Journal of Dental Sciences 17 (2022) 1185—1192

Available online at www.sciencedirect.com

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journal homepage: www.e-jds.com

Original Article

Detection of swallowing disorders with a multiple-channel surface electromyography sensor sheet

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Received 14 October 2021; Final revision received 18 December 2021
Available online 7 January 2022

KEYWORDS
Dysphagia;
Electromyography;
Neck muscles;
Swallowing;
Swallowing disorders

Abstract *Background/purpose:* A sensor sheet comprising multiple electromyography electrodes that can be used to measure a series of multiple muscle activities related to swallowing was recently developed. In this study, we aimed to evaluate its utility in detecting swallowing disorders with a new method for the identification of muscle activity.
Materials and methods: All participants were evaluated by using the repetitive saliva swallowing test and modified water swallowing test and were classified accordingly into participants with ($n = 21$; mean age, 81.6 [standard deviation, 10.1] years) and those without ($n = 41$; mean age, 70.0 [8.4] years) dysphagia. The sheet contains four pairs of electrodes, and surface electromyography (sEMG) was performed on the suprahyoid (position A: upper front of the suprahyoid muscles; position B: bottom rear of the suprahyoid muscles) and infrahyoid (position C: above the infrahyoid muscles; position D: beneath the infrahyoid muscles) muscles while the participants swallowed liquid, thickened water, paste, and jelly. The sEMG findings, including the duration of swallowing waveforms and the delay in swallowing onset from position A to positions B, C, and D, were compared between the groups.
Results: The duration of muscle activity differed between the groups in the infrahyoid muscles when jelly (Mann—Whitney U test; position C, $P = 0.007$ and position D, $P = 0.018$) and thickened water (position C, $P = 0.033$) were swallowed.

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https://doi.org/10.1016/j.jds.2021.12.015

Conclusion: Our study demonstrates the utility of a novel sensor sheet developed for detecting swallowing disorders by using visual methods for identification of muscle activity.

Introduction

Swallowing is a complex sensorimotor process involving sequential activation of the oropharyngeal muscles.[1,2] Surface electromyography (sEMG) is an effective method for the evaluation of the swallowing function.[3,4] However, the application of electromyography can be difficult in clinical situations as it requires the attachment of electromyography electrodes or other sensors at appropriate positions; hence, it requires extensive knowledge of the anatomy of the muscles involved in swallowing.[5] Recently, a sensor sheet comprising multiple electromyography electrodes (multiple-sensor sheet) was invented.[6,7] The multiple-sensor sheet is used to measure a series of multiple muscle activities related to swallowing and to detect differences in sEMG activity between healthy volunteers without dysphagia and patients with dysphagia.[7] The duration and order of muscle activity at four specific positions in the region of the suprahyoid and infrahyoid muscles were revealed as possible indicators of swallowing dysfunction. However, identification of the onset and offset of muscle activities was difficult. Patients with dysphagia included those whose dysphagia was caused by resection and reconstruction of tissue for treatment for head and neck cancer, and the interpretation of their results was complicated.[6] In this study, we employed a new method of identifying muscle activity and aimed to re-assess the utility of the multiple-sensor sheet to detect swallowing disorders in patients with dysphagia.

Materials and methods

Ethical approval

The relevant ethics committees approved this study protocol (approval no. 3937). All participants provided written informed consent prior to their participation. This study was conducted in accordance with the ethical guidelines of the Declaration of Helsinki and the Ethical Guidelines for Medical and Health Research involving Human Subjects by the Ministry of Education, Culture, Sports, Science and Technology, and the Ministry of Health, Labor and Welfare of Japan.

Participants

Patients and staff members at one hospital, all aged $\geq$60 years, were invited to participate in this study. Participants with an embedded pacemaker, dermatitis grade of $\geq$2, impaired consciousness, pneumonia, enteroenteric perforation/acute bleeding as a result of perforation caused by intestinal blockage, bleeding and intestinal blockage, a medical history of allergy to test foods, contact dermatitis, subcutaneous bleeding, a history of head and neck reconstruction, and those otherwise deemed unsuitable by the researcher in charge were excluded from this study.

All participants were evaluated by using the repetitive saliva swallowing test and modified water swallowing test and were classified into two groups according to the results: those with and those without dysphagia. Those with dysphagia had a score of $<$3 in the repetitive saliva swallowing test[8] or $<$4 in the modified water swallowing test.[9]

Multiple-sensor sheet and laryngeal microphone

The multiple-sensor sheet was fixed at an attachment mark made at the thyroid cartilage on the left side of the neck. Eight electrodes were placed in four positions (position A: the upper front of the suprahyoid muscles, located close to the chin; position B: the bottom rear of the suprahyoid muscles, located near the hyoid bone; position C: above the infrahyoid muscles; and position D: beneath the infrahyoid muscles; the lower edge of the position D was above the clavicle). The electrodes in all four positions were used to record surface muscle activities (Fig. 1). A laryngeal microphone (SH-12jKL®; Nanzu Electric Co. Ltd., Shizuoka, Japan) was affixed to the lateral border of the trachea immediately inferior to the cricoid cartilage, to monitor the swallowing sound.[10] As the sheet has a fixed size and eight electrodes,[6] the accuracy of the measurement of muscle activity dose not depend on the examiner's skill.

Test foods

Four test foods with different textures, viscosities, and liquid proportions were prepared according to a previous study:[6] jelly, paste, thickened water, and liquid. The jelly (Otsuka Pharmaceutical Factory, Inc., Tokyo, Japan) slices (approximately 5 $\times$ 10 $\times$ 2 mm in size) were easy to swallow but did not easily dissolve in the mouth. Two grams of a homogeneous, smooth, non-greasy, and easy-to-swallow paste (Kewpie Corporation, Tokyo, Japan) was administered by using a K spoon® (Aoyoshi Co. Ltd., Niigata, Japan). The thickened water was a semi-solid nutrient, made by adding dextrin thickener (Nisshin OilliO Group, Ltd., Tokyo, Japan) to water at a 2% concentration. Both the thickened water and the liquid (approximately 3 mL) were injected onto the floor of the mouth with a syringe (Terumo Corporation, Tokyo, Japan). The physical characteristics of the four tests foods were investigated at the Nagano Prefecture General Industrial Technology Center (Table 1).

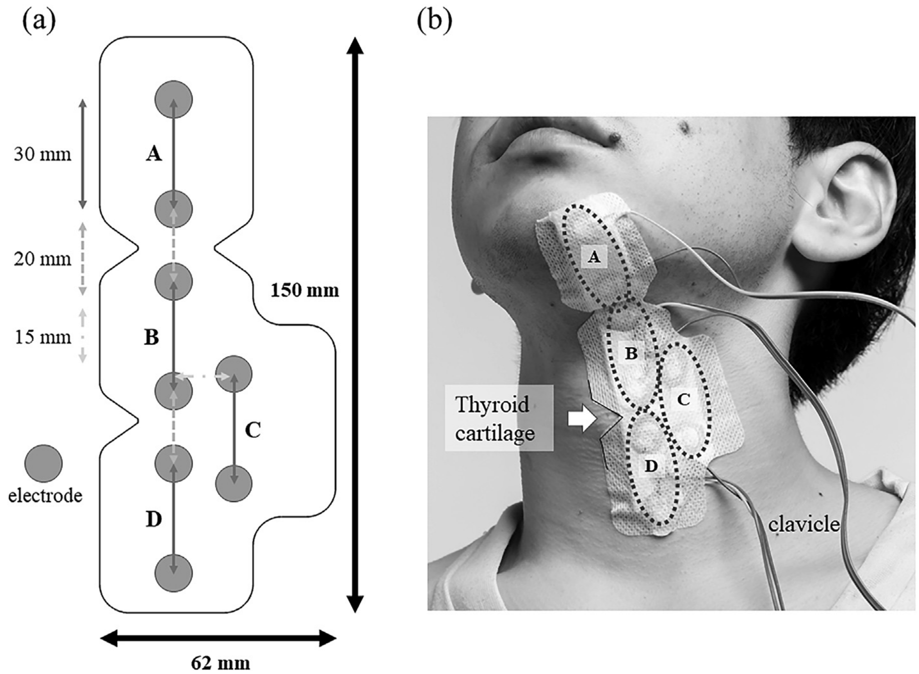

Figure 1 Layout of the multiple-sensor sheet. (a) Schematic diagram of the surface of the multiple-sensor sheet. (b) Attachment of the multiple-sensor sheet. The multiple-sensor sheet dimensions were: height, 150 mm and maximum width, 62 mm. Its maximum thickness was 3 mm. The multiple-sensor sheet was fixed based on the thyroid cartilage as a positioning mark. A pair of electrodes was placed 30 mm apart at each position. Surface muscle activity was recorded at the four locations (position A: upper front of the suprahyoid muscles, located close to the chin; position B, bottom rear of the suprahyoid muscles, located near the hyoid bone; position C, above the infrahyoid muscles; and position D, beneath the infrahyoid muscles; the lower edge of position D was above the clavicle).

Table 1 Physical characteristics of each test food.

Test food	Yield stress (Pa)	Cohesion	Adhesion (J/m^3)	Viscosity (mPa-s)
Jelly	4.5×10^3	0.50	3.2×10	272
Paste	1.5×10^3	0.66	3.2×10^2	2190
Thickened water	3.8×10^2	0.83	7.4×10	414
Liquid	1.3×10^2	0.99	1.5×10	1.01

The yield stress, adhesion values, and cohesiveness of the foods were measured by using a CREEP METER (RE2-33005C; Yamaden Co. Ltd., Tokyo, Japan) fitted with a Teflon plunger (diameter = 20 mm, height = 8 mm, speed = 10 mm/s). Data was analyzed by using an analysis software package (TAS-3305, Texture Analyzer for Windows version 2.300; Yamaden Co. Ltd, Tokyo, Japan). After processing for 1 min at a shear rate of 50 s^{-1}, the viscosity was measured by using a viscometer (Rheometer MCR300; DKSH Japan K.K., Tokyo, Japan).

Data collection

The sEMGs were performed and swallowing sounds measured for each test food. Each participant was asked to sit on a dental chair with his/her head kept motionless and parallel to the Frankfort plane. The participant's head was stabilized and the food was inserted into his/her mouth by the researcher. After resting, the participants started to swallow at their own pace. A button, corresponding to a signal that indicated the onset of swallowing, was subsequently pressed by the participant. Measurements were taken three times for each test food. If swallowing of a particular test food was deemed to pose a high risk of aspiration, measurement was discontinued.

Analysis of sEMG

For the analysis of sEMG, we used the BIOPAC® MP150 system (Biopac Systems Inc., Goleta, CA, USA) and AcqKnowledge® software version 4.1 (Biopac Systems Inc.). The experiment was performed according to the protocol described in a previous study.[6] A frequency band of 100—200 Hz was extracted from the electromyography waveforms by using a bandpass filter. Subsequently, full-wave rectification and smoothing were performed by using a low-pass filter with a frequency of 10 Hz (Fig. 2).

The onset and offset of swallowing waveforms were defined in reference to the studies by Crary and Baldwin[11] and Sugita et al.[12] Two blinded computer operators

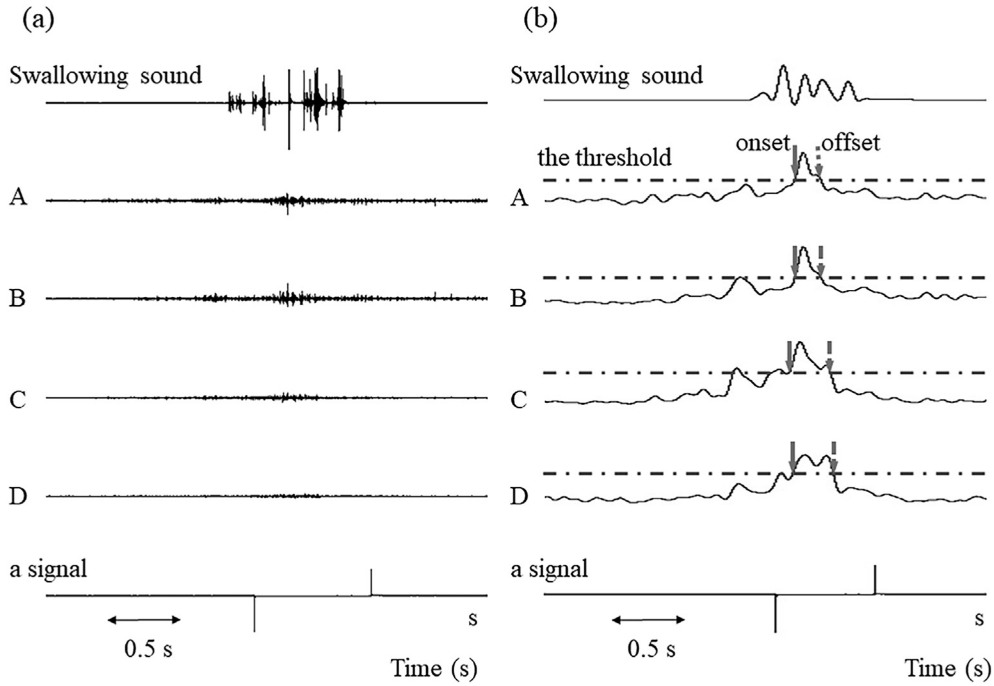

Figure 2 Examples of waveforms before and after preprocessing at each electrode position and swallowing sounds. (a) Before preprocessing. (b) After preprocessing. From the top: Swallowing sounds, waveforms at positions A, B, C, and D, and a signal that indicated the onset of swallowing. The threshold of the muscle activity was not calculated but determined visually; it was set at an approximately two-fold larger value than the average of the amplitude when there was a much lower surface electromyography response, lasting for approximately 0.5 s. Onset was defined as the beginning of the swallowing waveform, whereas offset was defined as the end of the swallowing waveform. The vertical axis of each electrode position and swallowing sounds are optimized in (b).

observed the onset and offset of the swallowing waveform and met regularly with researchers to unify their evaluations. The swallowing waveform was recorded such that the waveform had the largest and clearest amplitude at 2 s before and 2 s after the most pronounced swallowing sound and around the signal that indicated the start of swallowing. With respect to the waveforms, "onset" was defined as the beginning of the swallowing waveform, whereas "offset" was defined as the end of the swallowing waveform. With respect to time, "onset" was defined as the time when the value of the sEMG voltage exceeded a the threshold, whereas "offset" was defined as the time when the voltage fell below that threshold. The threshold of the muscle activity was set at a value approximately two-fold larger than the average of the amplitude when there was a substantially lower sEMG response, lasting for approximately 0.5 s. This threshold was not calculated but determined visually. If the time at which the participant pressed the button as a signal that he/she was going to swallow was not close to the swallowing sound, the waveform nearest the most pronounced swallowing sound was prioritized as the swallowing waveform. We excluded measurements for which the onset and offset of swallowing were unclear in more than one of the four positions (A, B, C, and D). Additionally, we excluded measurements where the waveforms did not exceed the threshold, repeating waveforms exceeded the threshold, waveforms occurred before the onset and after the offset, and waveforms occured near unclear swallowing sounds.

Data assessment

The primary parameters of the sEMG outcome were the duration of muscle activity and the delay times of the sEMG activities. The duration of muscle activity was defined as the time elapsed between the onset and offset of the swallowing waveform.[6] The delay times corresponded to the time elapsed from the onset of position A to the onset of positions B, C, andD. The duration of muscle activities in positions A, B, C, and D and the delay times were compared between participants with and without dysphagia for each food type.

Statistical analysis

The quartile was obtained by using Tukey's hinge method. The median differences in the duration of muscle activity and the delay times between the two groups were analyzed by using the Mann—Whitney *U* test. All statistical analyses were performed by using IBM SPSS Statistics for Windows, version 26 (IBM Corp., Armonk, NY, USA), and a probability value of <0.05 was considered statistically significant.

Results

The characteristics of the participants are summarized in Table 2. In total, 21 patients with dysphagia (mean age, 81.6 [standard deviation, 10.1] years) and 41 without dysphagia (mean age, 70.0 [8.4] years) were included. There were no statistically significant differences in sex distribution between these two groups.

Table 2 Characteristics of the participants.

	n	(Men/Women)	Mean Age, years [SD]
With dysphagia	**21**	**(10/11)**	**81.6 [10.1]**
Participants with brain disorders	**10**	**(7/3)**	
Cerebral infarction	*8*	*(7/1)*	
Cerebral hemorrhage	*2*	*(0/2)*	
Participants with respiratory disease	**2**	**(2/0)**	
Emphysema	*1*	*(1/0)*	
Chronic obstructive pulmonary disease	*1*	*(1/0)*	
Participants with other diseases	**9**	**(1/8)**	
Without dysphagia	**41**	**(25/16)**	**70.0 [8.4]**
Participants with brain disorders	**5**	**(3/2)**	
Cerebral infarction	*4*	*(3/1)*	
Brain tumor	*1*	*(0/1)*	
Participants with respiratory disease	**0**		
Participants with other diseases	**29**	**(20/9)**	
No medical history	**7**	**(2/5)**	

Participants with dysphagia were classified into groups of those with brain disorder, respiratory disease, or other diseases, according to the cause of dysphagia.
SD: standard deviation.

The number of participants and measurements obtained for sEMG analyses in each swallowing task are summarized in Table 3. Initially, we planned 744 measurements (four test foods × three exams × 62 participants); however, six measurements (three exams in two test foods; jelly and liquid) were canceled to prevent aspiration in one patient with dysphagia. Therefore, 738 sEMG data points were collected, of which 122 measurements were excluded for exhibiting an unclear onset or offset in more than one position, a success rate of 83.5% (616/738). The success rates for participants with and without dysphagia were 74.8% (184/246) and 87.8% (432/492), respectively.

Comparison of the duration of muscle activity between participants with and those without dysphagia

The median and interquartile range of the duration of muscle activity in each position during each swallowing task are summarized in Table 4. When jelly was swallowed, the duration of muscle activity was significantly shorter in participants with dysphagia than in those without dysphagia at positions C (Mann—Whitney U test, $P = 0.007$) and D ($P = 0.018$). When thickened water was swallowed, the duration of sEMG activity at position C was significantly shorter in participants with dysphagia than in those without dysphagia ($P = 0.033$).

Comparison of delay time of the sEMG activities between participants with and those without dysphagia

There was no difference in any of the delay times (A—B, A—C, and A—D) between the groups (Table 5). The largest apparent difference between groups, although not statistically significant, was observed in the delay time (A—D) while swallowing paste (Mann—Whitney U test, $P = 0.08$), with the delay time in participants with dysphagia being <0 s.

Table 3 Values obtained for the sEMG analysis in each swallowing task.

Swallowing task	Group (number of participants)	Number of measurements (participants)		Percentage of data available
		Values obtained	Values used for analysis[a]	
Jelly	With Dysphagia (21)	60 (20)	45 (19)	75.0
	Without Dysphagia (41)	123 (41)	106 (40)	86.2
Paste	With Dysphagia (21)	63 (21)	49 (21)	77.8
	Without Dysphagia (41)	123 (41)	103 (39)	83.7
Thickened water	With Dysphagia (21)	63 (21)	45 (17)	71.4
	Without Dysphagia (41)	123 (41)	112 (39)	91.1
Liquid	With Dysphagia (21)	60 (20)	45 (16)	75.0
	Without Dysphagia (41)	123 (41)	111 (40)	90.2

sEMG: Surface electromyography.
[a] We excluded 122 out of the 738 values because the onset or offset of swallowing was unclear in more than one position.

Table 4 Comparison of the duration of muscle activity in each position between participants with and those without dysphagia in each swallowing task.

		Duration of muscle activity, s [median (25th percentile–75th percentile)]							
		Position A	*P*	Position B	*P*	Position C	*P*	Position D	*P*
Jelly	With Dysphagia (19)	**0.29** (0.19–0.40)	0.183	**0.28** (0.18–0.40)	0.070	**0.30** (0.18–0.46)	0.007	**0.32** (0.26–0.45)	0.018
	Without Dysphagia (40)	**0.35** (0.27–0.50)		**0.43** (0.27–0.54)		**0.45** (0.32–0.58)		**0.45** (0.34–0.57)	
Paste	With Dysphagia (21)	**0.32** (0.21–0.38)	0.255	**0.43** (0.26–0.59)	0.598	**0.33** (0.21–0.47)	0.056	**0.44** (0.27–0.57)	0.325
	Without Dysphagia (39)	**0.36** (0.29–0.45)		**0.48** (0.36–0.57)		**0.46** (0.32–0.57)		**0.47** (0.34–0.60)	
Thickened water	With Dysphagia (17)	**0.33** (0.27–0.47)	0.612	**0.33** (0.28–0.45)	0.094	**0.39** (0.22–0.45)	0.033	**0.38** (0.30–0.44)	0.079
	Without Dysphagia (39)	**0.38** (0.28–0.49)		**0.47** (0.32–0.58)		**0.49** (0.33–0.62)		**0.47** (0.34–0.61)	
Liquid	With Dysphagia (16)	**0.38** (0.29–0.46)	0.814	**0.46** (0.36–0.55)	0.892	**0.48** (0.31–0.57)	0.863	**0.47** (0.31–0.54)	0.670
	Without Dysphagia (40)	**0.38** (0.27–0.45)		**0.47** (0.35–0.57)		**0.45** (0.36–0.61)		**0.45** (0.35–0.57)	

P: Mann–Whitney *U* test; square bracket: $P < 0.05$.

Discussion

In this study, we improved the method of determining the start and end times of swallowing muscle activity with the sEMG waveform data. In a previous study, the data acquisition success rate was 65% in patients with dysphagia when using the threshold method.[6] In this study, we adopted a visual method to increase the data acquisition rate. Consequently, we could use data with a large amount of noise. The data acquisition rate for all participants was 83.5%. Compared to the previous study,[6] the acquisition rate in participants without dysphagia decreased from 89% to 87.8%, whereas the acquisition rate in those with dysphagia improved from 65% to 74.8%. In determining the onset and offset of swallowing with the threshold method, the value of the resting baseline interval affects the threshold, which corresponds to the times of onset and offset of swallowing muscle activity. Therefore, waveforms that did not clearly correspond to a state of not swallowing may be deemed as swallowing waveforms if the data indicated a large swallowing waveform around the swallowing sound. If the threshold is high, swallowing waveforms may not be detected. The visual method improved upon the abovementioned factors. However, the data acquisition rate is still not ideal; hence, it is necessary to improve the methodology.

Evaluation with the multiple-sensor sheet revealed statistically significant differences between the groups. During the swallowing of jelly and thickened water, the duration of muscle activity in the infrahyoid muscles of patients with dysphagia was statistically significantly shorter than that of those without dysphagia. Conversely, no statistically significant differences in the duration of muscle activity was observed when swallowing liquid. Differences in the duration of muscle activity are affected not only by the swallowing function but also by physical properties, as liquid is less viscous.[13–17]

It was previously reported that the duration of muscle activity in the infrahyoid muscle group was prolonged in patients with dysphagia during swallowing of thickened water and yogurt.[6] This is not compatible with our current results, which may be because of study cohort differences. Previous studies included patients with structural disorders who underwent head and neck reconstruction and those with severe dietary restrictions. In this study, test foods were selected to prevent aspiration according to previous findings in swallowing videofluorography, and 20 of the 21 patients with dysphagia in this study had no restrictions and were able to eat the prescribed test foods. Therefore, the severity of dysphagia in patients with dysphagia was lower in this study. Furthermore, while swallowing paste, the infrahyoid muscle group (position D) was activated earlier than the suprahyoid muscle group (position A) in patients with dysphagia; however, the difference between participant groups was not statistically significant. In a previous study, the infrahyoid muscle group-initiated muscle activity was earlier than the suprahyoid muscle group-initiated muscle activity among patients with dysphagia.[6] These findings are consistent with the current study results. Paste requires more muscle activity during swallowing than other test foods, and disorganized coordination of muscle activity may be a characteristic of patients with dysphagia.

This study has two main limitations. The first is the reproducibility and reliability of the visual method.[18] Although the success rate in patients with dysphagia increased with the use of the visual method, three or more people should observe the swallowing sEMG waveforms and discuss the results to improve the reproducibility and reliability. Unclear waveforms that were not used in the analysis were frequent in patients with dysphagia, in whom fluctuations of the sEMG waveform were likely to occur. Therefore, a more accurate detection method is required. The duration and onset time of muscle activity may differ depending on the method used to determine the swallowing

Table 5 Comparison of the delay time of the sEMG activities in each position between participants with and those without dysphagia in each swallowing task.

Swallowing task	Group (number of participants)	Delay time, s [median (25th percentile—75th percentile)]					
		[A—B][a]	*P*	[A—C][b]	*P*	[A—D][c]	*P*
Jelly	With Dysphagia (19)	**0.00** (−0.09—0.23)	0.75	**0.00** (−0.16—0.12)	0.85	**0.08** (−0.05—0.23)	0.74
	Without Dysphagia (40)	**0.00** (−0.07—0.05)		**0.00** (−0.10—0.16)		**0.02** (−0.10—0.19)	
Paste	With Dysphagia (21)	**0.00** (−0.30—0.04)	0.41	**0.02** (−0.01—0.22)	0.43	**−0.05** (−0.33—0.07)	0.08
	Without Dysphagia (39)	**0.00** (−0.09—0.09)		**−0.01** (−0.14—0.15)		**0.05** (−0.05—0.40)	
Thickened water	With Dysphagia (17)	**0.06** (−0.07—0.19)	0.60	**0.03** (−0.09—0.10)	0.71	**0.00** (−0.11—0.25)	0.49
	Without Dysphagia (39)	**0.00** (−0.02—0.04)		**0.00** (−0.16—0.22)		**0.02** (−0.11—0.30)	
Liquid	With Dysphagia (16)	**0.00** (−0.15—0.06)	0.22	**0.00** (−0.26—0.15)	0.41	**0.00** (−0.35—0.21)	0.15
	Without Dysphagia (40)	**0.00** (−0.05—0.16)		**0.00** (−0.05—0.12)		**0.06** (−0.05—0.34)	

A negative value means that the onset of position A was later than that of the other position.
P: Mann—Whitney *U* test.
sEMG: Surface electromyography.
[a] The delay time from the onset at position A to the onset at position B.
[b] The delay time from the onset at position A to the onset at position C.
[c] The delay time from the onset at position A to the onset at position D.

electromyogram.[19] Second, the patients' histories of dysphagia were heterogenous. Because of the differences in sEMG pathophysiology, it is necessary to standardize the participants' history, increase the data acquisition rate, and compare the data with those of participants without dysphagia; patients with different swallowing pathologies should not be included in one group. Therefore, further studies are required to compare sEMGs in participants with the same underlying disease.

The present study indicates that swallowing function can be evaluated by using a multiple-sensor sheet with visual methods of identification of muscle activity.

Declaration of competing interest

The authors' institutions (Shinshu University, Nagano Prefecture, SKINOS) have issued patents (patent numbers 6073709, 6802470, and 6802467) and the following pending patents: patent application numbers JP 2021-086653, and JP 2020-132080. Moreover, Mr. Momose is the chief executive officer of SKINOS.

Acknowledgments

We would like to thank Editage (www.editage.com) for English language editing. We would also like to thank the patients and staff at the Omachi General Hospital who participated in the experiments. The present study was supported by the Japan Society for the Promotion of Science KAKENHI (Grant Number JP18K18420, Ministry of Education, Culture, Sports, Science and Technology, Japan) and the Strategic Information and Communications R&D Promotion Programme (2019—2021) (Ministry of Internal Affairs and Communications).

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