The Journal of Aging Research & Lifestyle 14 (2025) 100038

Contents lists available at ScienceDirect

The Journal of Aging Research & Lifestyle

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

Swallowing behavior response to semi-solid foods with different textural properties in healthy older adults: an open-label randomized crossover trial

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A R T I C L E I N F O

Keywords:
Older adults
Semi-solid foods
Shape retention
Line-spread test
Neck-worn electronic stethoscope
Deglutition
Sensors

A B S T R A C T

Background: Semi-solid foods are widely consumed by older adults, yet the influence of their physical properties on swallowing remains unclear.
Objectives: To examine how variations in shape retention and spreadability affect swallowing in adults aged ≥75 years.
Design: An open-label randomized crossover trial with two food tests.
Setting: Controlled experimental setting.
Participants and numbers analyzed: Test 1 enrolled 21 adults and Test 2 enrolled 28; after exclusions, 14 and 16 were analyzed (mean ages 81.6 and 78.6 years).
Interventions: Participants ingested three semi-solid foods (P, Q, S) differing in physical properties.
Outcomes: Primary outcomes were oral processing time (OPT) and swallowing duration (SD), measured by a neck-worn electronic stethoscope and synchronized video. Secondary outcomes were subjective ratings of swallowing ease and food properties. Medians of five bites were analyzed, and first–fifth bite differences assessed.
Results: Subjective ratings differed only in collectability in Test 2. In Test 1, OPT was longer for P than Q (median difference 1.04 s, 95 % CI 0.15–2.04; $p = 0.030$). In Test 2, OPT was longer for S than P (median difference –1.88 s, –2.81 to –0.74; $p = 0.001$). SD did not differ significantly. With repeated swallows, OPT variance increased and SD variance decreased for P and Q, while both increased for S.
Harms: None observed.
Conclusions: Semi-solid food properties affect swallowing in older adults. Shape retention contributes to distinct swallowing patterns, supporting individualized food selection to promote safe intake.
Trial registration: UMIN000053442, UMIN000056840.

1. Introduction

In our aging society, increasing healthy life expectancy is a major challenge. One way to overcome this challenge is the prevention of frailty as a preliminary step in nursing care [1]. Appropriate nutrition is essential for preventing frailty [2]. However, the most important factors in nutritional intake and swallowing function change with increasing age, with 40–60 % of older adults presenting some reduction in swallowing function [3,4]. The consequences of reduced swallowing function include reduced meal volume, reduced nutritional intake, weight loss, and the onset of aspiration pneumonia [5], leading to the need for nursing care. Poor oral and swallowing functions have been reported to be linked to physical frailty [6], and the presence of reduced swallowing function is strongly associated with the prevalence of frailty [7]. It is essential to analyze swallowing function in daily living. Adjusting the types of food consumed according to the swallowing function helps prevent nutritional complications, aspiration pneumonia, and overall mortality [8,9]. The importance of investigating the physical

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https://doi.org/10.1016/j.jarlif.2025.100038
Received 2 September 2025; Received in revised form 2 October 2025; Accepted 9 October 2025
Available online 24 October 2025
2534-773X/

properties (e.g., texture and viscosity) of foods has been widely acknowledged [10–12].

Currently, semi-solid foods such as whipped cream, soft tofu, mango pudding, egg custard, boiled mashed potatoes, bean paste, and plain rice porridge are widely used as suitable types of foods for older adults with reduced swallowing function. They are not only used as texture-modified food that is easy for older adults to eat, but are also widely used in older adults' daily living [13]. However, semi-solid foods can have different physical properties, ranging from almost liquid to almost solid, and can also differ in how long they remain on the tongue [14]. It has also been reported that old age affects tongue control during bolus holds [15], and eating and swallowing movements during activities of daily living may differ according to the physical properties of semi-solid foods. Therefore, it is essential to investigate swallowing movements during activities of daily living according to the differences in the physical properties of semi-solid foods.

Shape retention is an indicator of the physical properties of semisolid foods. Shape retention refers to the quality of retaining the same shape under gravity if no additional force is applied; however, it is not a standardized measure. Texture Profile Analysis (TPA) [16] cannot obtain the relevant physical properties of liquids because they are filled into containers for measurement [17]. Therefore, TPA is inappropriate for semi-solid foods because they have both liquid and solid properties. Therefore, we focused on measuring the viscosity of swallowed foods using the line-spread test (LST) [18,19]. LST measures the extent to which a standard amount of food spreads over a horizontal surface when released from a cylinder [20]. Shape retention, as both a liquid and solid property of semi-solid foods, represents the ability to retain the same shape under gravity and can be determined using LST.

The standard methods for the medical assessment of eating and swallowing function are fiberoptic endoscopic evaluation of swallowing (FEES) and videofluoroscopic swallowing study (VFSS). FEES uses endoscopic observations of the pharynx and larynx to assess the swallowing function, whereas VFSS uses fluoroscopy. However, because contrast agents are used to observing changes in physical properties and physical burden, neither method is suitable for assessing the differences in the physical properties of semi-solid foods in daily living, as in this study. Contrast agents change the firmness of the target food, making it difficult to compare the physical properties of semi-solid foods, including liquid foods. Endoscope insertion and X-ray exposure also meant that the subjects would not be assessed in terms of daily living conditions.

Studies using infrared sensors to measure routine eating behaviors have shown that routine behaviors are associated with oral cavity function and masticatory behavior [21]. In research on eating, including the present study, assessments should be minimally invasive and performed under conditions that are as close to normal swallowing as possible.

Various devices and assessment methods other than FEES and VFSS have been suggested to measure routine swallowing behavior. Examples include using an accelerometer to assess muscle movements during swallowing [22], and applying deep learning models to collect chewing and swallowing sounds [23,24]. Tools using cameras and neural network systems have been developed [25,26], viscosity models [27], and estimation of swallowing durations [28] have been proposed, and it is now possible to assess swallowing activities objectively. One such option, the neck-worn electronic stethoscope (NWES), for measuring swallowing movements in the neck, has been used to show that liquid swallowing sounds last longer with increasing age [29]. Our study also focused on the timing of swallowing sounds and eating in older adults, attempting to assess them using NWES and video data.

Therefore, this study focused on shape retention, a key property of semi-solid foods commonly consumed in daily meals, and examined changes in swallowing behavior by monitoring the process from intake to swallowing.

To the best of our knowledge, no reports using NWES under close-to-routine conditions to measure swallowing behaviors starting from food intake into the oral cavity and comparing them over time, using swallowing indicators for semi-solid foods with different physical properties, and using shape retention as a benchmark, currently exist. Therefore, the present study is important because it considers the relationship between swallowing function in older adults and methods for selecting forms of nutritional intake. Our study aimed to explore the relationship between the physical properties of semi-solid foods and their ease of eating by comparing quantitative swallowing-related indicators during the ingestion of foods with different physical properties.

2. Methods

2.1. Subjects

We recruited healthy men and women aged ≥75 years from a regional community. Exclusion criteria were poorly fitting or dysfunctional dentures that interfered with normal daily eating; history of cerebral infarction; other brain dysfunctions; or eating- and swallowing-related disorders, including preexisting head and neck neoplasms.

2.2. Study design

This study was designed as an open-label randomized crossover trial. The trial followed the CONSORT reporting guidelines (Supplementary 1). The trial was registered at the University Hospital Medical Information Network Clinical Trials Registry before recruiting participants; UMIN000053442 (https://center6.umin.ac.jp/cgi-open-bin/ctr/ctr_view.cgi?recptno=R000060984) and UMIN 000056840 (https://center6.umin.ac.jp/cgi-open-bin/ctr/ctr.cgi?function=brows&action=brows&recptno=R000064956).

2.3. Methods for measuring physical properties of foods

2.3.1. Shape retention

Twenty grams of the sample were placed in a ring with an inner diameter of 30 mm at the center of concentric circles and left to stand for 30 s. The ring was then lifted vertically and, after an additional 30 s, the mean sample-spread distance was calculated at six points. Five replicates were prepared and measured for each sample. The foods were kept at a controlled temperature of 20±2 °C.

2.3.2. Viscosity

The viscosity of the samples was measured using an MCR-302 rheometer (Anton Paar, Ostfildern, Germany) with a parallel plate (25 mm diameter) setup. A gap of 1.0 mm was set between the stage and plate, both of which had rough surfaces to prevent slippage. Measurements were conducted at a shear rate of 50 s^{-1}, based on criteria used in Japan [30] and the USA [31]. Temperature was maintained at 20 °C using a Peltier system. Each sample was measured in five replicates, and the mean value was used for analysis.

2.4. Test methods and materials

Two tests were conducted. Tests 1 and 2 were conducted with different participants. Test 1 used two types of food, P and Q, with different shape retention (P had greater shape retention). Test 2 used the same food, P, as in Test 1, as well as food S, which had even greater shape retention.

Foods P, Q, and S had different shape retentions (Supplementary Table 2) that is, different LST values representing the spreadability of each food, and were almost identical in terms of viscosity (Test 1 P: LST 19±0.40 mm, viscosity 1404±136 mPa·s, Q: LST 27±0.92 mm, viscosity 1310±32 mPa·s; Test 2 P: LST 20±1.97 mm, viscosity 1536±46 mPa·s, S: LST 16±0.49 mm, viscosity 1721±61 mPa·s). All the samples had the same flavor and nutritional content. The methods for measuring shape retention and viscosity were standardized as described above.

2.5. Test protocol

To assess participants' routine swallowing ability, a brief questionnaire was administered. Participants were asked to evaluate their swallowing experiences in daily life by answering the following questions: 1) Do you require extra strength to swallow solid food? 2) Do you need extra strength to swallow the tablets? 3) Is swallowing stressful? 4) Are you aware of dryness in the oral cavity? and 5) Do you have any dentures?

Next, the water swallowing test (swallowing 30 mL of water) and cracker-eating test (based on the Test of Masticating and Swallowing Solids (TOMASS), which measures the time taken to eat and swallow one cracker) were performed as basic assessments of safety and swallowing function [32,33].

Then, a taste test was performed. Participants ate a standard portion of each test food and subjectively rated its flavor and smell on a five-point scale: 1) Not at all strong; 2) Not very strong; 3) Neither strong nor weak; 4) Somewhat strong; and 5) Extremely strong.

Participants were randomly assigned to one or two food order groups (e.g., P→Q or Q→P; or P→S or S→P), using block randomization with a block size of four by an allocation manager, who considered only session schedules and participant sex to ensure that the distribution of the first test food was as even as possible between men and women. Only the allocation manager had access to the assignment list and conveyed the order to the staff member responsible for handing the test foods to participants. The staff who delivered the foods were unaware of the overall allocation table. Containers, food colors, and, as far as possible, flavors were made comparable to minimize recognition of the test foods, and partitions separated participants so that they could not observe each other's eating behavior.

For each type of food, participants consumed five spoonfuls (5 g each), swallowing each portion before taking the next. There were no time restrictions, and participants proceeded at their own pace once their mouths were clear of food. After eating, participants responded to each of the following questions (rating their answers on a five-point scale): 1) When you put it in your mouth, did it have a strong flavor?; 2) When you put it in your mouth, did it have a strong scent?; 3) When you put it in your mouth, does it collect easily on your tongue?; 4)When you put it in your mouth, does it spread easily around your mouth?; 5) Is there anything left on the roof of your mouth or under your tongue?; 6) After swallowing, does it feel like there is something left at the back of your throat?; 7) After swallowing, do you want to drink water? The five-point rating scale was 1) Not at all; 2) Not really; 3) Neither yes nor no; 4) A little, and 5) Very much so. Between different test foods,

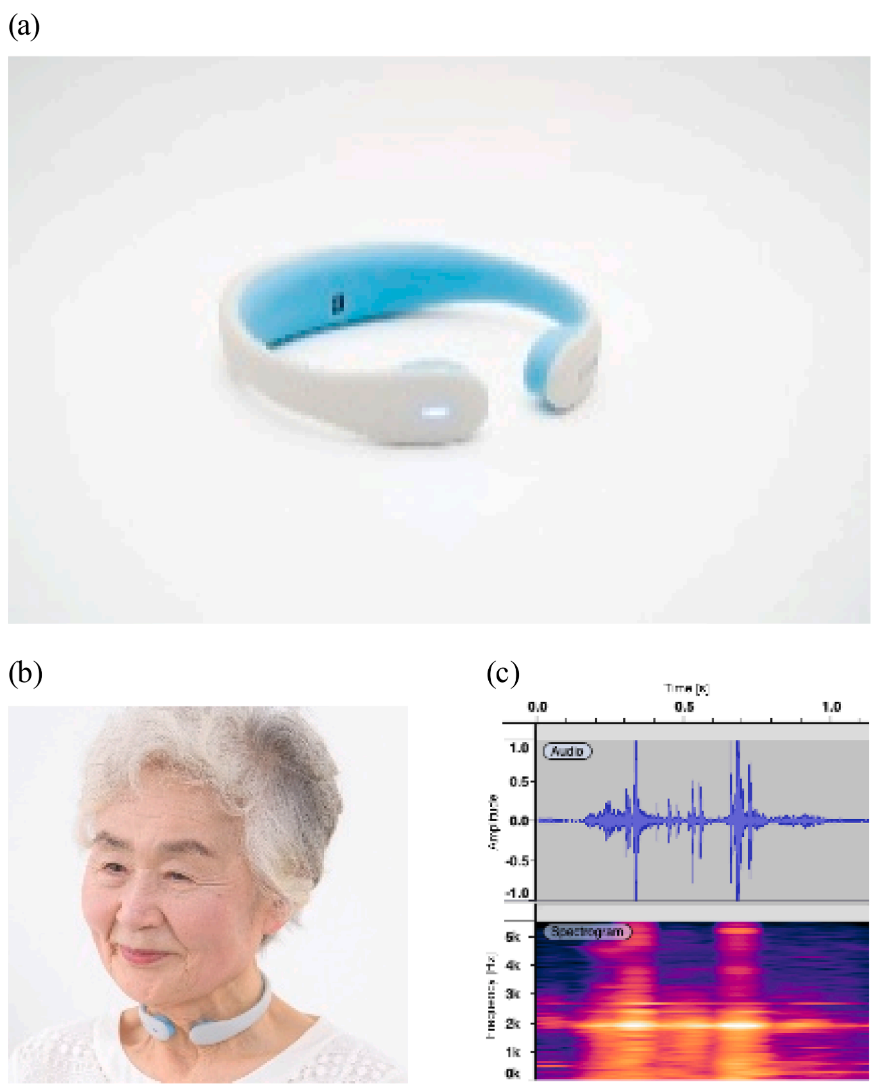

Fig. 1. (a) (b) Neck-worn monitoring device for swallowing activities used in the study (NeW-MDSA; GOKURI PLIMES Inc.). (c) Example waveform of swallowing sounds recorded using NeW-MDSA, showing the amplitude (top) and corresponding spectrogram (bottom), with the y-axis representing frequency.

participants rinsed their mouths with water and rested for at least 5 min. All assessments were conducted with participants seated in a chair.

2.6. Swallowing assessment method

In this study, we used a smartphone-based real-time swallow monitoring device to objectively assess swallowing: the NWES (GOKURI® Neckband, PLIMES, Inc., Japan) (Fig. 1).

The NWES collected neck vibration data at a sampling rate of 11.025 kHz using a piezoelectric contact microphone worn around the neck (between C2 and C5) and transmitted the data via Bluetooth to an Android application for real-time analysis [34,35].

The Android application performed four tasks:

1. **Detection**: The application identified incoming acoustic activity by checking whether any sample in a 484-sample packet exceeded a normalized amplitude threshold ($\theta_s = 0.17$). This threshold was empirically determined using over 20,000 samples from prior experiments.
2. **Segmentation**: A segment was initiated at the first sample that crossed the threshold. If five consecutive packets (approximately 220 ms) contained no samples above the threshold, the segment was considered complete.
3. **Recognition**: Each segmented waveform was analyzed using a convolutional neural network (CNN) composed of four convolutional layers, one pooling layer, and a softmax classifier. The input to the CNN was a spectrogram with a 10.1 ms resolution, and the output was a binary classification: swallowing or non-swallowing. This pattern recognition method was inspired by the swallowing sound model proposed by Morinière et al. [36], which characterizes swallowing sounds based on acoustic and frequency features. The model achieved a classification accuracy of 97.3 % [37].
4. **Synchronized video recording**: The application also recorded video in synchronization with neck vibration data, enabling multimodal analysis of the swallowing event.

Final judgments were made visually and aurally by three or more evaluators using waveform editing software, with the model output used as a supporting reference. Using the NWES swallowing waveform, swallowing sound, and video recording measured during five consecutive bites, and based on the Four Stage Model [14], "oral processing time" (OPT) was determined by the eating and swallowing actions occurring in the preparatory and oral stages of each bite. The point at which NWES begins detecting swallowing sounds closely corresponds to the moment when the bolus reaches the pharyngeal inlet near the base of the tongue and the larynx begins to elevate. Detection ends when the first large portion of the bolus passes through the upper esophageal sphincter [34,37]; this period was measured as the "swallowing duration" (SD). In cases where multiple eating and swallowing actions occurred within a single bite, OPT and SD were measured for each action and summed to obtain the total OPT and SD per bite. These were defined as OPT per bite and SD per bite, respectively.

For the first eating and swallowing actions, the action of putting food into the mouth was confirmed by video, and the OPT was determined as the time until the start of the swallowing sounds. For the second and subsequent actions, the OPT was determined as the time from the disappearance of the previous swallowing sound to the start of the next swallowing sound.

SD was not defined in relation to the number of eating and swallowing actions, but was defined as the time from the start to the end of the swallowing sounds.

For the cracker-eating test, the action of taking one cracker into the mouth was confirmed by video, and the eating duration was defined as the time to the disappearance of the swallowing sounds.

The primary outcome measures were outcome OPT and SD. Secondary outcome measures were subjective responses from participants.

2.7. Analysis methods

Basic descriptive statistics for features of the participants were recorded as means and standard deviations, medians (first and third quartiles), frequencies, and proportions (percentages). For group comparisons, median differences with 95 % confidence intervals (Hodges–Lehmann estimates) were also calculated. Subjective assessments, taste tests, and SD were analyzed using the Wilcoxon signed-rank test. The F-test was used to determine the variance in the SD. The Mann–Whitney U test was used to compare the two tests of Q/P and S/P, with a statistical significance level of $p < 0.05$, and median differences were calculated for S/P–Q/P, P–Q, and P–S. No formal adjustment for multiple comparisons was performed, as no plan for multiplicity adjustment had been prespecified in the study protocol. Unadjusted p-values are reported together with effect size estimates and 95 % confidence intervals.

All data management and statistical analyses were conducted using JMP 17 software (SAS Institute, Cary, NC, USA), and R (version 4.4.1).

3. Results

3.1. Demographic data

The CONSORT flow diagram is shown in Supplementary Figure 1. Test 1 had 21 participants and Test 2 had 28 participants. All measurements were performed without omissions during either test. After completing all measurements, one participant was excluded from Test 1 for meeting an exclusion criterion (age < 75 years at the time of measurement). In the analysis, six participants were excluded due to device errors ($n = 1$), missing eating records or data ($n = 1$), or swallowing two bites at the same time ($n = 4$). Twelve participants were excluded from Test 2 for device errors ($n = 2$), taking a second bite before swallowing the first ($n = 8$), dividing a single bolus into two swallows ($n = 1$), and concurrent conduct of a swallowing test and subjective assessment ($n = 1$). Analyses of OPT, SD and subjective responses, therefore were conducted with 14 participants (7 men, 7 women, mean age 81.57±3.50) in Test 1 and 16 participants (5 men, 11 women, mean age 78.56±4.06) in Test 2.

None of the participants chose the water swallow test, and none reported subjective feelings of pain when swallowing water. The mean eating durations in the cracker eating test were 42.03±12.15 s for Test 1 and 48.83±16.08 s for Test 2, with no significant difference between the two tests (Table 1).

3.2. Taste test and subjective assessment

There were no major differences in taste tests 1 and 2 (Table 1). However, there was a significant difference in the subjective assessment in Test 2 for the question "When you put it in your mouth, did it collect easily on your tongue?" ($p = 0.004$).

3.3. Eating and swallowing duration

Although significant differences in OPT were found in both tests for Q/P and S/P ($p = 0.002$, Mann–Whitney U test; median difference [95 % CI], 0.62 [0.40, 1.07]; Hodges–Lehmann estimate), there were no significant differences in SD for Q/P or S/P (median difference [95 % CI] 0.03 [–0.18, 0.25]) (Fig. 2).

Comparing all subjects in Test 1, OPT per bite was significantly longer for food P than food Q (P: median 4.73 s, Q1 3.97, Q3 5.27; Q: median 3.12 s, Q1 2.66, Q3 3.89; $p = 0.030$, Wilcoxon signed-rank test; median difference [95 % CI] 1.04 [0.15, 2.04]). There were no significant differences in the SD per bite between the two foods, but food P showed significantly less variance (P variance 0.023, Q 0.116, $p = 0.003$, F test; P: median 0.72 s, Q1 0.63, Q3 0.75; Q: median 0.68 s, Q1 0.58, Q3 0.81, not significant; median difference [95 % CI] −0.03 [−0.27, 0.07])

Table 1
Demographic data.

	Test 1			Test 2		
N (men: women)	14 (7:7)			16 (5:11)		
Age, years (mean, SD)	81.57 (3.50)			78.56 (4.06)		
Cracker eating time (sec)	42.03±12.15			48.33±16.08		
Do you require extra strength to swallow solid food? (N)	0			0		
Do you need extra strength to swallow the tablets? (N)	0			1		
Is swallowing stressful? (N)	0			1		
Are you aware of dryness in the oral cavity? (N)	0			0		
Do you have any dentures? (N)	10			8		
Food	**P**	**Q**		**P**	**S**	
Taste			**p-value**			**p-value**
When you put it in your mouth, did it have a strong flavor?	4.0	4.0	0.36	3.5	3.0	0.79
When you put it in your mouth, did it have a strong scent?	3.0	2.0	0.19	2.5	2.5	1.00
Subjective assessment						
When you put it in your mouth, does it collect easily on your tongue?	4.0	2.0	0.18	4.0	5.0	0.004
When you put it in your mouth, does it spread easily around your mouth?	2.0	3.0	0.09	4.0	3.5	0.17
Is there anything left on the roof of your mouth or under your tongue?	2.0	2.0	0.91	2.0	2.0	0.75
After swallowing, does it feel like there is something left at the back of your throat?	2.0	1.5	0.38	2.0	2.0	1.00
After swallowing, do you want to drink water?	2.5	2.5	1.00	3.0	3.0	1.00

Wilcoxon signed-rank test.

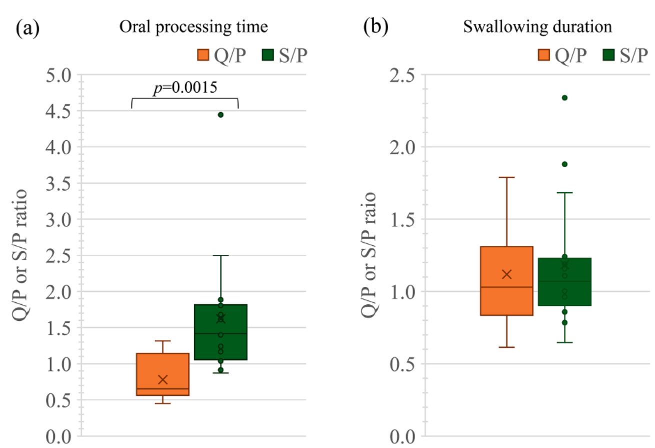

Fig. 2. Comparison of food P vs food Q and food S. (a) Oral processing time. (b) Swallowing duration. Test 1: Q/P; Test 2: S/P; p-values (Mann–Whitney U test) for each individual test are shown. Five bites for each food were measured for each participant; the median value of Q was divided by the median value of P, and similarly the median of S was divided by the median of P.
Test 1 N = 14 P: LST 19±0.40 mm, viscosity 1404±136 mPa·s, Q: LST 27±0.92 mm, viscosity 1310±32 mPa·s.
Test 2 N = 16 P: LST 20±1.97 mm, viscosity 1536±46 mPa·s, S: LST 16±0.49 mm, viscosity 1721±61 mPa·s.

(Fig. 3).

In Test 2, OPT per bite was significantly longer for food S than food P (P: median 4.16 s, Q1 2.45, Q3 4.57; S: median 5.26 s, Q1 3.51, Q3 8.10; $p = 0.001$, Wilcoxon signed-rank test; median difference [95 % CI] −1.88 [−2.81, −0.74]). In contrast, although there was no significant difference in SD per bite between the two foods (P: median 0.81 s, Q1 0.60, Q3 0.92; S: median 0.80 s, Q1 0.72, Q3 0.94, not significant; median difference [95 % CI] −0.06 [−0.30, 0.05]), in Test 1, food P showed significantly less variance (P variance 0.044, S 0.122, $p = 0.03$, F test;) (Fig. 3).

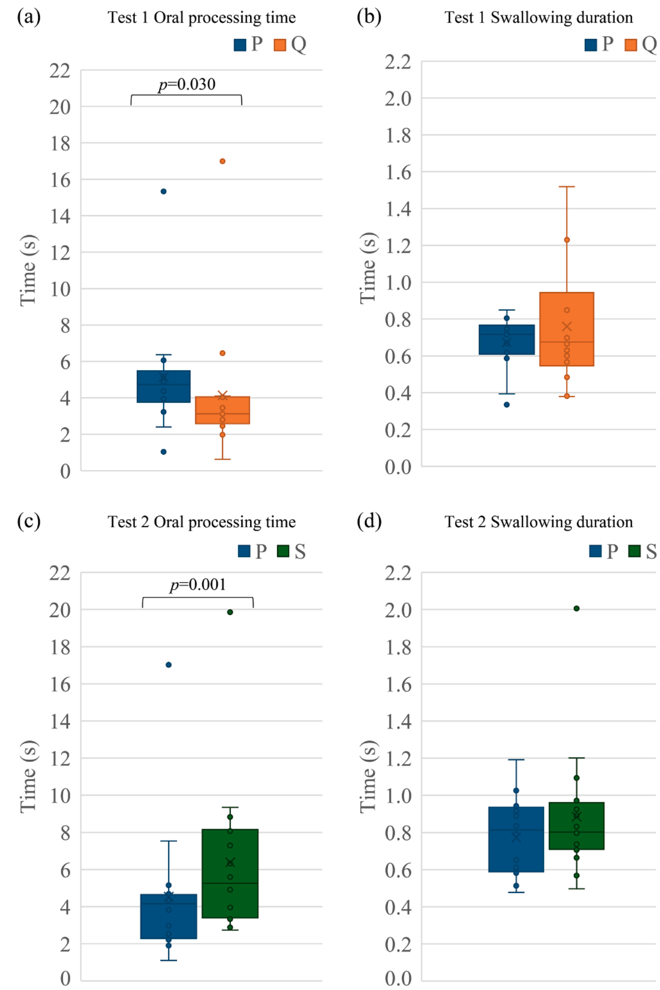

Fig. 3. Oral processing time and swallowing duration for all participants. Wilcoxon signed-rank test was used. (a) Test 1: oral processing time. (b) Test 1: swallowing duration. (c) Test 2: oral processing time. (d) Test 2: swallowing duration. Five measurements were obtained for each food (P, Q, S) for each participant, and the median of these five values was used for analysis.
Test 1 N = 14 P: LST 19±0.40 mm, viscosity 1404±136 mPa·s, Q: LST 27±0.92 mm, viscosity 1310±32 mPa·s.
Test 2 N = 16 P: LST 20±1.97 mm, viscosity 1536±46 mPa·s, S: LST 16±0.49 mm, viscosity 1721±61 mPa·s.

Furthermore, in the inter-individual comparisons, Test 1 showed a significant increase in OPT variance between the first and fifth bites of food P (variance of first bite: 13.00, fifth bite: 72.30, $p = 0.002$, F-test) and a significant reduction in SD variance (variance of first bite: 0.117, fifth bite: 0.036, $p = 0.020$, F-test). There was a significant reduction in the SD variance for food Q (variance of the first bite, 0.301; fifth bite, 0.070; $p = 0.007$).

Test 2 showed a significant increase in the OPT variance for food P (variance of the first bite: 9.44, fifth bite: 42.60, $p = 0.003$, F-test). There was also a significant increase in the OPT variance for food S (variance of first bite: 18.86, fifth bite: 91.35, $p = 0.002$, F-test) and a significant increase in the SD variance (variance of first bite: 0.149, fifth bite: 0.500, $p = 0.013$) (Fig. 4).

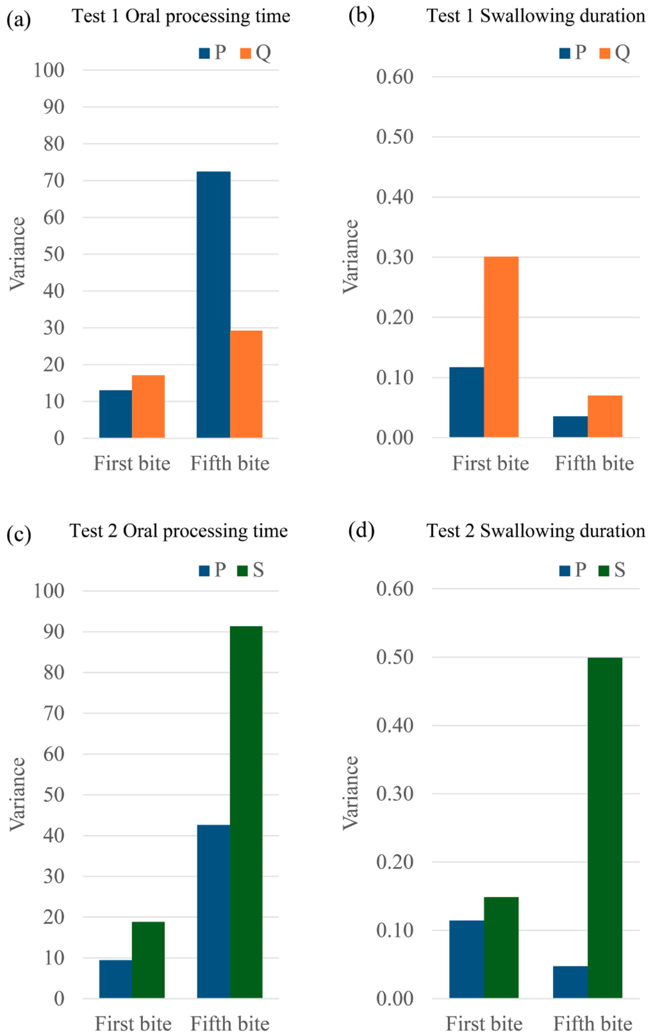

Fig. 4. Interindividual comparison of variance in the first and fifth bites. (a) Test 1: oral processing time. (b) Test 1: swallowing duration. (c) Test 2: oral processing time. (d) Test 2: swallowing duration. For each test, the variance of the measure for the first bite across 14 participants was calculated and compared with the variance for the fifth bite, for each food type.

4. Discussion

This is the first study to analyze eating and swallowing movements with various semi-solid foods with different physical properties using the NWES. In this study, we performed a non-invasive and quantitative assessment of the effects on the continuous activity of consuming food into the mouth, chewing or holding it in the oral cavity, and swallowing.

4.1. Application of NWES for food analysis

We obtained video recordings and swallowing waveforms while food was being consumed using a system that can provide an overall understanding of eating and swallowing behaviors. One of the primary features of this study is its use of the NWES, which has the following major advantages: it is minimally invasive, as it only needs to be worn around the neck to perform assessments; it can assess swallowing without causing any changes in the physical properties of the food; it can be used to measure information on routine swallowing behaviors; and it enables the analysis of quantitative indicators. The swallowing sounds detected by NWES correspond to three major acoustic events: (1) the timing of velar and laryngeal movement as the bolus enters the pharynx, (2) the timing of bolus passage through the upper esophageal sphincter into the esophagus, and (3) the timing of laryngeal return to the resting position [34]. Although these acoustic events are subject to anatomical variability [36] and VFSS remains indispensable for directly visualizing bolus transit and structural movement, NWES provides superior temporal resolution compared to VFSS, which is typically limited to 30 fps. This high temporal resolution enables more precise detection of swallowing timing. Moreover, the validity of NWES has been demonstrated in a recent study employing a deep learning–based swallowing detection system synchronized with VFSS, which achieved 97.3 % accuracy using 1859 swallowing and 2021 noise samples [23].

The NWES has been utilized in earlier studies to evaluate swallowing ability during daily activities such as physical exercise and calculation tasks [38], to compare swallowing function and frailty in older adults using the water-swallowing test [29], and to assess masticatory–swallowing function through the intake of crackers [39]. However, to our knowledge, no studies have systematically investigated swallowing responses to semi-solid foods with adjusted physical properties using this device, highlighting the novelty of the present study. Previous food research has been limited to the assessment of the sensitivity to physical properties and physiological assessments other than swallowing. With the most common assessment being contrast-enhanced imaging of swallowing, contrast agents can change food viscosity. However, our study involved observing the ingestion of food itself, not food that had been altered for testing, and analyzing the changes in swallowing behavior based on quantitative indicators. Some older adult participants also dropped out of the study because of the burden of testing. In this study, all subjects were able to complete the tests, and none dropped out because of physical or emotional stress. As all subjects were able to complete the tests, this method could be used in future food analyses and eating safety assessments for older adults. It is important to assess reproducibility in daily life when evaluating the swallowing function. This is because older adults may experience intraday variability and differences in responses between days because of the effects of medications and alertness levels. In addition, it is essential to evaluate changes that gradually decline with age. Therefore, repeated evaluations of the swallowing function in daily life are of great importance. In this study, which had no dropouts, evaluating the swallowing function non-invasively in a state close to daily life was a key point, as repeated evaluations are required for swallowing function assessment.

4.2. Demographic data

This study included adults aged ≥75 years. Almost no participants reported subjective feelings of stress associated with swallowing in their daily lives (Table 1). The water swallowing test was also performed with no issues, and the analysis population consisted of healthy older adults without swallowing dysfunction. Regarding the oral environment, 10 (71.4 %) of the subjects in Test 1 and 8 (50.0 %) in Test 2 had dentures; participants in Test 1 had a slightly higher mean age and a higher proportion of denture use. However, it has been reported that the rate of denture use in the age group of the study subjects is approximately 80 % in Japan [40], indicating that we recruited subjects with healthy oral environments, as those with difficulties in daily eating were excluded by the study criteria.

4.3. Subjective assessment and taste test

In both Tests 1 and 2, no differences in the taste or scent of the food samples were identified, and there was no impact on subjective taste. Therefore, we consider that the swallowing function assessment had no impact on taste or scent. In the subjective assessment, there were no significant differences between foods P and Q in Test 1, whereas in Test 2, food S was reported to collect more easily on the tongue. This may be because food S had a higher LST value and therefore collected on the tongue more easily. No significant differences were observed in any of the other assessment items; therefore, this study was considered to have no major impact on the physical properties of the foods (LST value and viscosity) and little subjective impact.

4.4. Swallowing analysis

In Test 1, the OPT per bite was significantly longer for food P ($p = 0.03$). There were no significant differences in SD per bite between the two groups. However, the variance in SD per bite was significantly smaller for food P ($p = 0.003$, F-test). That is, although the P group had a longer OPT per bite, the variance in the SD per bite was smaller. In Test 2, the OPT per bite was significantly longer for food S ($p = 0.001$). Similar to Test 1, there were no significant differences in the SD per bite between the two groups; however, the variance in the SD per bite was significantly smaller for food P ($p = 0.03$, F-test).

A previous study reported changes in the proportion of use of two oral strategies, squeezing (crushing the gel against the palate with the tongue, without using the teeth to chew) and mastication (chewing freely), depending on the physical properties of the gel [41]. For example, hard gels require more tongue work to produce the pressure required for squeezing than soft gels. Our study also identified different strategies based on the level of solidity, suggesting that a similar phenomenon may occur in semi-solid foods based on differences in the OPT per bite.

In contrast, both tests found that P showed less variance in SD. This low variance in SD is the time from the moment the bolus reaches the pharyngeal inlet near the base of the tongue. The larynx begins to move up to the moment the first large portion of the bolus passes through the upper esophageal sphincter, suggesting that food may have physical properties that make it safe to swallow.

One factor that could explain this difference in the variance in SD per bite is the relationship between OPT and tongue work during related oral strategies; it has been reported that the tongue plays a leading role in swallowing, and the food mass is transferred so that it is pushed out from behind [42].

As bolus formation in the oral cavity can be controlled with food P, each bite can be safely eaten and swallowed. This was expected to reduce the variance in the SD per bite.

In contrast, as food Q had more liquid properties, it also had a shorter OPT per bite. Naturally, it entered the pharyngeal stage before bolus formation could be controlled, which may have produced the differences in SD per bite. Furthermore, in the analysis of swallowing sounds, all subjects swallowed all bites of food P in one swallow, whereas with food Q, some subjects swallowed multiple times; that is, there were differences in the ability to swallow each bite whole. With food S, the participants were observed to lightly chew the food in their oral cavities and form a bolus, suggesting that there was also some variance in the physical properties of the bolus before swallowing. Therefore, the variance in SD per bite for food S may have been affected by the degree of chewing.

A previous VFSS study in patients with dysphagia showed that differences in food texture significantly affected swallowing dynamics. Specifically, jelly required the greatest number of chewing cycles, thick liquids resulted in the highest level of pharyngeal residue, and oral and pharyngeal transit times were the shortest for thick liquids, showing a significant reduction compared to jelly [43].

Even older individuals without dysphagia, as in our study, may have differences in swallowing depending on the physical properties of the food. From a preventive point of view, it is important to clarify an appropriate, non-burdensome diet for older individuals whose swallowing function is declining. Unlike previous reports, this study was conducted in a less invasive setting close to daily life, and further analysis is required.

Another feature of this study was the consecutive assessment of multiple swallows. The older group has been reported to have a delayed swallowing rhythm and decreased swallowing frequency [44], and reductions in anterior tongue strength and saliva swallowing pressure during meals have been reported in older adults [45]. The time taken to begin swallowing saliva after being instructed to do so was also reported to be longer after eating than before eating in older adults only [46]. These findings indicate that the swallowing function may decrease with continuous eating and swallowing. Therefore, we also investigated the changes with continuous eating (Fig. 4). In Test 1, the OPT variance was greater for the fifth bite of food P or Q than for the first bite, whereas the SD variance decreased. This increase in OPT variance for the fifth bite could reflect reduced bolus formation and swallowing function as a result of continuous chewing and swallowing preparation.

In Test 2, food P showed results similar to those of Test 1, whereas food S showed increases in both the OPT and SD variance from the first to the fifth bite. This inter-individual difference in the reduction in bolus formation function when chewing and forming a bolus of food S manifests as differences in the physical properties of the bolus before swallowing and could be linked to inter-individual differences in SD. For OPT, the time required for bolus formation, including chewing, was longer, which may have increased the burden. A study on bolus viscosity and volume assessed the differences in pharyngeal transit time and reported that boluses with higher viscosity were associated with significantly longer pharyngeal transit times [47]. Therefore, because food S was firmer than food P, it may have required greater effort to swallow, and these factors may have led to an increase in the OPT and SD variance with continuous eating. In contrast, the effect on the physical properties of the food bolus before swallowing may have been limited compared with that of food S.

In this study, the longest total time required by subjects from the start of the first bite to completion of the fifth bite was only approximately 2 min, so even when including the preliminary water swallow and cracker-eating tests, the burden of eating was not large. However, as in this study, there may be changes because of the physical properties of the food, which may be useful for assessing reductions in swallowing function during continuous eating and swallowing activities.

In this study, we identified distinct changes in the shape retention values of semi-solid foods in the three groups, rather than uniform changes. Regarding the physical properties of food, the correlation between bolus formation through tongue and palate movements within the oral cavity, and eating and swallowing behaviors when moving the bolus to the pharynx is expressed as food–swallowing behavior compatibility. This compatibility may have contributed to the differences in the variance in SD per bite observed in this study because of differences in swallowing behaviors. As the results were not uniform, we can theorize that there may be threshold physical properties of foods that alter behavioral strategies.

A notable feature of this study is its focus on shape retention assessed by the LST. Tongue movements are selectively controlled across anterior, middle, and posterior regions, contributing respectively to bolus formation, pressure transfer, and propulsion [48]. Although age-related changes mainly involve prolonged movement duration, functional partitioning is preserved. Hayashi et al. reported that tongue squeezing correlates with bolus viscosity but not volume, with substantial individual variation in bolus head position at swallow initiation [49]. If shape retention measured by LST reflects similar properties, foods with higher shape retention may allow safer and slower bolus transport, enabling individuals to better control swallow timing and optimize bolus position. Moreover, since both oral and pharyngeal transit times are prolonged with aging and increased viscosity [50–52], LST-based shape retention may offer complementary control beyond viscosity, supporting stable swallow initiation and safer bolus transfer, particularly in older adults. The potential usefulness of shape retention as an additional design parameter in dysphagia management warrants further investigation in future studies.

This study suggests that food–swallow compatibility, particularly shape retention, may play an important role in oral and pharyngeal swallowing strategies. In frail older adults, thickened meals often alter taste and texture, leading to early satiety or poor palatability and thereby worsening malnutrition. Solid-like foods are considered to combine ease of oral processing with high shape retention. As some reports have shown that pharyngeal clearance is delayed only at specific viscosity levels [53], viscosity assessment alone may not always be sufficient. Accordingly, detailed evaluation using NWES could help guide safer food selection, optimize nutrition, and reduce aspiration risk, while also mitigating the drawbacks of conventional thickening. In addition, future studies should also incorporate other texture parameters such as adhesiveness and cohesiveness to provide a more comprehensive understanding of food–swallow compatibility. The application of NWES to assess food–swallow compatibility in commercial products and home-prepared recipes may therefore be anticipated in the future.

FEES and VFSS are not routinely performed in community-dwelling older adults without swallowing disorders because of their invasiveness and, for VFSS, the need for contrast agents; direct comparisons were therefore not feasible in this study. Nevertheless, in clinical contexts, head-to-head studies of NWES against FEES/VFSS will be essential to validate its utility. Given that NWES can be applied to actual foods, it also warrants further exploration as a screening tool.

Finally, incorporating quantitative swallowing assessments into health checkups may enable earlier detection of frailty and better nutritional management. NWES could also support monitoring of swallowing fluctuations related to medications or daily activity rhythms, such as daytime naps, common in older adults.

5. Limitations

This study has several limitations. First, although shape retention and viscosity were unique features of our analysis, further studies are required to clarify whether these parameters can serve as comprehensive indices of the physical properties of semi-solid foods and whether LST values represent the best measure of shape retention. Second, the study was divided into two tests to reduce fatigue in older participants. Although baseline characteristics were comparable, the use of independent cohorts limits generalizability, and reproducibility should be validated in future studies. Some dropouts occurred due to device misuse, data errors, or failure to follow instructions; thus, simplified and more accurate methodologies, as well as improved explanation strategies for older adults, are needed to reduce bias and enhance reproducibility. Third, strict blinding could not be maintained, as evaluators had the potential to identify the food type during motion analysis. While motion verification was essential to ensure consistency with actual swallowing, this represents a possible source of bias. Fourth, multiple comparisons were not formally adjusted because this was not prespecified, and therefore secondary findings should be interpreted with caution. Finally, although denture use was confirmed, denture position was not assessed. Because semi-solid foods were used, the influence was likely minimal; however, given that tooth loss and age-related declines in masticatory function can alter bolus formation and swallowing, future research should investigate the effects of denture position more comprehensively.

6. Conclusions

This study used NWES and semi-solid foods with different shape-retention properties to assess changes in swallowing actions owing to differences in the physical properties of foods. Because NWES measurements do not use contrast agents, they do not affect these physical properties; therefore, we were able to compare semi-solid foods with different physical properties. Other major features of this study include the lack of participant dropouts and the successful use of minimally invasive measurements under close-to-routine conditions.

By establishing the application of the NWES as a method for assessing food under routine conditions, as in this study, and by identifying food–swallowing behavior compatibility in relation to the physical properties of foods and individual characteristics, suggestions can be made to select suitable foods for physically frail older adults. In addition, this study was non-invasive, allowing repeated measurements. By establishing evaluation methods using non-invasive devices such as those used in this study, it may be possible to continuously evaluate age-related gradual functional decline and provide appropriate foods as required. This may lead to a reduced physical burden from oral feeding in older adults, prevention of aspiration, and longer healthy life expectancies.

Ethical approval and informed consent

This study was approved by the Ethics Review Committee of Meiji Co., Ltd. (approval numbers: 2023–020, 2024–017). This study was conducted according to the guidelines of the Declaration of Helsinki. Written informed consent was obtained from all participants prior to the experiment. Data were analyzed to preserve the anonymity of the participants.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: the work was supported by Meiji Co, Ltd.

Data availability

Data generated during this study are available from the corresponding author upon reasonable request.

CRediT authorship contribution statement

Masashi Tsujimoto: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Conceptualization. **Tomoko Hisajima:** Visualization, Formal analysis, Data curation. **Saho Matsuda:** Investigation. **Keisuke Suzuki:** Supervision. **Tomoya Shimokakimoto:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Yoshio Toyama:** Writing – review & editing, Visualization, Validation, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

This study was jointly performed by the National Center for Geriatrics and Gerontology, PLIMES Inc., and Meiji Co., Ltd. YT holds the position of joint research chair, and MT is a leading researcher in joint research. MT, SM, and TS received funding for this study from Meiji Co., Ltd. TH and YT are employees of Meiji Co., Ltd., who provided the foods used in this study. KS declares no competing interests.

Acknowledgements

We would like to thank Editage (www.editage.jp) for English language editing.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jarlif.2025.100038.

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