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Exploratory analysis of swallowing behaviour in community-dwelling older adults using a wearable device: Differences by age and ingestant under different task loads

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Abstract

Objective: To develop a new method of evaluating swallowing behaviour.

Methods: Sixty-nine healthy participants were divided into a younger (16 males and 16 females, mean age 39.09 ± 12.16 years) and older (18 males and 19 females, mean age 71.43 ± 5.50 years) group. The participants ingested water and yoghurt twice (directed and free swallowing) at rest and after performing simple daily life tasks (calculation and exercise). To measure swallowing frequency, we employed a smartphone-based, portable and neck-worn swallowing-sound-monitoring device. This device monitors swallowing behaviour continuously by collecting biological sounds from the neck without imposing behavioural restrictions. A neural network model of swallowing sound identification by deep learning was used for the subsequent evaluation. This device was used to obtain two types of saliva-swallowing sounds associated with different ingestants, at rest and after performing a stimulating task. Furthermore, we assessed the associated subjective psychological states.

Results: The younger group showed a higher directed swallowing frequency (for both water and yoghurt) than the older group did. Regarding the type of ingestant, the swallowing frequency for yoghurt was higher during free swallowing in both the young and the older groups. 'Feeling calm' was reported significantly more often in the older group after swallowing yoghurt following exercise.

Conclusions: Swallowing status in daily life was measured non-invasively using a wearable mobile device. It is important to consider the type of ingestant, daily living activities, and age when assessing swallowing.

Keywords

Wearable, deglutition, activity of daily living, yoghurt, real-time monitoring method, biomedical monitoring, audio data microphones, mHealth, older adults, frailty

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Introduction

Extending people's healthy life expectancy is a major challenge in today's ageing society. One way to approach this challenge is to prevent frailty, which is the preliminary stage to long-term care,[1] and frailty prevention requires adequate nutrition.[2] The swallowing function of the elderly is an important aspect that must be considered, as

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the physical properties of foods can influence the swallowing function, ultimately affecting nutritional intake. Unlike dysphagia associated with diseases, such as stroke, age-related functional decline (presbysphagia) progresses slowly.[3,4] Presbyphagia is a condition attributed to ageing, including sarcopenia, cognitive function and tissue elasticity,[5,6] and is characterised by a lack of awareness of the elderly and their families. The decline in swallowing ability may cause fear and anxiety about eating, thereby affecting the quality of life[7] and a tendency to avoid eating.[8] Consequently, aspiration pneumonia, malnutrition, and dehydration occur in the elderly.[9]

The physical properties of the ingested food can significantly affect swallowing. In addition, ingested substances affect the oral environment and subsequent swallowing dynamics even after ingestion.[10,11] Therefore, along with evaluation during ingestion, it is essential to assess the swallowing status after. For example, although frequent drinking of water is recommended, it has been reported that decreased spontaneous swallowing after drinking may induce aspiration in individuals with impaired swallowing function.[12] Elderly individuals require caution as they often develop a state of presbycusis without being aware of it. The relationship between changes in swallowing dynamics and food properties in the ageing elderly population remain to be addressed.

Physical and mental stress, such as exercise and emotional stress, can cause sympathetic dominance, which affects hormones, immunoglobulins and salivary enzymes, changing the components of saliva and increasing its viscosity.[13–15] Due to the oral dryness and increased viscosity associated with changes in the salivary components, better swallowing function is required during these states than under normal conditions. Therefore, stressed conditions are likely to require higher-than-normal swallowing function, and the elderly who may show presbycusis should be cared for accordingly.

To date, the standard methods of evaluating swallowing function are the fibre-optic endoscopic evaluation of swallowing (FEES) and the video-fluoroscopy swallowing study (VFSS).[16] FEES is an endoscopic procedure that observes the pharynx and larynx; the VFSS evaluates swallowing function under fluoroscopic conditions and with different food components.[17] Non-instrumental evaluation includes morphodynamic and taste function assessment,[18] the 3-ounce water swallow test[19] and the cough reflex test.[20]

These methods are limited in that the results depend on the evaluator and require more sensitivity or predictivity.[21] These standardised assessments are performed in clinical settings and nursing homes as resting assessments.

In addition, various instruments have been developed to address these limitations. For instance, accelerometers have been used to evaluate muscle movements during swallowing[22] and collect chewing and swallowing sounds; deep learning models have also been used.[23–25] Non-contact tools have also been developed using cameras and neural network systems,[26,27] allowing for the development of viscosity models[28] and estimation of swallowing time.[29] Advances in technology have enabled a more objective assessment of swallowing at rest.

Presbyphagia is affected by physiological changes in the elderly, which may result in changes from disease-based dysphagia.[30] Sensors and tools may be difficult to implement for the elderly.[31] Considering that swallowing is affected by various factors, different assessment methods are needed, not only in rest but also in other daily scenarios.[32]

In this study, we evaluated the frequency of swallowing events and the relationship between food intake and swallowing dynamics following ingestion in daily life, which differs from the resting state, considering that swallowing dynamics after ingestion may cause aspiration pneumonia and other events.[10,11] To date, no studies have evaluated swallowing, especially the relationship between food intake and subsequent swallowing dynamics, under various conditions in daily life, such as after exercise. This study established a method to evaluate swallowing situations in daily life, which declines with ageing.

Method

Participants and research method

Participants were adults aged 20 years or older without underlying diseases that may cause motor decline or swallowing dysfunction. Changes in their swallowing frequency and subjective conditions were measured in a temperature-controlled test room; the temperature was controlled at ∼27 °C to the participants' liking. Water and yoghurt (Meiji Bulgarian Yoghurt LB81 Plain) were used to evaluate changes in response to different ingestants. For this study, we considered the importance of using moderately viscous, cohesive and fluid food such that swallowing is not burdensome.[12,33] Thus, yoghurt, a familiar food, was considered appropriate, as it meets these conditions and has a high nutritional value. The participants were randomly assigned to two groups. While both groups were tasked with ingesting 40 g of both water and yoghurt at their own pace, one group ingested water first and yoghurt second, and the other group ingested yoghurt first and water second. In this way, all participants, in either order, were evaluated using both water and yoghurt. Prior to ingesting a different ingestant, the participants were urged to drink water and rinse their oral cavity. Then, after at least a 5-min interval, they swallowed the other ingestant and were evaluated in the same way.

Regarding the evaluation schedule, measurements were taken while the participants were at rest, as well as after performing calculation and exercise tasks that stimulated them (Figure 1). The calculation tasks were selected for evaluation after mental stress, and the exercise tasks were selected for evaluation under physical stress. The

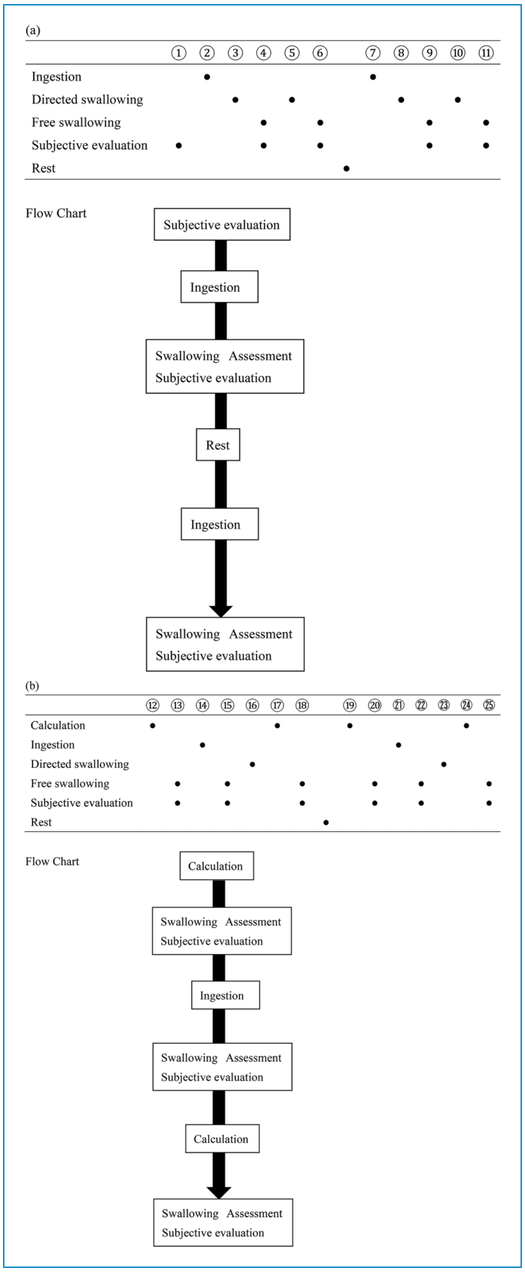

Figure 1. Evaluation flowchart. (a) Resting. Order of ingestion randomised from yoghurt to water or water to yoghurt. Due to the crossover design, the order of ingestion is yoghurt to water or water to yoghurt, based on each participant, randomly. (b) Calculation. Order of ingestion randomised from yoghurt to water or water to yoghurt. Repeating the same flow after the rest with the other kind of intake. Due to the crossover design, the order of ingestion is yoghurt to water or water to yoghurt, based on each participant, randomly. (c) Exercise. Order of ingestion randomised from yoghurt to water or water to yoghurt. Repeating the same flow after the rest with the other kind of intake. Due to the crossover design, the order of ingestion is yoghurt to water or water to yoghurt, based on each participant, randomly.

(continued)

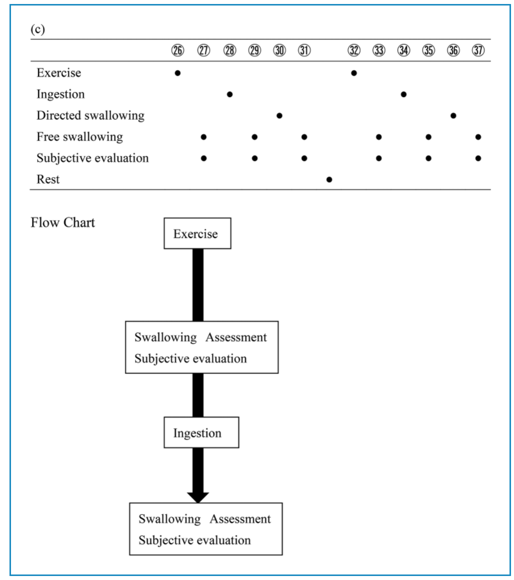

Figure 1. Continued.

calculation task involved writing answers on a grid sheet. On a sheet with the numbers 0 to 9 arranged randomly on the left and top sides, participants filled in additional answers at the intersection of the rows and columns, starting from the space at the top left in order (Supplemental Figure 1). The participants performed single-digit additions for 3 min. The sheets were used randomly, and the same number order was not used for the same participant. The participants were instructed to provide accurate answers as much as possible. We did not evaluate their performance because the purpose was to impose a task in a simple manner.

The exercise task involved a simple exercise, radio calisthenics, that could be performed at any age. This exercise is regularly performed in Japan; therefore, we expected no differences in the amount of load due to mistakes in performing it. We used routine health maintenance, disease prevention and research tasks.[34]

This task involved effectively moving muscles and joints to the rhythm of music, including arm circles, stretches and twists, as well as promoting flexibility and muscle activation and requires a moderate-intensity aerobic activity in succession. The task was performed for approximately 3 min. The participants performed the exercise task at an intensity of 4–4.5 metabolic equivalents.[35]

For the resting state assessment (Figure 1(a)), participants completed a self-evaluation of their emotional and physical state while in a sitting position and before ingestion. After ingestion, they performed free and directed swallowing twice to evaluate the effects of both types of ingestants. Then, they completed the calculation task (Figure 1(b)). We assumed that directed swallowing immediately after the task would be affected by the task; thus, directed swallowing was performed after free swallowing. The calculation task was performed twice to evaluate changes over time. The exercise was performed only once in consideration of the physical burden. As in the resting state assessment, measurements for the other ingestant were taken after a mouth rinse and a resting period of at least 5 min (Figure 1(c)).

Swallowing evaluation

To objectively assess swallowing frequency, we used a smartphone-based real-time device that monitors swallowing, a neck-worn monitoring device for swallowing activities (NeW-MDSA) (GOKURI® Neckband, PLIMES, Inc, Tsukuba, Japan) (Figure 2(a)).

NeW-MDSA collects vibrations from the neck using an electric condenser throat microphone at 11.025 kHz. Based on the swallowing sound model proposed by Morinière et al.,[36] it uses a series of feature values and frequency characteristics of acoustic waveforms to identify the swallowing sound. Previous studies[37,38] have confirmed the accuracy of this device's quantitative assessment of swallowing. A piezoelectric contact microphone (frequency range 200 Hz–8 kHz) was used to measure biological sounds, including swallowing sounds, with the neckband worn anterior to the neck (between the C2 and C5 levels of the spinal cervical region).[38] To analyse swallowing, we used a deep learning model based on a convolutional neural network with four convolutional layers, a pooling layer, and a SoftMax base for binary classification. For input, the network uses a 10.1 ms resolution spectrogram of

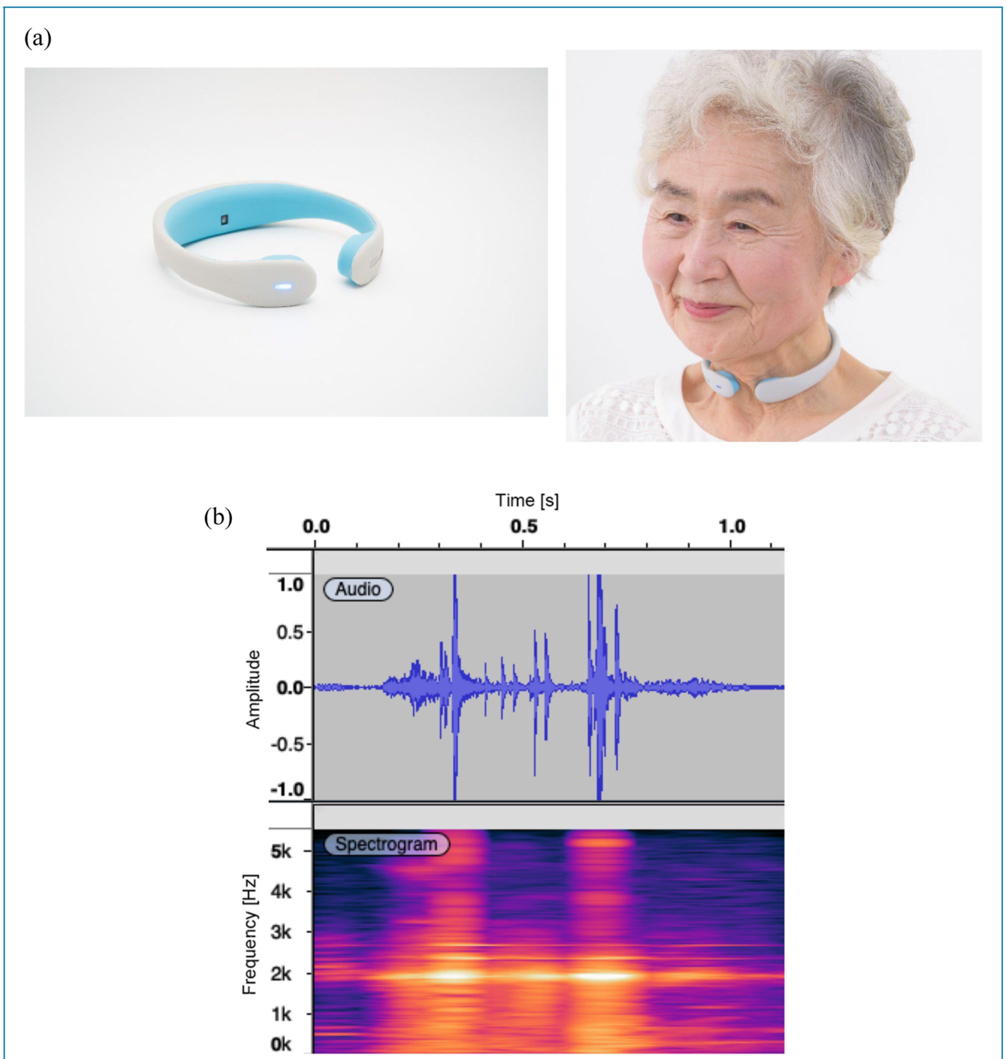

Figure 2. (a) The neck-worn monitoring device for swallowing activities used in this study (NeW-MDSA) (GOKURI PLIMES, Inc). (b) Waveform. Example of a recording of swallowing sounds using NeW-MDSA showing the amplitude (top) and the respective spectrogram (bottom) with the y-axis representing the frequency.

sound and outputs a binary classification of either swallowing sound or some other sound. Based on the recorded laryngeal sounds and the binary classification, we used waveform editing software to visualise the sound and determine whether it was a swallowing sound (Figure 2(b)). Final visual and auditory determinations were made by three or more evaluators using the results of the binary classification evaluations as support material. The training data set included swallowing data from 226 individuals belonging to three broad groups that have participated in this study: a group of 192 individuals for evaluating dysphagia, older healthy residents at a geriatric health services facility and healthy young adults. The swallowing data set was used as the total training data set of 1859 swallowing sounds and 2021 noise samples; 20% of the data was used for validation, resulting in a convolutional neural network with 97.3% accuracy.[24]

Swallowing measurements were recorded with the participants seated on a chair. For directed swallowing, the participants were instructed to intentionally swallow their saliva as much as possible, and these actions were measured for 30 s. For free swallowing, we measured the participants' natural swallowing without providing any specific instructions. Since measurement times varied from person to person, the evaluation was based on the frequency of swallowing per minute. A previous study has identified the origin of swallowing sound components, namely the laryngeal ascension, the laryngeal release, and the upper-sphincter opening sounds, using modern techniques that can provide numeric, synchronised acoustic–radiologic data.[39] Based on these findings, we determined the frequency of the swallowing events. We evaluated the frequency of swallowing events, i.e. directed and free swallowing, which are used as indicators for understanding the frequency of swallowing events.[40,41]

Subjective evaluation

We evaluated subjective psychological changes as these can affect swallowing and saliva volume.[17,42]

Awareness of swallowing in daily life. We evaluated the participants' awareness of swallowing problems in their daily lives using the following questions: 'Do you need extra strength when swallowing solid items?', 'Do you need extra strength when swallowing pills?', 'Is swallowing stressful?' and 'Do you sometimes become aware of dryness in your oral cavity?' based on the validated questionnaire of the eating assessment tool-10 (EAT-10).[43,44] The respondents were asked to answer these questions on a scale of 0 to 4, where 0 = not at all, 1 = rarely, 2 = sometimes, 3 = often, and 4 = always. Responses of 2 to 4 were regarded as being aware of their swallowing problems.

Evaluation of food ingestion. In this study, we did not use existing evaluation scales for patients with dysphagia[43] since our aim was to obtain subjective evaluations of healthy participants in various situations. Instead, we used a visual analogue scale to evaluate the participants' self-reported emotions (feelings of pain, frustration, nervousness, having fun, refreshed or calm) and physical state (such as whether the inside of the mouth feels viscous or moist, or feeling thirsty, tired, clear-headed or energetic), referring the emotional relaxation scale and the temporary mood scale (In Japanese).[45] To evaluate psychological changes associated with ingestion, changes in values were examined for both swallowing water and yoghurt in the following manner:

For the resting task: after the first directed swallowing – before ingestion (④ − ① and ⑨ − ①) and after the second directed swallowing – before ingestion (⑥ − ① and ⑪ − ①). For the calculation task: after ingestion – after calculation (⑮ − ⑬ and ㉒ − ⑳) and after the second calculation – after the first calculation (⑱ − ⑬ and ㉕ − ⑳). For the exercise: after ingestion – after exercise (㉙ − ㉗ and ㉟ − ㉝) and after directed swallowing – after exercise (㉛ − ㉗ and ㊲ − ㉝).

Ethical considerations

This study was approved by the ethics review committee of Meiji Co., Ltd. (approval number: 2022-010) and was registered in the University Hospital Medical Information Network clinical trial system before recruiting participants (UMIN000049263). This study was also conducted according to the guidelines of the Declaration of Helsinki. Informed consent was obtained from all participants before the experiment. Data were analysed in a manner that preserved the anonymity of the participants.

Statistical analysis

The basic descriptive statistics of the population characteristics are presented as means and standard deviations or counts and percentages. Comparisons of the psychological scores per age group and the pharyngeal results were performed using the Wilcoxon rank-sum test. For subjective evaluations, we performed the Wilcoxon signed-rank tests and subsequent Bonferroni correction to account for multiplicity. We regarded $0.05/12 = 0.004$ as significant. For other evaluations, there was no need to consider multiplicity. Thus, we made no corrections and regarded $P < 0.05$ as statistically significant. Analytical values are expressed as medians (first and third quartiles) since this is a nonparametric test. All data management and statistical analyses were performed using JMP 17 (SAS Institute, Cary, NC, USA).

Results

Participants

A total of 105 participants (49 males, 56 females) were evaluated. Among them, 36 were excluded because of missing data, erroneous use of the device, difficulty in deciphering waveforms or different waveform evaluations provided by different raters. Thus, we analysed the data of 69 participants (34 males, 35 females). To analyse the data according to age, the participants were divided into two groups: those over 60 years (the older group) and those under 60 years (the younger group). The data of 32 people (16 males and 16 females, mean [standard deviation] 39.09 [12.16] years) in the younger group and 37 people (18 males and 19 females, mean [standard deviation] 71.43 [5.50] years) in the older group were analysed. Regarding participants who reported being aware of their swallowing problems, people in the older group were more likely to experience stress when swallowing. Further, more people in the older group were aware of oral dryness (Table 1).

Swallowing frequency involving ingestants: Comparison between the two groups

The swallowing frequencies related to ingesting water and that related to ingesting yoghurt were compared between the younger and older groups (Table 2). When resting, participants in the younger group had a significantly higher directed swallowing frequency than those in the older group for both water and yoghurt ($P < 0.0010$) (③ and ⑧, and ⑤ and ⑩). In the calculation task, those in the younger group had a significantly higher swallowing frequency, for both directed and free swallowing, than those in the older group after ingestion, except for the first free swallowing after yoghurt ingestion (⑬ and ⑳). After the exercise task, the two groups showed a significant difference in free swallowing (㉙ and ㉟) immediately after ingesting yoghurt ($P = 0.004$). Regarding directed swallowing (㉚ and ㊱), those in the younger group had a significantly higher swallowing frequency (water: $P = 0.0011$, yoghurt: $P < 0.0010$).

Analysis of responses to swallowing water and yoghurt in the younger and older groups

We analysed the differences between the two groups regarding the frequency of swallowing water and yoghurt (Table 3). At rest (Table 3a), there was a difference in the frequency of swallowing water and swallowing yoghurt in the younger group in the first directed swallowing activity (③ and ⑧) ($P = 0.0164$); however, no significant differences were observed between swallowing water and swallowing yoghurt in the older group. In the second directed swallowing activity (⑤ and ⑩), there were no significant differences in the frequency of swallowing water and swallowing yoghurt in either group. For the first free swallowing activity (④ and ⑨), the frequency of swallowing was significantly higher for yoghurt than for water in both groups ($P = 0.0108$ in the younger group, $P < 0.0010$ in the older group). In the second session (⑥ and ⑪), there were no significant differences in the frequency of swallowing between water and yoghurt in either group. In the subjective evaluation (Table 4a), at rest, yoghurt was significantly more effective when it came to helping participants think clearly ($P < 0.0010$) and feeling that the inside of the mouth was moist ($P < 0.0010$) among those in the younger group in the first evaluation (④ − ① and ⑨ − ①).

In the calculation task (Table 3b), there was a difference in the frequency of swallowing water and swallowing yoghurt in the younger group for directed swallowing (⑯ and ㉓) ($P = 0.0010$), but no significant differences were observed in the older group. In the first free swallowing activity after ingestion (⑮ and ㉒), the frequency of swallowing was significantly higher for yoghurt than water in both groups (younger group, $P = 0.0027$; older group, $P < 0.0010$). In the second free swallowing activity after directed swallowing (⑱ and ㉕), only the older group showed a significant difference ($P = 0.0375$).

In the exercise task (Table 3c), there were no significant differences in directed swallowing (㉚ and ㊱) between

Table 1. Demographic data.

	Younger group	Older group
N (males:females)	32 (16:16)	37 (18:19)
Age (mean, SD)	39.09 (12.16)	71.43 (5.50)
Extra strength required to swallow solid items (%)	3.1	5.4
Extra strength required to swallow tablets (%)	21.9	18.9
Swallowing is stressful (%)	3.1	10.8
Aware of dryness of the oral cavity (%)	43.8	48.6

Table 2. Comparison of the swallowing frequency after ingesting water and yogurt between younger and older individuals (times/minute).

	Water			Yoghurt		
	Younger group	Older group	P-value	Younger group	Older group	P-value
(a) Rest						
③ and ⑧	14.518 (10.307, 18.708)	8.296 (6.231, 12.406)	< 0.0010	12.369 (8.271, 16.549)	10.246 (6.166, 12.332)	< 0.0010
④ and ⑨	0.74 (0.213, 1.362)	0.422 (0.196, 1.024)	0.3140	1.174 (0.665, 2.192)	0.868 (0.613, 1.335)	0.2709
⑤ and ⑩	12.388 (8.252, 16.554)	10.246 (6.157, 10.401)	< 0.0010	11.423 (8.227, 16.630)	8.321 (6.213, 11.369)	< 0.0010
⑥ and ⑪	0 (0,1.180)	0 (0,0.644)	0.9828	0 (0,0.912)	0 (0,0.633)	0.6198
(b) Calculation						
⑬ and ⑳	0.988 (0, 1.367)	0 (0, 0.763)	0.0044	0.750 (0, 1.226)	0 (0, 0.849)	0.0611
⑮ and ㉒	1.445 (0.83, 2.114)	0.676 (0.214, 0.935)	< 0.0010	1.799 (1.109, 2.293)	1.025 (0.607, 1.722)	0.0025
⑯ and ㉓	12.350 (8.359, 20.677)	10.307 (6.270, 12.332)	0.0032	10.465 (10.284, 16.122)	10.246 (6.222, 12.444)	0.0272
⑱ and ㉕	0.840 (0, 1.497)	0 (0, 0.803)	0.0148	1.090 (0, 2.174)	0.582 (0, 0.918)	0.0289
(c) Exercise						
㉗ and ㉝	0.754 (0, 1.181)	0 (0, 0.843)	0.1685	0.883 (0, 1.506)	0 (0, 0.719)	0.0155
㉙ and ㉟	0.890 (0.506, 1.360)	0.621 (0, 1.205)	0.1966	1.677 (1.047, 2.417)	0.888 (0.573, 1.683)	0.0038
㉚ and ㊱	12.482 (8.246, 22.074)	8.296 (6.166, 12.406)	0.0011	13.572 (10.276, 17.992)	8.271 (6.203, 10.401)	< 0.0010
㉛ and ㊲	0.581 (0.222, 1.159)	0.470 (0, 1.088)	0.3794	0.913 (0.289, 1.587)	0.851 (0.411, 1.729)	0.8568

Data are shown as median value (1st quartile, 3rd quartile).

water and yoghurt in both the younger and older groups. In the first free swallowing activity after ingestion (㉙ and ㉟), the frequency of swallowing was significantly higher for yoghurt than for water in both groups (younger group, $P < 0.001$, older group, $P = 0.021$). In the free swallowing activity (㉛ and ㊲) after directed swallowing, the frequency of swallowing was also significantly higher for yoghurt than for water in both groups (younger group, $P = 0.020$, older group, $P < 0.001$).

In subjective evaluations of the participants' psychological states at rest, significant differences were found in clear thinking ($P < 0.0010$) and moistness of the oral cavity ($P = 0.0010$) during the first session (④ − ① and ⑨ − ①, respectively; Table 4a).

In subjective evaluations of the participants' psychological states during the exercise task, the older group exhibited a significant difference in the feeling of calmness when swallowing yoghurt in both the first (㉙ − ㉗ and ㉟ − ㉝) and second (㉛ − ㉗ and ㊲ − ㉝) sessions ($P = 0.0039$, 0.0039, respectively; Table 4c).

Discussion

This study enabled the non-invasive measurement of the swallowing function considering some of the emotional changes caused by ingestion-associated stimulation and physiological changes related to swallowing.

The purpose of our study was not to strictly evaluate dysphagia but rather determine the swallowing status of older adults in their daily lives. Therefore, we used a wearable device that can measure changes in daily life, rather than video endoscopic examination of swallowing, video fluoroscopic examination of swallowing or other devices that generally evaluate dysphagia at rest. For this trial, we selected water, a standard drink, and yoghurt, which has a high salivary secretion effect. To the best of our knowledge, this study is the first to compare physical and psychological changes at different time points and ages using water and yoghurt as intake.

Several standard swallowing tests rely on the evaluator's skill, which may affect data interpretation. However, in this

Table 3. Comparison of the swallowing frequency of younger and older individuals after ingesting water versus yogurt (times/minute).

	Younger group			Older group		
	Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
(a) Rest						
③ and ⑧	14.518 (10.307, 18.708)	12.369 (8.271, 16.549)	0.0164	8.296 (6.231, 12.406)	10.246 (6.166, 12.332)	0.3224
④ and ⑨	0.74 (0.213, 1.362)	1.174 (0.665, 2.192)	0.0108	0.422 (0.196, 1.024)	0.868 (0.613, 1.335)	< 0.0010
⑤ and ⑩	12.388 (8.252, 16.554)	11.423 (8.227, 16.630)	0.7908	10.246 (6.157, 10.401)	8.321 (6.213, 11.369)	0.9645
⑥ and ⑪	0 (0, 1.180)	0 (0, 0.912)	0.7390	0 (0, 0.644)	0 (0, 0.633)	0.9498
(b) Calculation						
⑬ and ⑳	0.988 (0, 1.367)	0.750 (0, 1.226)	0.2761	0 (0, 0.763)	0 (0, 0.849)	0.8048
⑮ and ㉒	1.445 (0.83, 2.114)	1.799 (1.109, 2.293)	0.0027	0.676 (0.214, 0.935)	1.025 (0.607, 1.722)	< 0.0010
⑯ and ㉓	12.350 (8.359, 20.677)	10.465 (10.284, 16.122)	0.0010	10.307 (6.270, 12.332)	10.246 (6.222, 12.444)	0.7604
⑱ and ㉕	0.840 (0, 1.497)	1.090 (0, 2.174)	0.5057	0 (0, 0.803)	0.582 (0, 0.918)	0.0375
(c) Exercise						
㉗ and ㉝	0.754 (0, 1.181)	0.883 (0, 1.506)	0.6595	0 (0, 0.843)	0 (0, 0.719)	0.4744
㉙ and ㉟	0.890 (0.506, 1.360)	1.677 (1.047, 2.417)	< 0.0010	0.621 (0, 1.205)	0.888 (0.573, 1.683)	0.0209
㉚ and ㊱	12.482 (8.246, 22.074)	13.572 (10.276, 17.992)	0.7700	8.296 (6.166, 12.406)	8.271 (6.203, 10.401)	0.3005
㉛ and ㊲	0.581 (0.222, 1.159)	0.913 (0.289, 1.587)	0.0199	0.470 (0, 1.088)	0.851 (0.411, 1.729)	< 0.0010

Data are shown as median value (1st quartile, 3rd quartile).

study, the speech-based waveform allows quantitative objective evaluation; for example, the sound pressure becomes stronger when saliva is sufficiently produced; hence, counts when saliva is not produced are eliminated. Furthermore, since the swallowing evaluation was performed in a healthcare facility, patients may be in an unusual environment that differs from everyday life; this may create some nervousness.

Previous studies have used mobile devices[22–25] and cameras[26–29] as evaluation devices. However, these devices require postural retention in front of the camera and do not allow for movement since identifying swallowing indicators, such as the hyoid bone, is essential.

Therefore, measurements are limited to the resting state. Routine measurements are difficult, and using the device can be burdensome for the examinee, making evaluating the elderly challenging.[31]

Notably, no participants dropped out of the present study due to stress from wearing the NeW-MDSA. In this respect, we believe that our method enables evaluation in familiar situations that resemble daily conditions.

To the best of our knowledge, this is the first device-measured swallowing (free swallowing) report of the effects of food ingestion. Swallowing sounds and subjective evaluation measures were used simultaneously, and measuring swallowing sounds using NeW-MDSA did not interfere with the subjective evaluation. This suggests that these methods are useful for clarifying changes in swallowing over time and the relationship between frequency of swallowing events and saliva production, which is induced by swallowing. Given that conventional swallowing evaluation requires constant visual monitoring of whether swallowing has occurred, continuous evaluation over an extended period is challenging. However, such constant visual monitoring is not required when a device continuously records – and digitises – biological data from the body surface. In this study, we conducted measurements using a digital auscultation method. The use of NeW-MDSA allowed the elucidation of swallowing behaviour over time, which enabled the evaluation of free swallowing and its digital representation considering swallowing frequency per hour (swallows/min). In the data analysis, the neural network model of swallowing sound identification by deep learning assisted the evaluator's judgment.

Comparison of swallowing frequency between the younger and older groups

When analysing the younger and older groups (Table 2), we found that participants in the older group tended to have a lower swallowing frequency than those in the younger group in all instances of directed swallowing and in most instances of free swallowing. The decline in swallowing frequency associated with ageing is consistent with clinical findings and the results of previous studies.[46] However, comparisons of free swallowing accompanied by calculation and exercise tasks revealed instances in which the frequency of swallowing did not differ significantly between the two groups. For example, no differences were observed between the younger and older groups regarding the ingestion of water after exercise, suggesting that the mechanism of saliva induction after exercising may be different from that after performing a calculation task. Therefore, for the evaluation of the ingestion function (which includes salivation, chewing and swallowing), more detailed studies that consider the relationship between task loads and ingestants are required.

Comparison between ingestants

In this section, we describe the comparison between two age groups with respect to the frequency of swallowing different ingestants and participants' subjective evaluation of their swallowing function (Tables 3 and 4).

Directed swallowing. In the first directed swallowing activity while the participants were at rest (③ and ⑧), there was a difference between the frequency of swallowing water and that of swallowing yoghurt ($P = 0.0164$) in the younger group, but no significant differences were observed in the older group. In the second directed swallowing activity (⑤ and ⑩), there were no significant differences between the frequency of swallowing water and that of swallowing yoghurt in either group. These results suggest that directed swallowing may be influenced by the ingestant and that the degree of influence may vary with age. For directed swallowing after the calculation and exercise tasks, differences were found between swallowing water and swallowing yoghurt after the calculation task (⑯ and ㉓) in the younger group ($P = 0.0010$). However, no differences were observed between swallowing water and swallowing yoghurt after the exercise task in the younger group and after both the calculation and exercise task in the older group. This suggests that, while the swallowing response to ingestants varies with age, as in the case of the resting state, there is a possibility that the effects of different task loads may also vary with age.

While the oral conditions of those in the younger group may have been the same when resting as when performing the calculation task, it may have changed after the exercise task, as in the case of those in the older group. It is also possible that the salivation effect of yoghurt became stronger.

Free swallowing.

In the first free swallowing activity (④ and ⑨), the frequency of swallowing yoghurt was higher than that of swallowing water in both the younger and older groups (younger $P = 0.0108$, older $P < 0.0010$) while at rest. Similarly, the frequency of swallowing yoghurt was significantly higher in both groups after both the calculation (⑮ and ㉒) (younger $P = 0.0027$, older $P < 0.0010$) and exercise tasks (㉙ and ㉟) (younger $P < 0.0010$, older $P = 0.0209$). This suggests that yoghurt may

Table 4. Subjective evaluation

			Younger Group			Older Group		
			Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
(a) Rest								
Emotion	Painful	④ − ① and ⑨ − ①	0.5 (−2.75, 5)	0.5 (−4, 3.5)	0.2322	0 (−6.5, 5.5)	0 (−7, 3)	0.9055
		⑥ − ① and ⑪ − ①	2.5 (−1.75, 22)	2.5 (−1.75, 9.75)	0.0572	1 (−3, 9.5)	0 (−13, 8.5)	0.1983
	Frustrated	④ − ① and ⑨ − ①	0 (−3.75, 3.75)	−2.5 (−16, 0)	0.0059	−2 (−22.5, 1)	−2 (−21.5, 0)	0.1975
		⑥ − ① and ⑪ − ①	−1 (−8.5, 3.75)	−1 (−7.75, 3.75)	0.1297	−6 (−20.5, 0)	−14 (−35.5, −0.5)	0.2568
	Nervous	④ − ① and ⑨ − ①	−30.5 (−52, −1)	−28 (−48, −5.25)	0.1367	−16 (−56.5, 0)	−22 (−58.5, −0.5)	0.3209
		⑥ − ① and ⑪ − ①	−26.5 (−43, −3.75)	−36.5 (−47, −11)	0.0993	−25 (−55, 0.5)	−23 (−52, −2)	0.7843
	Fun	④ − ① and ⑨ − ①	10.5 (−5.25, 53.75)	25 (1, 47.75)	0.0305	3 (−4.5, 56)	3 (−7, 62.5)	0.0451
		⑥ − ① and ⑪ − ①	22 (−8.5, 51)	18.5 (−11, 48.75)	0.3007	1 (−2.5, 53.5)	18 (−7, 55)	0.4717
	Refreshed	④ − ① and ⑨ − ①	4 (−2.75, 12.75)	13.5 (−6.5, 31.75)	0.0749	1 (−7, 15)	1 (−6.5, 21)	0.2787
		⑥ − ① and ⑪ − ①	−1.5 (−14.75, 8.75)	3 (−7.5, 16.5)	0.0572	−1 (−6.5, 16.5)	3 (−7.5, 30.5)	0.2971
	Calm	④ − ① and ⑨ − ①	3 (−1.75, 14)	6 (−0.75, 16)	0.0758	0 (−5.5, 9.5)	1 (−0.5, 22)	0.0125
		⑥ − ① and ⑪ − ①	0.5 (−7.5, 19.75)	2 (−5.75, 12.75)	0.2595	0 (−4, 15.5)	9 (−7.5, 22)	0.4536
	Tired	④ − ① and ⑨ − ①	−2.5 (−22.5, 2.75)	−1 (−12.25, 2.5)	0.7766	0 (−3, 6.5)	−1 (−11.5, 2.5)	0.0080
		⑥ − ① and ⑪ − ①	2.5 (−8.25, 10)	−1 (−13.5, 4)	0.5212	0 (−7, 4.5)	−1 (−11, 8)	0.4903
	Clear thinking	④ − ① and ⑨ − ①	1.5 (−5, 11.75)	5.5 (−0.75, 19.5)	< 0.0010	1 (−2, 11)	5 (−0.5, 19.5)	0.1655
		⑥ − ① and ⑪ − ①	0.5 (−6.5, 8)	5.5 (−3.75, 11)	0.1497	4 (−2, 11.5)	2 (−10.5, 22)	0.6251

(continued)

Table 4. Continued.

			Younger Group			Older Group		
			Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
	Energetic	④ − ① and ⑨ − ①	1 (−3.75, 7.75)	4 (0.25, 17)	0.0062	0 (−8.5, 5.5)	1 (−4.5, 13)	0.0115
		⑥ − ① and ⑪ − ①	0 (−11.25, 8)	3 (−4.75, 11.75)	0.0065	−1 (−10.5, 3)	0 (−21, 12)	0.1290
Oral cavity	Viscous	④ − ① and ⑨ − ①	−12 (−22, 7)	0 (−25.25, 23.25)	0.2118	−6 (−18, 2)	−5 (−21.5, 7.5)	0.4763
		⑥ − ① and ⑪ − ①	0.5 (−10.5, 25)	1 (−12.25, 26)	0.9562	−4 (−12.5, 8)	0 (−24, 9)	0.1905
	Thirsty	④ − ① and ⑨ − ①	−19.5 (−36.75, 0)	−30 (−51, −3.5)	0.1270	−8 (−35.5, 2)	−10 (−48.5, −3.5)	0.0853
		⑥ − ① and ⑪ − ①	3 (19.75, 15.75)	−8.5 (−22.75, 12.5)	1.0000	0 (−10, 10.5)	−7 (−38, 6)	0.0560
	Moist	④ − ① and ⑨ − ①	11.5 (−0.25, 26.75)	24.5 (7.75, 50.75)	< 0.0010	6 (−2.5, 24)	21 (0, 36.5)	0.0139
		⑥ − ① and ⑪ − ①	0 (−11, 17.5)	10 (−8.25, 20)	0.0852	−2 (−11.5, 19)	16 (−1.5, 30.5)	0.0301
(b) Calculation								
Emotion	Painful	⑮ − ⑬ and ㉒ − ⑳	−1 (−4.75, 1)	0 (−2.75, 2)	0.3377	−1 (−8, 1.5)	−1 (−9.5, 1)	0.3842
		⑱ − ⑬ and ㉕ − ⑳	−1 (−2, 4.75)	0 (−1, 6.5)	0.5147	0 (−4, 4)	−2 (−8, 4)	0.4006
	Frustrated	⑮ − ⑬ and ㉒ − ⑳	0 (−6.5, 1)	0 (−5.5, 1)	0.3477	−3 (−8.5, 0)	−2 (−12, 3)	0.7391
		⑱ − ⑬ and ㉕ − ⑳	0 (−2.75, 0.75)	0 (−4, 7.75)	0.6535	−1 (−6.5, 5.5)	0 (−5, 9)	0.5189
	Nervous	⑮ − ⑬ and ㉒ − ⑳	0 (−12, 2)	−1.5 (−8.75, 0)	0.5083	−1 (−5, 1)	−4 (16.5, 1)	0.0853
		⑱ − ⑬ and ㉕ − ⑳	0.5 (−5.75, 5.5)	−1 (−8.75, 0.75)	0.2135	−1 (−6, 3.5)	−2 (−11.5, 3)	0.9823
	Fun	⑮ − ⑬ and ㉒ − ⑳	−1 (−6.75, 2.75)	1 (−1.75, 8.75)	0.0733	2 (−0.5, 6.5)	3 (−1, 12)	0.4809
		⑱ − ⑬ and ㉕ − ⑳	−2 (−6, 2.75)	1 (−2, 3.75)	0.3721	0 (−4.5, 3.5)	4 (−4, 8.5)	0.1752

(continued)

Table 4. Continued.

			Younger Group			Older Group		
			Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
	Refreshed	⑮ − ⑬ and ㉒ − ⑳	0 (−4.5, 3)	6 (−1, 16.5)	0.0305	6 (1, 11)	3 (−1.5, 13)	0.7392
		⑱ − ⑬ and ㉕ − ⑳	−1 (−9, 6.75)	1.5 (−1.75, 9)	0.0384	1 (−1, 8)	0 (−6, 10)	0.8187
	Calm	⑮ − ⑬ and ㉒ − ⑳	5 (−0.75, 13)	1 (−2, 9.75)	0.2223	3 (0, 12.5)	4 (−1, 14)	0.6947
		⑱ − ⑬ and ㉕ − ⑳	1 (−3.75, 6.75)	0 (−3.75, 5)	0.8908	1 (−2.5, 7.5)	3 (−0.5, 9)	0.1956
	Tired	⑮ − ⑬ and ㉒ − ⑳	−0.5 (−6, 1)	−1 (−9.25, 1)	0.4572	−3 (−8, 1)	−4 (−7.5, −1)	0.5431
		⑱ − ⑬ and ㉕ − ⑳	0 (−1.75, 5)	1.5 (−7.75, 7)	0.8192	−1 (−8, 6.5)	−1 (−8, 3.5)	0.8475
	Clear thinking	⑮ − ⑬ and ㉒ − ⑳	0 (−5.75, 6.75)	−0.5 (−7.75, 5)	0.7910	2 (−2, 5.5)	1 (−1, 6.5)	0.5086
		⑱ − ⑬ and ㉕ − ⑳	−0.5 (−7, 5)	0 (−3.75, 2.75)	0.8982	0 (−10.5, 8.5)	0 (−7, 6)	0.4268
	Energetic	⑮ − ⑬ and ㉒ − ⑳	−2 (−6.75, 1)	1 (−2, 8.75)	0.0319	2 (−2, 6)	2 (−1, 7)	0.2144
		⑱ − ⑬ and ㉕ − ⑳	−2 (−6, 2)	0 (−2, 5)	0.1367	0 (−6, 4)	2 (−3.5, 6)	0.2968
Oral cavity	Viscous	⑮ − ⑬ and ㉒ − ⑳	−5.5 (−22.5, 1)	−5.5 (−17.25, 0.75)	0.2725	−3 (−10.5, 0.5)	−6 (−12.5, 0)	0.2287
		⑱ − ⑬ and ㉕ − ⑳	−1 (−8.75, 5.5)	0 (−11.25, 4.75)	0.9787	−1 (−5.5, 7)	−5 (−12.5, 0.5)	0.0397
	Thirsty	⑮ − ⑬ and ㉒ − ⑳	−7 (−22, −1.25)	−5 (−21.75, −1)	0.8407	−2 (−15.5, 1.5)	−5 (−25, 0.5)	0.3186
		⑱ − ⑬ and ㉕ − ⑳	−0.5 (−7, 11.5)	−0.5 (−8.5, 3.75)	0.6805	−1 (−8, 6.5)	−2 (−11, 7)	0.3560
	Moist	⑮ − ⑬ and ㉒ − ⑳	6.5 (0, 24.75)	12 (0.25, 27)	0.6942	2 (−2.5, 11)	8 (1, 23.5)	0.0797
		⑱ − ⑬ and ㉕ − ⑳	−2 (−8.5, 5.25)	0 (−10, 13.5)	0.3201	0 (−10.5, 8.5)	1 (−2.5, 14.5)	0.1124

(continued)

Table 4. Continued.

			Younger Group			Older Group		
			Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
(c) Exercise								
Emotion	Painful	㉙ − ㉗ and ㉟ − ㉝	−1 (−4.5, 2)	−1.5 (−7.5, 0)	0.1557	0 (−2, 2)	−1 (−3.5, 1)	0.1546
		㉛ − ㉗ and ㊲ − ㉝	1 (−3.75, 5.75)	−1 (−6.5, 2)	0.3146	0 (−2, 1.5)	−1 (−7, 1)	0.0787
	Frustrated	㉙ − ㉗ and ㉟ − ㉝	0 (−2.75, 1.75)	0 (−4.5, 2.75)	0.9054	0 (−3.5, 1)	−2 (−6, 1)	0.6619
		㉛ − ㉗ and ㊲ − ㉝	−2 (−7, 1)	1 (−1.75, 3)	0.0460	−1 (−7, 0.5)	−1 (−4, 1)	0.4249
	Nervous	㉙ − ㉗ and ㉟ − ㉝	0 (−4, 2)	−1 (−2.75, 1.75)	0.9635	0 (−1, 1)	0 (−2, 1)	0.8646
		㉛ − ㉗ and ㊲ − ㉝	−0.5 (−5, 1)	0 (−3, 4.25)	0.3107	0 (−2, 3.5)	0 (−3, 4)	0.7834
	Fun	㉙ − ㉗ and ㉟ − ㉝	0 (−5.75, 1.75)	0 (−4.75, 4.5)	0.5637	1 (−1, 4.5)	1 (−2.5, 6.5)	0.5085
		㉛ − ㉗ and ㊲ − ㉝	−6 (−13.75, −1.5)	−0.5 (−9.75, 2)	0.0487	−1 (−3, 2.5)	0 (−6, 5.5)	0.5980
	Refreshed	㉙ − ㉗ and ㉟ − ㉝	−2 (−14, 3)	0 (−9.5, 6.25)	0.4137	1 (−2, 4.5)	1 (−2, 4)	0.9351
		㉛ − ㉗ and ㊲ − ㉝	−2 (−19.25, 0)	−1 (−12.25, 3.75)	0.1368	−1 (−8, 1.5)	−2 (−7.5, 1)	0.8648
	Calm	㉙ − ㉗ and ㉟ − ㉝	1.5 (−1.5, 10.5)	2 (−1, 6.25)	0.5886	−1 (−2.5, 2.5)	4 (0, 9)	0.0039
		㉛ − ㉗ and ㊲ − ㉝	0 (−4, 7.5)	0 (−4.75, 5.75)	0.7008	−1 (−5, 2)	1 (0, 8)	0.0039
	Tired	㉙ − ㉗ and ㉟ − ㉝	−3 (−11.75, 1.75)	−1 (−8.5, 3)	0.7910	−1 (−5.5, 2)	−4 (−9, 0)	0.0043
		㉛ − ㉗ and ㊲ − ㉝	−1 (−9, 3.25)	−1 (−9, 6)	0.9200	0 (−6, 2)	−2 (−5.5, 1)	0.0427
	Clear thinking	㉙ − ㉗ and ㉟ − ㉝	0.5 (−4, 8)	−0.5 (−4, 5)	0.7077	1 (−1, 2.5)	1 (−0.5, 6.5)	0.0343
		㉛ − ㉗ and ㊲ − ㉝	0.5 (−6.75, 2.75)	0 (−5.75, 5.75)	0.3020	−1 (−6.5, 1)	0 (−1, 2)	0.0378

(continued)

Table 4. Continued.

			Younger Group			Older Group		
			Water	Yoghurt	*P*-value	Water	Yoghurt	*P*-value
	Energetic	㉙ − ㉗ and ㉟ − ㉝	1 (−4, 3)	0 (−5.75, 2.75)	0.4571	0 (−2.5, 2)	0 (−2, 1.5)	0.7782
		㉛ − ㉗ and ㊲ − ㉝	−4.5 (−14.75, 1)	−1 (−8.25, 175)	0.2598	−1 (−5, 1)	−1 (−5, 1)	0.7835
Oral cavity	Viscous	㉙ − ㉗ and ㉟ − ㉝	−12 (−25.75, −1)	0 (−10.25, 10.5)	0.0044	−1 (−12, 2)	−2 (−17, 0.5)	0.2933
		㉛ − ㉗ and ㊲ − ㉝	−2.5 (−14.75, 0.75)	0.5 (−5, 7)	0.2847	−1 (−8, 4.5)	0 (−10, 4)	0.9646
	Thirsty	㉙ − ㉗ and ㉟ − ㉝	−11.5 (−27.75, −2.5)	−8 (−25.75, 1)	0.5093	−7 (−19, 0)	−5 (−24.5, −2)	0.9234
		㉛ − ㉗ and ㊲ − ㉝	−2.5 (−12, 3.5)	−3.5 (−14, 1)	0.4574	−2 (−14.5, 2.5)	−4 (−19.5, 0)	0.3221
	Moist	㉙ − ㉗ and ㉟ − ㉝	15.5 (0, 42)	−1 (−8.5, 3)	0.0275	4 (−1, 15.5)	8 (1, 17)	0.1802
		㉛ − ㉗ and ㊲ − ㉝	2 (−5.75, 15.75)	0 (−11.5, 11.5)	0.6607	0 (−4, 9.5)	3 (−1, 9.5)	0.1608

Data are shown as median value (1st quartile, 3rd quartile).

promote saliva secretion. After directed swallowing, no significant differences were found in the younger group. However, significant differences were still found in the older group after the calculation task (⑱ and ㉕) ($P = 0.0375$). Thus, differences in swallowing responses by age group were observed. The results suggest that, for people in the older group, ingestants may have different effects on swallowing after a task, unlike in the case of the resting state.

Subjective evaluation. In the younger group, it was observed that yoghurt was more effective in promoting clear thinking ($P < 0.0010$) and the feeling of oral moistness ($P < 0.0010$) during rest. After exercise, only the older group experienced a significant difference in the feeling of calmness brought about by yoghurt ingestion during the first (㉙ − ㉗ and ㉟ − ㉝; P = 0.004) and second (㉛ − ㉗ and ㊲ − ㉝; $P = 0.0039$) swallowing activities. As opposed to water, yoghurt – which is more solid – promotes chewing. It is acidic and promotes salivation.[46,47] These characteristics may affect subjective feelings, and the degree of this influence may differ depending on the participant's age and the presence or absence of a task.

General discussion

This study included healthy participants for whom changes in free swallowing are more important than changes in directed swallowing, as the latter evaluates the degree of dysphagia. It has been reported that changes in emotions reduce the frequency of free swallowing,[33,44] consistent with the findings of this study. An increase in the frequency of free swallowing is believed to be largely associated with changes in saliva volume. Factors that influence changes in saliva volume include saliva viscosity and acidity.[12,48,49] Changes in viscosity are, in turn, influenced by changes in water volume and the ingestant in the oral cavity. In this study, we speculated that tasks such as exercising and calculating would cause sympathetic dominance. Sympathetic dominance tends to lead to the production of a small amount of viscous saliva that contains a high amount of protein.[50] On the other hand, parasympathetic stimulation leads to the secretion of a large volume of saliva and an increase in the water content. Thus, sympathetic dominance leads to a highly viscous environment in the oral cavity, whereas parasympathetic dominance leads to a serous environment with a high water content and promotes swallowing.[51,52] In the subjective evaluation, the feeling of calmness was significantly stronger in the older group, suggesting that yoghurt ingestion may have led to significant parasympathetic stimulation. Thus, in older adults, yoghurt, being moderately viscous, may have caused saliva components that tend to be mucous to become serous instead. Meanwhile, acidity increases salivation and promotes swallowing.[46,47] It is believed that sour stimuli facilitate better hyolaryngeal elevation,[53] and there are reports that it affects hemodynamic responses.[54] In addition, since yoghurt is familiar to many people, anticipatory salivary flow may be triggered by its acidity. Thus, yoghurt may induce not only direct acidity stimulation but also anticipatory salivation.[55] Meanwhile, yoghurt's effect on increasing swallowing frequency did not last long in the younger group compared to the older group after the calculation task. This may be because the tasks did not lead to a change in their oral cavity environment. Therefore, since the task load was light, the younger participants may have not experienced the aforementioned changes in their oral cavities. In the future, it will be necessary to conduct studies with varying task loads. Based on this study, ingestants and age must be considered when conducting further analyses.

Limitations

Saliva production is influenced by autonomic nerve activity and age. Thus, it is necessary to consider tasks with high mental and physical loads for people of all ages, further utilisation of food ingestion analysis to capture changes over time and methods such as the use of NeW-MDSA to continuously monitor swallowing function.

In this study, the temperatures of water and yoghurt were different since this study evaluated swallowing situation in daily life. Older adults often drink water at room temperature, while yoghurt is usually eaten out of the refrigerator; therefore, we evaluated conditions similar to those in daily life. Previous reports have shown that water changes the pharyngeal phase of oropharyngeal swallowing and latency of mean pace swallowing based on temperature.[56,57] Therefore, temperature might have influenced the present study. We also assessed the number of swallows following ingestion. Since the residence time of water and yoghurt in the oral cavity differs,[58,59] we assumed that the temperature difference when swallowing was negligible; hence, the effect on swallowing following ingestion was not significant. However, further analysis remains warranted.

Regarding the study of free swallowing, because of the increase in the swallowing frequency, we should consider the possibility that the use of yoghurt, which is more solid than water is, may have increased pharyngeal residuals and changed saliva volume. However, the difference was observed not only immediately after the ingestion of yoghurt but also during free swallowing after direct swallowing. Therefore, it is unlikely that the increase in the frequency of swallowing was the result of the pharyngeal residuals. We believe that the sustained saliva secretion effects of yoghurt may have influenced the increase in the frequency of free swallowing. Nevertheless, further analysis is needed, including an evaluation that involves multiple ingestants.

In future studies, we intend to measure the influence of physical properties in daily life in more detail by evaluating other physical properties, such as solids and semi-solids, as well as different taste sensations.

In addition, we evaluated swallowing using NeW-MDSA. Three evaluators examined the visual waveforms and eliminated swallowing actions with significantly low sound pressure levels. The number of times the swallow was definitely a swallow was counted, but this is not practical from the standpoint of general use because evaluation by three persons takes time. It is necessary to establish more standard criteria in the future from the viewpoint of reproducibility and reducing differences among evaluators.

In future studies, when assessing swallowing function (both directed and free swallowing) as in this study, it is necessary to pay attention not only to the selection of ingestants but also to the selection of age-appropriate tasks. A combination of tasks and ingestants should be considered.

Conclusion

We evaluated the state of swallowing using a mobile device, which also allows for the evaluation of free swallowing in daily life. Older participants tended to have a lower swallowing frequency than the younger participants did. In the comparison of ingestants, yoghurt – as opposed to water – was associated with a higher frequency of free swallowing. Differences were also observed in the participants' subjective evaluations. Through a partial simulation of some activities of daily life, this study demonstrated that it is possible to measure oral cavity conditions and saliva swallowing (which is a biological reaction triggered by ingestants), as well as subjective psychological conditions. Specifically, we demonstrated that it is possible to measure non-invasively the emotional changes caused by taste stimuli at the time of food ingestion and the physiological changes related to swallowing. Further, since directed swallowing is used to screen for conventional dysphagia, this study demonstrates that including the evaluation of free swallowing after food ingestion may be useful when assessing the relationship between the characteristics of the food, ingestion and swallowing. Moreover, this is the first study to evaluate swallowing-related indices using water and yoghurt as different ingestants and compare the physical and psychological changes in people of different age groups. We believe that this study is important in clarifying the relevance of both swallowing (as a physical reaction) and psychological states as reactions triggered by ingestion in each age group when assessing swallowing function. It is important to implement measures to prevent aspiration and extend people's healthy life expectancy. To this end, a method of assessing swallowing function in daily life should be established and sustained, and the physical and mental burden of oral ingestion should be reduced through appropriate food choices. The use of NeW-MDSA, as in this study, is one way to achieve this objective. This device can be used in the prevention of frailty and to analyse the relationship between people and food through data-informed observation of eating and swallowing behaviour.

Contributorship: All authors contributed to the design and implementation of the research. SM and TS performed the measurements. TH and YT processed the experimental data and performed the analysis. ST and KS were involved in supervising the work. MT wrote the manuscript. All authors contributed equally to the manuscript and read and approved the final version.

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