, during spoon insertion and withdrawal (Figure 2B). Additionally, we converted the time scale to percentage values (start of spoon insertion = 0%, end of spoon withdrawal = 100%). With this time scale, time-dependent changes in pressure were obtained for each participant. In addition to pressure onset and offset, we determined the time of maximal absolute value of the pressure and defined this as the time of peak pressure.

We performed descriptive statistics and two-way analysis of variance for comparison between food types and quantities using SigmaPlot 14 (Systat Software, Inc., Chicago, IL, USA). Tukey's test was used for multiple comparisons. Data are expressed as means ± SDs. A P value < 0.05 was considered statistically significant.

3. Results

Four wave patterns of lip-closing pressure were recognized during measurement. In Pattern 1, negative pressure occurred first, followed by positive pressure. In Pattern 2, only positive pressure occurred and in Pattern 3 only negative pressure occurred. In Pattern 4, positive pressure occurred first, followed by negative pressure (Figure S1). Table 1 summarizes the proportion of each wave pattern during intake of each test food. Pattern 2 was the most common, occurring in 70.0% to 82.1% of trials and seen during both yogurt and cream cheese intake. This was followed by Pattern 1, which occurred in a comparatively low proportion of participants (14.8%–22.2%). Patterns 3 and 4 were seen sporadically.

Figure 3 illustrates the maximum positive pressure and negative pressure data and their integrated values. There was no significant interaction between food type and quantity for these data. Positive pressure and integrated values during cream cheese intake were significantly greater than those during yogurt intake ($P < 0.001$). However, there were no significant differences in positive pressure among food quantities. Because many the participants generated only positive pressure and the frequency of negative pressure was low, as shown in Table 1, the mean negative pressure during intake of all test foods was small. No significant differences in negative pressure data were found between food types or among food quantities.

Figure 4 presents the spoon intraoral time and pressure time. There were significant differences in spoon intraoral time ($P < 0.05$) and pressure time ($P < 0.001$) between yogurt and cream cheese, with cream cheese intake having longer times than yogurt intake. The time required for spoon withdrawal during cream cheese intake was significantly longer than that for yogurt ($P < 0.01$); however, the time required for insertion did not differ by food type. Significant differences in spoon intraoral time were found between different food quantities ($P < 0.05$), with longer spoon intraoral times during 5-g intake than during 2-g intake. No significant differences in pressure time were found among different food quantities.

Figure 5 shows the timing of active pressure events from the start of spoon insertion to the end of spoon withdrawal. The pressure onset appeared at the beginning of the spoon-withdrawal period during water and yogurt intake and appeared near the turning point from insertion to withdrawal during cream cheese intake. All peak pressures and offsets appeared in the spoon-withdrawal period, later in the normalized time scale. Table S1 shows pressure event timing in the normalized time scale relative to spoon operation phases. Because time for withdrawal for cream cheese was significant longer than that for yogurt and the insertion time did not differ between foods, the ratios of insertion-to-withdrawal periods were significantly different between yogurt and cream cheese ($P < 0.05$). There were no significant differences in insertion-to-withdrawal ratios among food quantities.

4. Discussion

4.1 Lip-closing pressure waveform

We defined the pressure detected by a miniature pressure sensor glued to the bowl surface of a spoon as lip-closing pressure during food intake in this study. Several previous studies have measured lip-closing pressure and quantitatively evaluated lip strength in adults[13,16] and children[12] by using a similar method. Nakamura et al. reported that negative pressure appeared prior to positive pressure during intake of adhesive food; they hypothesized that participants sucked or squeezed the spoon to intake such foods. We therefore classified the pressure waveform as one of four patterns according to the style of pressure generation. In the most common pattern, accounting for 70.0% to 82.1% of trials, only positive pressure was generated and negative pressure was not seen. In the second most common pattern, negative pressure appeared first, followed by positive pressure; this pattern occurred in 14.8% to 22.2% of cases. Nine participants (three boys, six girls; mean age 6.4 years, range 4.9 to 8.1 years) showed only Pattern 1 or 2 through all test foods. This group included a higher proportion of girls than the total study group, but did not differ in age. There was no difference between food types in the proportion of wave patterns (Table 1). Many children pressed their upper lip to the spoon surface without sucking or squeezing the spoon surface during food intake. This result is different from that reported for adults in a previous study. Adults changed the way their lips acted on the spoon depending on the food type. They sucked or squeezed the spoon and subsequently pressed their upper lip to the spoon during intake of adhesive food, and simply pressed their upper lip to the spoon surface without sucking or squeezing during intake of non-adhesive food, such as yogurt.[13] This age-related difference may be related to immaturity of feeding function in children. Additionally, in a few cases of cream cheese intake, only negative pressure occurred (Table 1), indicating that these children only sucked or squeezed the spoon to remove food, especially adhesive food, from the spoon surface, which might be a sign of immature feeding function. We speculate that alterations in lip-closing movement depending on food adhesivity are learned after children reach school age.

4.2 Influence of food adhesivity and quantity on pressure associated with lip closing

In this study we used two food types, yogurt and cream cheese, for the following reasons: (1) these foods have a stable consistency, (2) they differ in adhesivity, and (3) they are generally acceptable to children.[17] According to the framework of the International Dysphagia Diet Standardization Initiative (IDDSI) and the description of the cohesiveness and adhesiveness of foods on a spoon-tilt test, yogurt is a liquidized food categorized as IDDSI Level 3 that is smooth and cohesive, but not sticky or adhesive. In contrast, cream cheese is sticky or adhesive, leaving more residue on the spoon.[18] Cream cheese is categorized as IDDSI Level 4, but is too sticky. We also examined differences related to food quantity on the spoon; the quantities assessed were 2 g, 3 g, and 5 g. The quantities of test food in previous studies have varied depending on spoon size or participant age.[12,13,16,19] Fisher et al. reported that the average bite size of preschool children was 6.6 ± 0.4 g of a reference lunch.[20] We generated a situation as close as possible to a normal meal and considered whether a child could repeatedly perform the method when determining the test food quantities. We found that positive pressures during cream cheese intake were significantly greater than those during yogurt intake. However, we found no clear influence of food quantity on lip closing pressure, although positive pressure tended to decrease as food quantity increased. Food adhesivity may be an important factor influencing lip closure during food intake. Adhesiveness and cohesiveness of food, and to a greater degree food hardness, are important rheological factors in oral food processing, mainly affecting mastication.[21,22] It was reported that medical professionals and food industries need to consider the importance of food diversity in mastication development and maturation because some masticatory regulation according to food properties could already be present in preschool children.[23] The same recommendation could also apply to lip-closing function during food intake. Regarding the effect of food quantity on lip-closing pressure, Nakamura et al. suggested that the lip-closing force to seal the superior and inferior lips gradually weakens as food quantity on the spoon increases,[13] although this effect was not clear in the present study. The test food quantity in this study did not greatly exceed the average bite size of children. It is possible that the influence of food quantity is not clear at quantities that do not exceed the average bite size.

The negative pressure generated did not differ among food types or quantities and the mean value was small, < 1.0 kPa. Because this value was small, even compared with the reported intraoral negative pressure at the mandibular rest position,[24] we speculate that the negative pressure often resulted simply from mouth closing[24,25] and tongue repositioning.[26] The main force exerted to remove food from the spoon surface is likely positive pressure because in the most common pressure pattern only positive pressure was generated.

4.3 Comparison with lip-closing pressure of adults in earlier studies

Lip-closing pressure during food intake is supposed to vary depending on the feeding condition, the quantity and type of food, and whether the food is taken with assistance or independently. It is necessary to consider differences in experimental conditions, but we will compare and discuss differences in lip-closing pressure between children and adults from earlier studies. Table S1 shows positive lip-closing pressure measured with an embedded miniature sensor in four previous studies.[12,13,16,19] The values during yogurt intake in young adults were similar among three studies and tended to be larger during assisted ingestion. The values among children in our study were 2.7 ± 2.6 kPa, 2.3 ± 2.0 kPa, and 1.8 ± 1.1 kPa for 2-, 3-, and 5-g yogurt intake, respectively, and 5.1 ± 2.8 kPa, 4.0 ± 2.5 kPa, and 4.1 ± 1.7 kPa for 2-, 3-, and 5-g cream cheese intake, respectively. These pressures were approximately half those of adults, indicating that lip closing force during food ingestion is still under development during preschool and early elementary school. Additionally, pressures in our study were smaller than those among children in the study of Chigara et al. This difference might be related to the difference between assisted and independent feeding. Because a child’s head control during ingestion is immature,[27,28] larger forces may be generated to capture and hold the spoon during food intake from a spoon offered by an operator. Further study is needed on head posture and spoon withdrawal angle to examine these differences.

4.4 Temporal relationship between lip pressure and spoon operation

We investigated the duration during which the spoon was present in the oral cavity (Figure 5) and found that withdrawal time was longer than insertion time. Pressure onset appeared at the beginning of the spoon withdrawal period or at the point when insertion changed to withdrawal, and pressure peaked in the latter half of the withdrawal period. Additionally, there were differences in spoon intraoral times between food types and among quantities; the pressure time also changed between food types and was longer for adhesive food. Not only total time but also the time ratios of insertion-to-withdrawal were longer for adhesive food. These results are similar to those observed in adults in previous studies that used similar measuring methods.[13] Preschool and early elementary school children changed their spoon operation and lip movements depending on the food type in ways similar to adults. However, there are differences in the timing of pressure events between children and adults. In all adults, pressure onset occurred during the spoon-withdrawal period, whereas pressure onset in children occurred earlier than in adults and occurred at the turning period from insertion to withdrawal for adhesive food. We hypothesize that the moment when the lips first contact the spoon surface may shift later in the process with maturation of feeding skills. The maximum lip pressure on the spoon surface was exerted in the latter withdrawal period.

One critical skill for self-feeding is coordination of hand and mouth motions. Tamura et al. reported that four observation items (spoon-holding technique, flexion of elbow and shoulder, taking food from the spoon with the lips, and patterns of neck rotation) can be useful in assessing the development of hand and mouth coordination in independent spoon-feeding.[29] Our results suggest that careful attention to spoon-withdrawal movements and lip-closing performance is necessary when assessing adequate food intake from the spoon by the lips in the developmental process of feeding. In an investigation of the relationship between lip pressure and spoon operation, Kayanaka-Sekine et al. reported that lip pressure was related to spoon angle during withdrawal.[16] The maximum lip-closing pressure in their study was significantly higher at higher spoon angle than at lower spoon angle. However, that study evaluated passive spoon feeding in adults. We think that it is important to examine the relationship between lip pressure and spoon angle during self-feeding in children because of the importance of coordination of hand and mouth motion in children.

4.5 Limitations

This study had certain limitations. First, we did not examine the intake of excessive quantities of test food in children. Although few studies have investigated the volume of a mouthful of food in children, Fisher et al. reported the average bite size in preschool children.[20] We set the test food quantities to be below the average mouthful quantity reported in that study to ensure that children could repeatedly perform the movements. Low muscle tone in the lips weakens the ability to keep food and saliva from spilling from the mouth;[3] lip-closing training improves maximal lip-closure force, decreasing food spill rates.[30] It is necessary to examine the lip-closing pressure during intake of quantities above the average intake to clarify the effect of excess quantities on food-intake skill in children. Second, our participants were a single group of 15 healthy children aged 4.9 to 9.8 years (mean: 6.5 years), which did not allow for grouping or consideration according to age. Our results in children were compared with those in adults by referring to earlier studies that used similar measuring methods. Further examination of the signs of developmental landmarks in self-feeding skills and when to expect them is needed, with studies that group participants across a wide range of ages.

Despite these limitations, the present study produced new findings about lip-closing pressure and spoon operation in children during food intake. Our results may increase understanding of normal lip function during food acquisition in the developmental stage and aid assessment of feeding skills.

5. Conclusions

We examined pressures associated with lip closing and oral and spoon operation during food intake from a spoon in children. Our results support the following conclusions.

1. Positive pressure during intake of adhesive food, such as cream cheese, was significantly higher than that during intake of non-adhesive food. Lip-closing force varied depending on food adhesivity, suggesting that we need to consider the importance of food diversity in lip function development and maturation.
2. Irrespective of food type, many children pressed their upper lip to the spoon surface without sucking or squeezing the spoon surface during food intake.
3. Lip pressure onset occurred during the spoon-withdrawal period or at the turning period from insertion to withdrawal and maximum lip pressure on the spoon surface was exerted in the later withdrawal period. These findings indicate that careful attention to spoon withdrawal movements and lip performance is needed when assessing the feeding skills of children.

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Table 1 Proportion of each wave pattern seen with intake of each test food (%)

	Pattern 1	Pattern 2	Pattern 3	Pattern 4
Yogurt, 2 g	14.8	77.8	—	—
Yogurt, 3 g	16.7	70.0	—	3.7
Yogurt, 5 g	16.0	80.0	—	14.8
Cream cheese, 2 g	17.9	82.1	7.4	—
Cream cheese, 3 g	22.2	74.1	10.0	3.3
Cream cheese, 5 g	14.8	70.4	—	4.0
Total	17.1	75.7	2.9	4.3

Pattern 1: Negative pressure occurs first, followed by positive pressure. Pattern 2: Only positive pressure occurs. Pattern 3: Only negative pressure occurs. Pattern 4: Positive pressure occurs first, followed by negative pressure

Table S1 Timing of pressure events relative to spoon operation phase (%)

	Onset	Peak	Offset
Water 2 ml	43.1	72.7	89.3
Yogurt, 2 g	39.2	73.5	90.8
Yogurt, 3 g	42.1	78.9	94.4
Yogurt, 5 g	47.3	76.9	91.9
Cream cheese, 2 g	30.5	72.1	97.4
Cream cheese, 3 g	29.6	73.6	96.2
Cream cheese, 5 g	28.1	71.4	94.9

Table S2 Lip-closing pressure during food intake in previous studies

Authors	Participants	N; Age	Ingestion method	Food	Measuring device	Mean lip-closing pressure, kPa
Chigira et al. 1994	Children	N = 104; 0–5 years	Assisted ingestion	Yogurt; 0.5 g	Miniature pressure sensor embedded in spoon	3.8 (0 y) 6.2 (1–2 y) 9.4 (3–5 y)
Tamura et al. 2009	Young adults Elderly adults	N = 59; Mean age 32.0 N = 84; Mean age 79.4	Assisted ingestion	Yogurt; 1 g	Miniature pressure sensor embedded in acrylic plate	6.6 ± 4.2 (Young) 11.2 ± 8.9 (Elderly)
Kayanaka-Sekine et al. 2011	Young adults	N = 15; Mean age 24.5	Assisted ingestion	Yogurt; 0.6 ml	Miniature pressure sensor embedded in spoon	4.2 ± 0.8 (Spoon angle 0°) 6.4 ± 1.0 (Spoon angle 60°)
Nakamura et al. 2019	Young adults	N = 20; Mean age 24.4	Self-feeding	Yogurt, Cream cheese; 3, 5, 10 g	Miniature pressure sensor embedded in spoon	3.3–4.0 (Yogurt) 8.4–10.3 (Cream cheese)

Figure Legends

Figure 1 Photo of stainless steel spoon with pressure sensor and light-reflective markers attached to participant

(A) Interface spoon pressure was measured with a miniature pressure transducer (arrow) glued to the bowl of a stainless steel spoon. Pressure was detected on one side of the spoon.

(B) Four lightweight markers were attached to the rear portion of the spoon to record spoon movements.

(C) One of the lower facial markers was the superior lip marker (Ls). Five markers were attached to right and left rims, right and left temples, and bridge of eyeglasses to configure the reference coordinate system (H). Four markers were attached to the rear portion of the spoon in a regular tetrahedron to record spoon movements (S).

Figure 2 Representative pressure and spoon operation recordings for 2-g cream cheese intake

(A) Solid line shows lip-closing pressure. The unit of pressure in our study was the kilopascal (kPa): kPa = kN/m^2. Dotted line indicates the distance of intraoral spoon insertion (spoon insertion distance). Positive values indicate that the spoon edge is extraoral, negative values indicate intraoral location.

(B) Spoon intraoral time. The head plane was configured by markers on right and left rims, right and left temples, and bridge of eyeglasses (as described in Fig. 2H). The Ls plane (superior lip plane) was perpendicular to the reference coordinate plane of the head and contained the superior lip marker (Ls). Spoon intraoral time was defined as the time after the spoon edge passed through the Ls plane and was present in the oral cavity.

Figure 3 Positive and negative pressures

The upper figures show maximum positive pressure and negative pressure for each food type and quantity. The lower figures show the integrated value of positive pressure and negative pressure for each food type and quantity. Data are expressed as mean ± SD. No significant interaction between food type and quantity was observed (P = 0.783 for positive pressure, P = 0.086 for negative pressure, P = 0.838 for integrated value of positive pressure, P = 0.226 for integrated value of negative pressure). Results of Tukey's test for multiple comparisons are also shown. *** $P < 0.001$

Figure 4 Spoon intraoral and pressure times

Dark gray bars indicate spoon insertion time and light gray bars indicate withdrawal time for each food type and quantity. Intraoral time was defined as the time between the start of spoon insertion and the end of spoon withdrawal. White and black bars indicate the pressure time, defined as the time between pressure onset and offset; white bars indicate positive pressure time and black bars indicate negative pressure time. Data are expressed as mean ± SD. No significant interactions between food type and quantity were observed (spoon insertion time: P = 0.110, spoon withdrawal time: P = 0.060, spoon intraoral time: P = 0.472, positive pressure time: P = 0.820, negative pressure time: P = 0.292). Significant differences in both spoon intraoral time (spoon intraoral time: $P < 0.05$, spoon insertion time: P = 0.388, spoon withdrawal time: P < 0.01) and pressure times (pressure time: $P < 0.001$, positive pressure time: $P < 0.001$, negative pressure time: P = 0.668) were observed between cream cheese and yogurt intake. Results of Tukey’s test for multiple comparisons among different food quantities are also shown. * $P < 0.05$

Figure 5 Timing of pressure events relative to spoon operation phases

Pressure event timing relative to the mean durations of the two phases, spoon insertion and withdrawal, are shown. Dark bars indicate insertion phase and light bars indicate withdrawal phase. White, black, and gray circles show pressure onset, peak, and offset, respectively. Data are expressed as mean ± SD of the ratio of each timing.

Figure 1

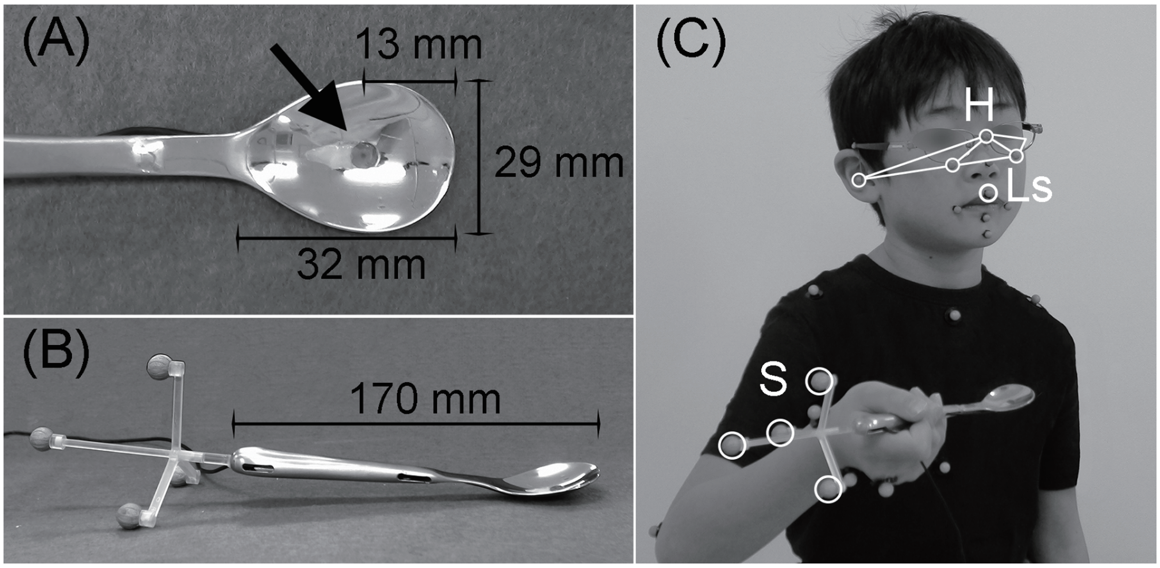
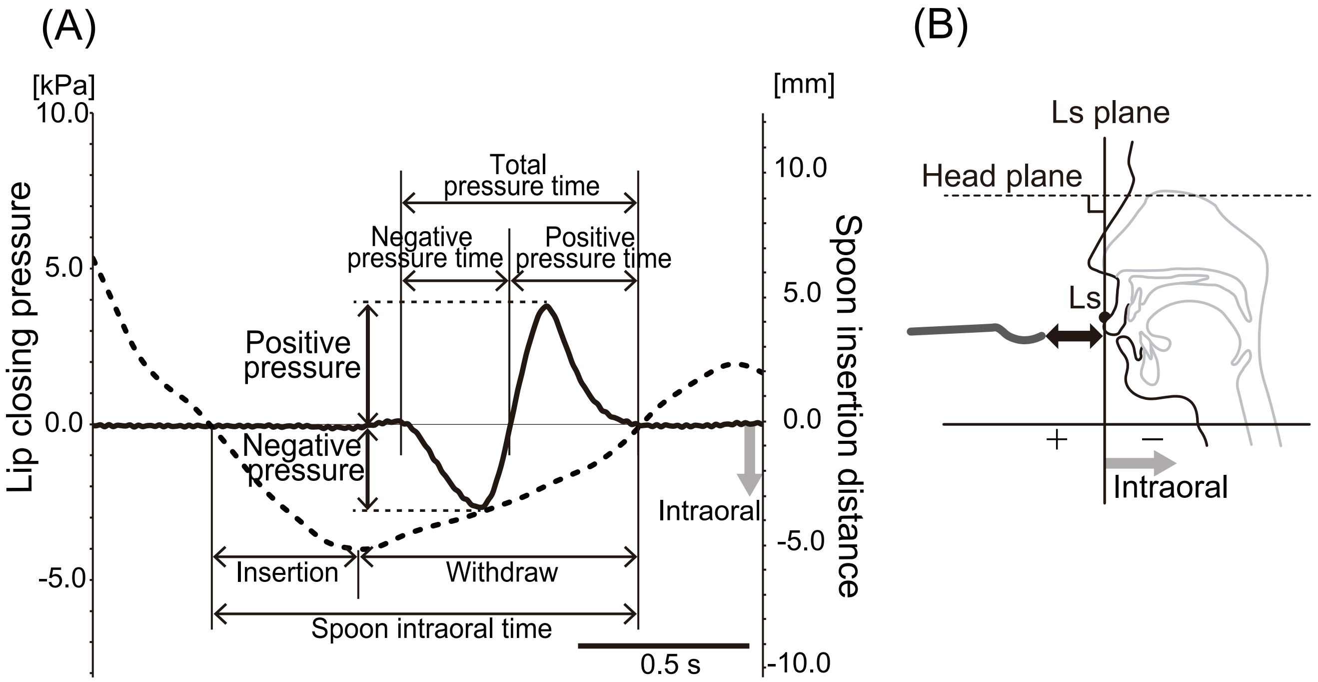
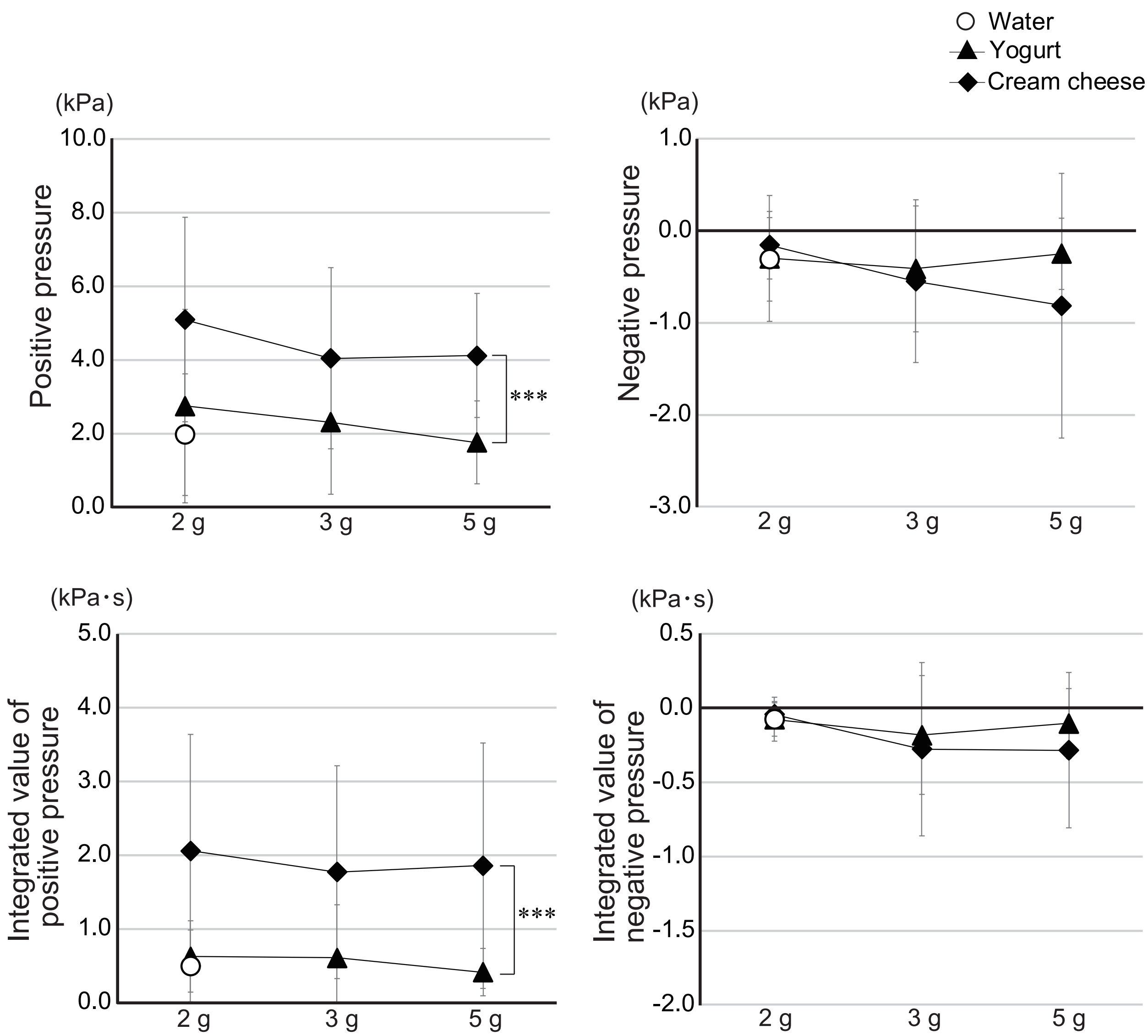


Figure 2



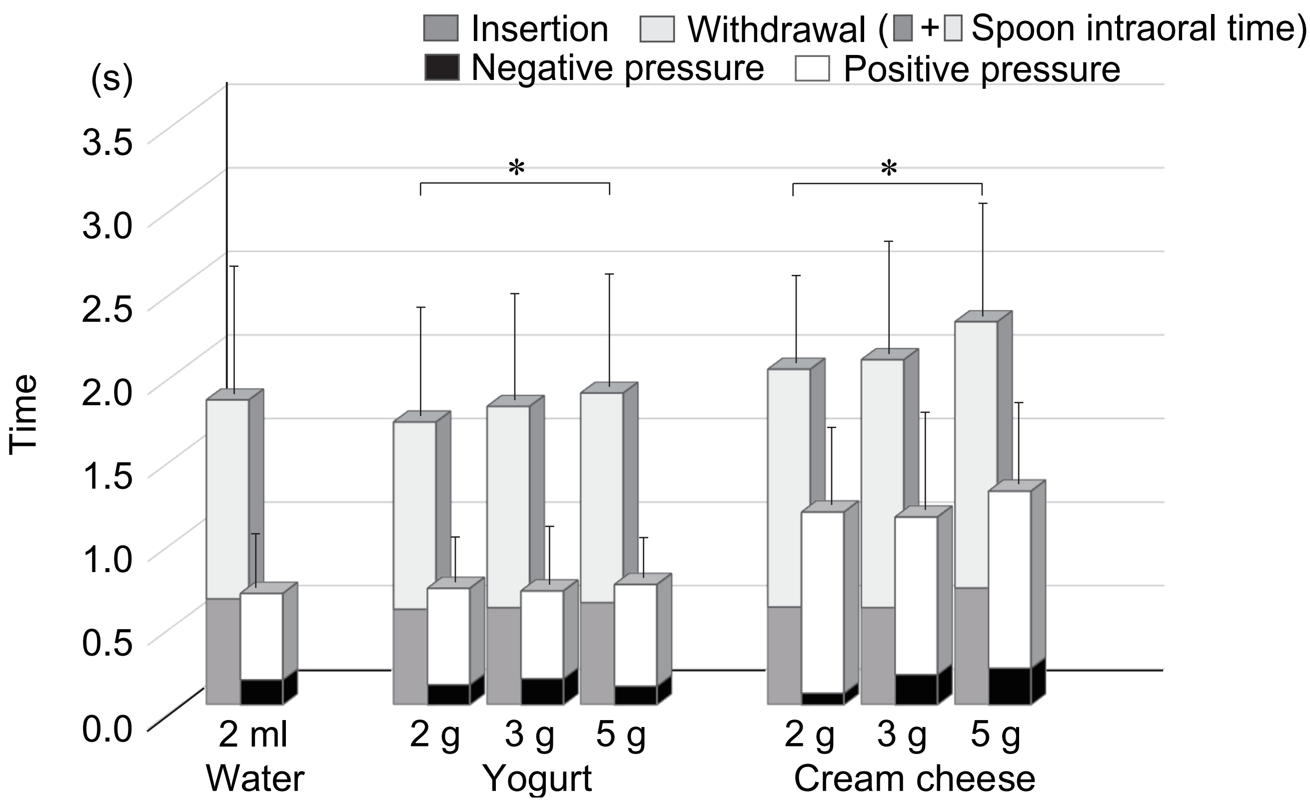
(A)
[kPa]
10.0
5.0
0.0
-5.0
Lip closing pressure
[mm]
10.0
5.0
0.0
-5.0
-10.0
Spoon insertion distance
Total pressure time
Negative pressure time
Positive pressure time
Positive pressure
Negative pressure
Intraoral
Insertion
Withdraw
Spoon intraoral time
0.5 s
(B)
Ls plane
Head plane
Ls
+
−
Intraoral

Figure 3



Water
Yogurt
Cream cheese
(kPa)
10.0
8.0
6.0
4.0
2.0
0.0
Positive pressure
***
2 g
3 g
5 g
(kPa)
1.0
0.0
-1.0
-2.0
-3.0
Negative pressure
2 g
3 g
5 g
(kPa・s)
5.0
4.0
3.0
2.0
1.0
0.0
Integrated value of positive pressure
***
2 g
3 g
5 g
(kPa・s)
0.5
0.0
-0.5
-1.0
-1.5
-2.0
Integrated value of negative pressure
2 g
3 g
5 g

Figure 4



Insertion
Withdrawal (+ Spoon intraoral time)
Negative pressure
Positive pressure
(s)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Time
*
*
2 ml
Water
2 g
3 g
5 g
Yogurt
2 g
3 g
5 g
Cream cheese

Figure 5

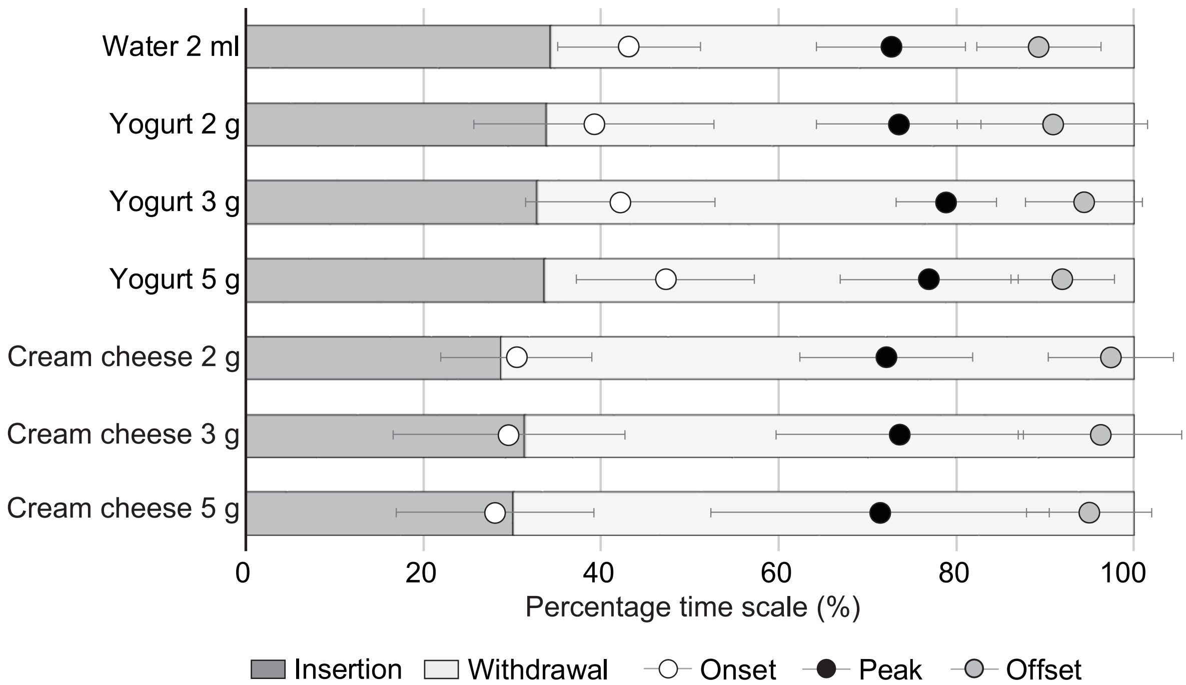
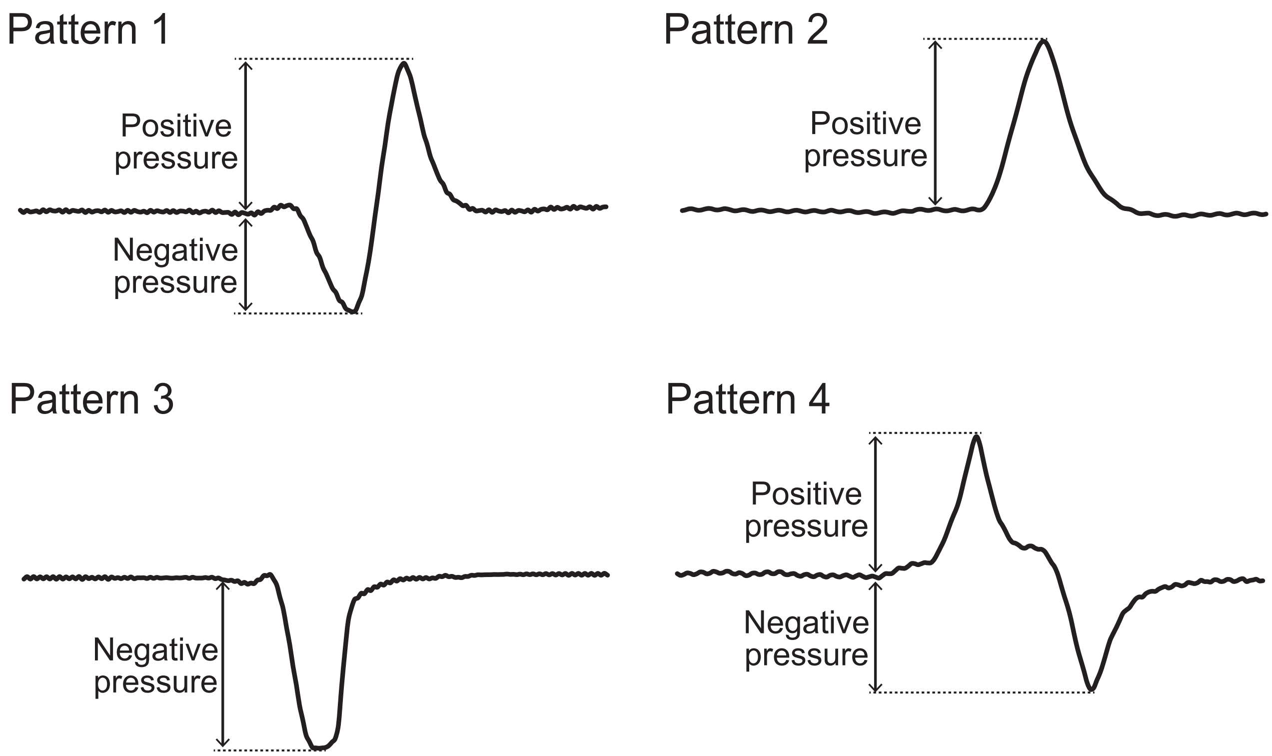

Water 2 ml
Yogurt 2 g
Yogurt 3 g
Yogurt 5 g
Cream cheese 2 g
Cream cheese 3 g
Cream cheese 5 g
0
20
40
60
80
100
Percentage time scale (%)
Insertion
Withdrawal
Onset
Peak
Offset

Figure S1


Pattern 1
Positive pressure
Negative pressure
Pattern 2
Positive pressure
Pattern 3
Negative pressure
Pattern 4
Positive pressure
Negative pressure