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Original Article

Detection of swallowing disorders using a multiple channel surface electromyography sheet: A preliminary study

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KEYWORDS
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Abstract *Background/purpose:* We invented a sensor sheet with multiple electromyogram electrodes, which can be easily attached to the front of the neck, to evaluate surface electromyograms (sEMG) during swallowing function. In this paper, we evaluated sEMG in healthy volunteers and dysphagia patients using the sensor sheet and discussed its potential to evaluate swallowing function.
Materials and methods: Ten healthy volunteers (age, 29.5 ± 3.9 years) and 18 clinically diagnosed dysphagia patients (age, 67.8 ± 12.1 years) were included. The sensor sheet had four pairs of electrodes, and sEMG at the suprahyoid muscles (positions A and B) and the infrahyoid muscles (positions C and D) were recorded while swallowing water, thickened water, yogurt, and jelly; sEMG findings were compared between these positions.
Results: Significant differences in the duration of muscle activity was observed when swallowing yogurt at position D and when swallowing jelly, thickened water, and water at position B (Mann–Whitney U test, $p < 0.05$). In healthy volunteers, muscle activation typically began from positions A or B to position D, whereas in dysphagia patients, it sometimes began from position D.
Conclusion: There were significant differences in duration and sequence patterns of four sEMG activities between healthy young volunteers and dysphagia patients in the assessment using the sensor sheet, although some technical and scientific problems remained

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unresolved. These results indicate that swallowing function could be evaluated using the sensor sheet.

Introduction

Swallowing is a complex, sensorimotor process involving sequential oropharyngeal muscle activation. Swallowing and respiration coordination are monitored using videofluoroscopic examination of swallowing (VF), videoendoscopic evaluation of swallowing, pharyngeal manometry,[1] piezoelectrical sensor measurements,[2] recording swallowing sounds,[3] and surface electromyography (sEMG). These methods are sometimes complex and invasive; establishing simple and noninvasive means for evaluating swallowing function would allow more widespread examination/rehabilitation, thus improving patients' quality of life.

Recently, sEMG has been receiving increased attention to evaluate swallowing.[4–6] Perlman[7,8] suggested that sEMG is useful for objectively estimating swallowing function. Vaiman et al.[9,10] suggested that sEMG is an effective objective method for evaluating swallowing function. Measuring tools should be reliable, noninvasive, radiation-free, inexpensive, efficient, and simple to operate. sEMG has not been widely used as it requires anatomical knowledge because electrodes should be attached at appropriate positions.[11] Most human studies on sEMG have concentrated on single muscle or muscle pair activity. We recently invented a sEMG sensor sheet comprising multiple electromyogram electrodes that can be easily attached to the front of the neck.[12] The sensor sheet can measure various muscle activities (suprahyoid and infrahyoid muscles) related to swallowing; thus, it can easily and noninvasively measure muscle activity during swallowing.

We used the sensor sheet to evaluate swallowing function in healthy volunteers and dysphagia patients and discussed its possibility for monitoring swallowing function.

Table 1 Characteristics of patients in this study.

	N	(Men/Women)	Age (mean ± SD)
Dysphagia patients			
Patients with brain disorder	**6**	**(4/2)**	69.7 ± 16.5
Cerebral infarction	2	(2/0)	
Chronic subdural hematoma	1	(0/1)	
Large occipital meningioma	1	(1/0)	
Frontotemporal lobar degeneration	1	(0/1)	
Subarachnoid hemorrhage	1	(1/0)	
Head and neck reconstructed patients	**6**	**(6/0)**	68.7 ± 10.5
Cancer of oral floor	3	(3/0)	
Tongue cancer	2	(2/0)	
Sublingual adenocarcinoma	1	(1/0)	
Patients with disuse atrophy	**6**	**(5/1)**	65.0 ± 9.8
Schizophrenia	1	(1/0)	
Fever of unknown etiology	1	(1/0)	
Acute aortic dissection	1	(1/0)	
After surgery of ovarian cancer	1	(0/1)	
Mitral insufficiency	1	(1/0)	
Angina	1	(1/0)	
Healthy volunteers	**10**	**(8/2)**	29.5 ± 3.9

Patients were classified into three groups based on the cause of dysphagia: brain disorder, head and neck reconstruction, or disuse atrophy.
SD: standard deviation.

Materials and methods

The Ethics Committee on Medical Research of Shinshu University approved this study protocol (approved no. 3179). All participants provided written informed consent. This study was conducted according to the principles and guidelines of the Declaration of Helsinki and its latest amendments.

Participants

Altogether, 10 healthy volunteers (mean age, 29.5 ± 3.9 years; eight men and two women) and 18 patients (mean age, 67.8 ± 12.1 years; 15 men and three women) with clinically diagnosed dysphagia participated. Table 1 summarizes the characteristics of patients in this study. All participants were aged >20 years. Healthy volunteers had repetitive saliva swallowing test scores of ≥3 and modified water swallowing test scores of ≥4. Dysphagia patients comprised those with brain disorder, head and neck reconstruction, or disuse atrophy. Exclusion criteria included embedded pacemaker; dermatitis grade ≥2; barium allergy; consciousness disorder; pneumonia; enteron enteric perforation, bleeding acutely in an enteron enteric blockade perforation; bleeding and enteronenteric blockade including the fear such as suspected cases and their doubt; medical history of allergy of the test foods; experience of skin symptoms including contact dermatitis; pruritus, eczema, erythema, and subcutaneous bleeding, etc. induced by the sensor sheet; pregnant or with possibility of pregnancy; and patients otherwise judged by the principal investigator as unsuitable.

Test foods

Four test foods were prepared. All liquid and solid food items were kept at room temperature. These test foods, except Barley jelly, mixed with 40 w/v% barium sulfate (Fushimi Pharmaceutical Co., Ltd., Kagawa, Japan) liquid because electromyogram was conducted during the VF test, are mentioned below:

- **Barley jelly** (about 5 mm × 10 mm slice): made of 3 g of Softia TesCup®(Nuturi Co., Ltd., Mie, Japan), 100 g of barium sulfate, and 200 mL of room temperature water
- **Yogurt** (3 cm^3): (Kyodo Milk Industry Co., Ltd., Tokyo, Japan)
- **Thickened water** (3 mL): half-solid nutrient, made of dextrin thickener (Healthy Food Co., Ltd., Tokyo, Japan) at concentrations using 2%
- **Water** (3 mL)

Data collection (evaluation of swallowing)

sEMG using the sensor sheet was performed while participants swallowed each test food. The healthy volunteers sat on a chair with their head vertical to the Frankfort plane, while the patients adopted a sitting position appropriate for their physical condition. All participants were instructed to begin swallowing immediately after receiving a cue from the investigator. Each healthy volunteer performed three tasks with four different test foods. In dysphagia patients, test foods and number of each task were selected to prevent aspiration according to the previously obtained findings in VF.

Sensor sheets and laryngeal microphone

We invented a sEMG sensor sheet comprising multiple electrodes that measure supra and infrahyoid muscle activities while swallowing.[12,13] The sensor sheet comprises disposable electrodes N-01IS3® (Nihon Kohden Corp., Tokyo, Japan), a foam pad 75 A® (Nihon Kohden Corp., Tokyo, Japan), and single-sided skin tape#1776® (3M Japan Limited, Tokyo, Japan). The sensor sheet was height 150 mm × maximum width 62 mm; the size was determined based on the human cervical configuration.[14] The sensor sheet size was determined based on 93.6 mm, the average anterior neck length of young adults (18–29 years), and 77.9 mm, the average for the elderly (≥60 years). Maximum thickness of the sensor sheet was 3 mm. The sensor sheet is soft enough to bend naturally. The sheet was fixed based on the thyroid cartilage as a positioning mark. Eight electrodes were placed at four positions (positions A–D). A pair of electrodes was placed in each position 30 mm apart. sEMG of the four positions recorded surface muscle activities (position A: upper front of the suprahyoid muscles, position B; rear bottom of the suprahyoid muscles, position C: above the infrahyoid muscles, and position D: beneath the infrahyoid muscles) (Fig. 1). Laryngeal microphone SH-12jKL® (Nanzu Electric Co., Ltd., Shizuoka, Japan) was affixed to the inferior margin of the cricoid cartilage to monitor swallowing sound. The test was performed by well-trained researchers.

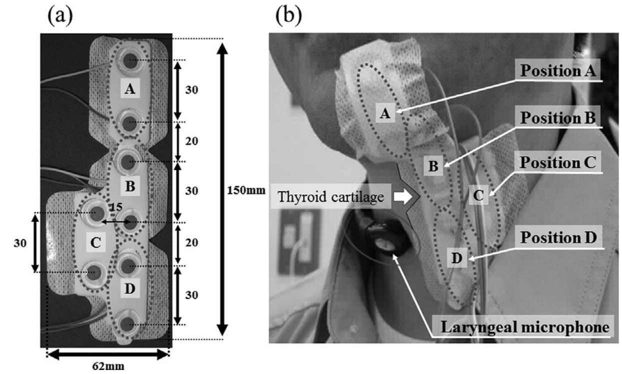

Figure 1 Layout of sensor sheet. (a) The back side of sensor sheet; (b) Photograph with sensor sheet and attached laryngeal microphone. Eight electrodes were placed at four positions (position A: upper front of the suprahyoid muscles, position B: rear bottom of the suprahyoid muscles, position C: above the infrahyoid muscles, and position D: beneath the infrahyoid muscles). A pair of electrodes was placed in each position 30 mm apart. A laryngeal microphone was affixed to the inferior margin of the cricoid cartilage to monitor swallowing sound.

sEMG analysis

For electromyogram and swallowing sound analyses, we used the BIOPAC MP 150 system and AcqKnowledge® ver. 4.1 software (Biopac Systems, Inc., Goleta, CA, USA). We used MATLAB 2016b® (Mathworks, Inc., Natick, MA, USA) for following signal processing. A frequency band of 100–200 Hz was extracted from the electromyogram waveforms using the bandpass filter. Full wave rectification and smoothing using a low pass filter of 10 Hz frequency were then performed.

A swallowing sound was generated when foods went through the throat; the time of the largest swallowing sound was defined as the time when the absolute value of the microphone voltage reached a peak. The thresholds for the activity onset and offset were defined as follows.[12] The threshold was set two-fold larger than the average sEMG amplitude of baseline interval in each position, which was the period when there was very less sEMG response for 0.5 s. The onset was defined as the time when the value of sEMG voltage exceeded a threshold, closest to the time of the largest swallowing sound, whereas the offset was defined as the time when the voltage fell below the threshold, closest to the time of the largest swallowing sound (Fig. 2). These analyses were performed by blinding to the participants' data. We have described the terms of sEMG parameters for analysis in the study:

- **Duration of muscle activity (the duration):** the time lapse between the onset and offset of swallowing.

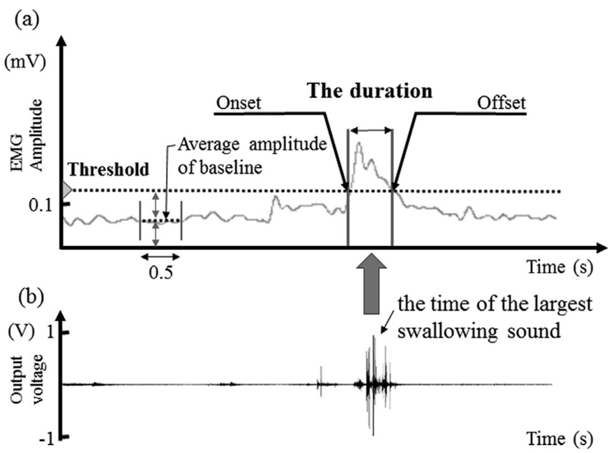

Figure 2 Analysis of sEMG.(a) Wave of muscle activity; (b) Swallowing sound. The threshold was set two-fold larger than the average sEMG amplitude of baseline interval in each position, which was the period when there was very less sEMG response for 0.5 s. The onset was defined as the time when the value of sEMG voltage exceeded a threshold, closest to the time of the largest swallowing sound, whereas the offset was defined as the time when the voltage fell below the threshold, closest to the time of the largest swallowing sound. Image is for illustration purposes.

- **Sequence patterns of four sEMG activities:** The order of the time for the onset of muscle activity at positions A, B, and D. Position C was excluded because it was close to the thyroid cartilage and unsuitable for sequence patterns.

Statistical analysis

Differences in the duration between healthy volunteers and dysphagia patients were tested using Mann–Whitney U test. Sequence patterns of the four sEMG activities were tested using Fisher's exact test. Moreover, these differences between males and females were tested in healthy volunteers and dysphagia patients. Statistical analyses were performed using IBM SPSS Statistics ver. 26.0® (IBM Corp., Armonk, NY, USA). Differences in the duration among healthy volunteers, brain disorder, head and neck reconstruction, and disuse atrophy were tested via Steel–Dwass test, using BellCurve® for Excel ver. 3.0 (Social Survey Research Information Co., Ltd, Tokyo, Japan). Further, $p < 0.05$ was considered statistically significant.

Results

Initially, we planned 30 measurements from 10 healthy volunteers and 54 measurements from 18 patients. However, in dysphagia patients, some test foods and measurements were avoided to prevent aspiration. Table 2 summarizes the numbers of measurements obtained for sEMG analyses in each swallowing task. Of these, 54 measurements were excluded because they showed unclear clear onset or offset. Accordingly, the success rate of value detection was 89% (107/120) in healthy volunteers but 65% (77/118) in dysphagia patients. The two groups showed few data deficiencies in swallowing water. The success rate of value detection was 41% (13/32) for swallowing jelly, yogurt, and thickened water in patients with brain disorder.

Table 2 Number of measurements obtained and analyzed for sEMG analyses in each swallowing task.

Swallowing task	Group	No. of measurements (No. of subjects)	
		Data obtained	Date analyzed
Jelly	**Dysphagia patients**	27 (9)	13 (4)
	Brain disorder	6 (2)	3 (1)
	Head and neck reconstructed	12 (4)	7 (2)
	Disuse atrophy	9 (3)	3 (1)
	Healthy volunteers	30 (10)	26 (10)
Yogurt	**Dysphagia patients**	44 (16)	28 (13)
	Brain disorder	17 (6)	9 (4)
	Head and neck reconstructed	14 (5)	10 (4)
	Disuse atrophy	13 (5)	9 (5)
	Healthy volunteers	30 (10)	26 (10)
Thickened water	**Dysphagia patients**	33 (11)	22 (9)
	Brain disorder	9 (3)	1 (1)
	Head and neck reconstructed	12 (4)	12 (4)
	Disuse atrophy	12 (4)	9 (4)
	Healthy volunteers	30 (10)	26 (10)
Water	**Dysphagia patients**	14 (7)	14 (7)
	Brain disorder	4 (2)	4 (2)
	Head and neck reconstructed	8 (3)	8 (3)
	Disuse atrophy	2 (2)	2 (2)
	Healthy volunteers	30 (10)	29 (10)

Values are expressed as number of measurements (number of subjects).
We excluded 54 of 238 measurements because they showed unclear onset or offset of swallowing.

Comparison of duration of muscle activity

Table 3 summarizes the comparison of the duration between healthy volunteers and dysphagia patients in each swallowing task. When swallowing yogurt, the duration was significantly longer in dysphagia patients than in healthy volunteers at position D ($p < 0.05$). When swallowing jelly, thickened water, and water, the duration at position B was significantly shorter in dysphagia patients than in healthy volunteers ($p < 0.05$).

When swallowing yogurt, the durations at positions A and D were significantly longer in female patients than in male patients ($p < 0.05$), whereas when swallowing thickened water, the duration at position C was significantly longer in male patients than in female patients ($p < 0.05$).

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Table 3 Comparison of the duration between healthy volunteers and dysphagia patients in each swallowing task.

Swallowing task	Group (No. of measurements)	The duration (s) Median 25 percentile -- 75 percentile Position A	p	Position B	p	Position C	p	Position D	p
Jelly	**Dysphagia patients (13)**	**0.07** **0.03 – 0.32**		**0.09** **0.02 – 0.68**		**0.92** **0.47 – 2.90**		**0.74** **0.29 – 4.49**	
	Brain disorder (3)	0.04 0.02 –		0.64 0.09 –		0.57 0.37 –		0.74 0.69 –	
	Head and neck reconstructed (7)	0.07 0.03 – 3.18		0.03 0.02 – 2.00	*	1.63 0.92 – 3.43		3.89 0.25 – 5.81	
	Disuse atrophy (3)	0.12 0.01 –		0.12 0.01 –		0.10 0.01 –		0.33 0.12 –	
	Healthy volunteers (26)	**0.34** **0.02 – 0.67**		**1.13** **0.60 – 1.48**		**0.81** **0.32 – 1.37**		**0.52** **0.11 – 0.83**	
Yogurt	**Dysphagia patients (28)**	**0.18** **0.05 – 5.10**		**0.68** **0.04 – 1.78**		**0.31** **0.06 – 1.34**		**0.98** **0.34 – 1.21**	
	Brain disorder (9)	0.15 0.12 – 4.52		0.75 0.08 – 2.02		0.25 0.10 – 1.45		1.18 0.91 – 1.35	
	Head and neck reconstructed (10)	0.50 0.03 – 6.24		1.10 0.03 – 3.50		0.31 0.04 – 1.82		0.68 0.36 – 2.21	*
	Disuse atrophy (9)	0.13 0.03 – 6.46		0.59 0.02 – 1.19		0.74 0.06 – 2.98		0.52 0.09 – 1.17	
	Healthy volunteers (26)	**0.10** **0.04 – 0.74**		**1.06** **0.71 – 1.73**		**0.72** **0.31 – 1.55**		**0.25** **0.03 – 0.92**	
Thickened water	**Dysphagia patients (22)**	**0.04** **0.02 – 0.33**		**0.26** **0.03 – 1.30**		**1.28** **0.57 – 2.61**		**0.71** **0.10 – 1.18**	
	Brain disorder (1)	5.92 not assessed		0.02 not assessed		0.37 not assessed		0.06 not assessed	
	Head and neck reconstructed (12)	0.07 0.02 – 0.27	*	0.21 0.02 – 1.39	*	1.54 0.94 – 2.72		0.28 0.04 – 0.86	
	Disuse atrophy (9)	0.03 0.01 – 0.35		0.56 0.15 – 2.06		0.65 0.37 – 3.11		0.91 0.58 – 1.86	
	Healthy volunteers(26)	**0.17** **0.04 – 1.10**		**0.95** **0.58 – 1.51**		**0.91** **0.27 – 1.32**		**0.36** **0.08 – 0.84**	
Water	**Dysphagia patients (14)**	**0.07** **0.03 – 0.31**		**0.56** **0.11 – 0.78**		**0.77** **0.15 – 1.95**		**0.74** **0.13 – 1.55**	
	Brain disorder (4)	0.31 0.20 – 0.92	*	0.61 0.28 – 0.74		0.40 0.11 – 1.06		0.20 0.09 – 1.12	
	Head and neck reconstructed (8)	0.04 0.03 – 0.05		0.26 0.01 – 0.72	*	1.05 0.14 – 3.06		0.97 0.56 – 2.25	
	Disuse atrophy (2)	8.86 0.22 –		1.56 1.19 –	*	1.16 0.62 –		0.41 0.07 –	
	Healthy volunteers (29)	**0.06** **0.03 – 0.63**		**0.81** **0.49 – 1.23**		**0.61** **0.44 – 1.25**		**0.47** **0.06 – 0.98**	

* $p < 0.05$, Mann-Whitney U test or Steel-Dwass test.
not assessed: data not displayed due to small number.

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Table 4 Comparison of sequence patterns of four sEMG activities between healthy volunteers and dysphagia patients in each swallowing task.

Swallowing task	Group (No. of measurements)	Sequence pattern AB→D	Sequence pattern D→AB	p
Jelly	**Dysphagia patients (13)**	8	5	
	Brain disorder (3)	2	1	
	Head and neck reconstructed (7)	3	4	n.s.
	Disuse atrophy (3)	3	0	
	Healthy volunteers (26)	23	3	
Yogurt	**Dysphagia patients (28)**	20	8	
	Brain disorder (9)	7	2	
	Head and neck reconstructed (10)	6	4	*
	Disuse atrophy (9)	7	2	
	Healthy volunteers (26)	25	1	
Thickened water	**Dysphagia patients (22)**	15	7	
	Brain disorder (1)	1	0	
	Head and neck reconstructed (12)	7	5	n.s.
	Disuse atrophy (9)	7	2	
	Healthy volunteers (26)	24	2	
Water	**Dysphagia patients (14)**	7	7	
	Brain disorder (4)	3	1	
	Head and neck reconstructed (8)	2	6	**
	Disuse atrophy (2)	2	0	
	Healthy volunteers (29)	27	2	

* $p < 0.05$, Fisher's exact test. ** $p < 0.01$, Fisher's exact test. n.s.: not significant.
AB→D: muscle activity starting point for positions A or B.
D→AB: muscle activity starting point for position D.
Position C was excluded because it was close to the thyroid cartilage and unsuitable for sequence patterns.

Comparison of sequence patterns of four sEMG activities

Table 4 summarizes the comparison of sequence patterns of four sEMG activities between healthy volunteers and dysphagia patients in each swallowing task. In healthy volunteers, muscle activation typically began from positions A or B to position D. In some dysphagia patients, muscle activation began from position D when swallowing some test foods. A significantly higher prevalence of inverted sequence pattern (from position D to positions A or B) was observed in dysphagia patients than healthy volunteers when swallowing water ($p < 0.01$). There was no significant difference between males and females in healthy volunteers and dysphagia patients.

Discussion

We used a multi-channel sEMG sheet to evaluate swallowing disorder. sEMG findings were significantly different between healthy volunteers and dysphagia patients. sEMG is reportedly effective in diagnosing pharyngeal phase dysphagia because each clinical condition tends to exhibit a characteristic sEMG waveform.[15] Accordingly, differences in the duration were noted between the groups in this study. Comparing the conventional sEMG evaluation, our sensor sheet's advantage is that it can be applied in a single action, with thyroid cartilage as a positioning mark. The layout from the thyroid cartilage at attachment mark of the sheet to each electrode is designed to be constant. Therefore, electrode layout reproducibility can be ensured even if the sensor sheet is replaced. Electrode positioning is important for swallowing electromyogram measurement;[11] the electrode attachment position is determined accurately by palpating the muscle position for each individual.[15–18] In the study finding, despite the ease of applying electrodes without palpation, the obtained results of sEMG were similar to those of the normal sEMG reported before. Another advantage was that the sensor sheet could easily analyze a sequence pattern of suprahyoid and infrahyoid muscle activities. In this study, a significantly higher prevalence of inverted sequence pattern was observed in dysphagia patients than in healthy volunteers. Conversely, the potential disadvantage is that it is not possible to freely change the position of the electrode according to individual differences because it is a fixed size. Accurately measuring representative sEMG may be difficult if the subject is out of averaged size; for example, in the case of children, different sensor sheet sizes are required.[12]

A unique finding was prolonged activation of the infrahyoid muscles and shorter activity of suprahyoid muscles. The longer duration in the infrahyoid muscle group in dysphagia patients was due to the lowering of the swallowing-related muscle strength and the timing of the initiation of swallowing muscle activity. Crary et al.[16] noted that prolonged activity of the infrahyoid muscle group in dysphagia patients may be caused by feelings of anxiety because these patients continued to experience difficulty when ingesting food. We presume that anxiety was also a factor in this study. Also, prolonged duration of muscle activity when swallowing was considered to be caused by effortful swallowing secondary to the lack of coordination of the swallowing muscles, which increases muscle activity amplitude. Theoretically, because they are antagonist muscles, activity of the infrahyoid muscle group should cause increased activity of the suprahyoid muscle group. However, we did not observe this pattern.

In this study, contrary to that observed in healthy volunteers, dysphagia patients often showed the following muscle activation pattern: infrahyoid muscle group activation followed by suprahyoid muscle group activation. Similarly, Ding et al.[19] reported that swallowing muscle activation in healthy individuals occurred in the following order: 1) orbicularis oris muscle, 2) suprahyoid muscle, and 3) infrahyoid muscle; moreover, Kim et al.[20] reported that patients with middle cerebral artery infraction had impaired muscle coordination and reduced duration of submental muscles activation compared with the healthy controls.

This study showed a problem in obtaining data in dysphagia patients. Although the efficacy of the data collection method itself has been proved in past research, it may not yet be applicable in some sEMG cases, including brain disorders in this study. In particular, the threshold method was used in this study, and the determination of swallowing onset was occasionally affected by noise[12,21] in the sEMG waveform; therefore, we excluded measurements not reaching the threshold. These data deficiencies are also considered to be influenced by biological causes and technical factors, including the recording electrodes' location in relation to the change of posture and variations in muscle size and activity among individuals (also between young and elderly patients). This reduced the number of measurements for our statistical analysis. In healthy volunteers, deficiencies in swallowing onset were few.

This study had another limitation. There was an unmatched sex and age distribution between dysphagia patients and healthy volunteers. In this study, we observed a slight difference in the duration between male and female patients. However, Vaiman et al. reported that there were no statistically significant sex-related differences in duration of muscles during single swallowing.[22] It is reported that the duration of oral and pharyngeal swallow is typically increased in older patients[17] and that the prevalence of dysphagia increases with age.[23] Moreover, lower laryngeal position due to aging[24] may have affected the results because the sheet is attached based on the larynx's position. However, in this study, sEMG was collected from young healthy volunteers to obtain ideal muscle activities during swallowing function, avoiding a possible influence duration increasing of aging. Therefore, it is impossible to conclude the significant difference in sEMG between the dysphagia and non-dysphagia in older subjects. Thus, the study to compare sEMG between age and sex-matched groups is ongoing.

Duration and sequence patterns of four sEMG activities were significantly different between young healthy volunteers and dysphagia patients in the assessment using the sensor sheet, although some technical and scientific problems remained unresolved. Our results indicate the possibility that swallowing function could be evaluated using the multiple sensor sheet.

Declaration of Competing Interest

The institution of the authors (Shinshu University, Nagano Prefecture, SKINOS) have issued a patent (Patent number 6073709) issued and have the following pending patents: Patent publication number JP 2016-154857, JP 2018-029634, and JP 2018-134125. Mr. Momose is chief executive officer of SKINOS. The authors declare no conflicts of interest other than above.

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