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A Predictive Model Based on Surface Electromyography to Assess the Easiness of Deglutition of Dysphagia Diets

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Abstract

Dysphagia diet is used for the people who have disorder of swallowing caused by aging or cerebral arterial diseases. The current standards for dysphagic diets are based on their physical characteristics. However, parameters that reflect the easiness of swallowing are also critical. Here, we developed a method to objectively evaluate the easiness of deglutition. First, we collected 68 terms that describe food textures related to easiness of deglutition, and selected 54 commercial dysphagia diets as samples. Using these terms and samples, we conducted a texture-perception questionnaire survey, and the results were subjected to a correspondence analysis. Referring to the results of this analysis, 10 textures that represent the easiness of deglutition were selected and dysphagia diets corresponding to each texture were selected as well. Then, sensory evaluation and surface electromyography (sEMG) of the anterior triangle of the neck (submental triangle) were recorded using these samples. We developed a predictive model for the easiness of deglutition by applying a partial least squares (PLS) regression technique to the sensory evaluation and sEMG data. Parameter fitting of the cross-validation model was significant (R^2, 0.87; RMSE, 0.34). The model accuracy was further investigated by fitting the model to test data, and results were again significant (R^2, 0.89; RMSE, 0.10). This indicates that our predictive model using sEMG measurements was highly accurate. Evaluating the easiness of deglutition with this predictive model will help identify and develop new foods that make swallowing easier for patients with dysphagia.

Keywords: Dysphagia; Sensory evaluation; Surface electromyography; Partial least square regression analysis; Aging; Submental triangle

Introduction

Recently, instances of aspiration pneumonia have led to an increased mortality rate in people of advanced age. As this is a disease caused by weakened swallowing of bolus, studying dysphagia–difficulty swallowing–has become especially important. In Japan, the standard diets for dysphagia are determined by the Japanese Society of Dysphagia Rehabilitation, which has two specifications: physical characteristics such as viscosity (assessed by the Line Spread Test) and thickness attributes. The Japan Consumer Affair Agency and Japan Care Food Conference have determined specifications for dysphagia diets that include desirable physical characteristics such as thickness attributes and ability to be swallowed. In the United States, the national standard for dietary treatment of dysphagia is based on food-texture and liquid levels [1]. However, for developing dysphagia diets, evaluating whether or not the food can be easily swallowed is crucial. Conventionally, a sensory test is carried out to evaluate the ease of swallowing, although reproducibility is difficult because of biased testing conditions and variation in individual evaluators. Here, we developed an objective method for more precisely assessing the ease with which diets designed for dysphagia can be swallowed.

By combing sensory data with the results of instrumental analysis, sensory evaluations can be correlated with objective factors. Partial least square (PLS) regression has been used to predict several lingual sensations. The bitterness of dairy protein hydrolysates was corresponded to the degree of hydrolysis which is analyzed by size-exclusive and reverse-phase chromatography elution patterns [2]. Additionally, PLS regression has shown that attributes of flavored mineral water are correlated with an electronic tongue device [3]. Thus, PLS analyses have been successful in providing datasets of instrumental measurement for variables that explain the sensations in the mouth during eating. Although the relationships between physical properties of food components and sensations have been investigated, reports of these relationships in physiological responses in human are limited.

Surface electromyography (sEMG) has been reported to provide a non-invasive method of assessing certain aspects of complex muscle activity for deglutition [4]. Miura et al. [5] reported that the carbonated or cooled beverages have effect on the submental muscles and these responses can be examined by sEMG. The aim of our present study was to develop a sEMG-based predictive model of easiness of deglutition by applying a PLS analysis to submental muscle contraction and sensory evaluations.

Materials and Methods

The schematic representation of study protocol is shown in Figure 1. All experiments were allowed by the ethics committee of the University of Tokyo. The application number is 16-26.

Participants

Forty-seven healthy young adults who had no current or past swallowing abnormalities (male, 9; female, 38; age, 19-30 years) participated in developing the predictive model and the cross validation dataset for sensory evaluation, and 10 different individuals (male, 5;

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female, 5; aged 22-24 years) participated in the sEMG measurement. A secondary test, validating the predictive model was carried out with test data set by 50 new participants (male, 24; female, 26; aged 22-25 years) for sensory evaluation and another 10 participants (male, 5; female, 5; aged 22-25 years) for sEMG measurement. Ten dysphagia patients (male, 5; female, 5; aged 57-86 years) participated to a sensory evaluation with the 4 experimental samples used for the test dataset. The objective of the experiment was explained to each participant, and an informed consent for use in publication was obtained for sensory evaluation and sEMG measurements.

Texture terms and dysphagia diets

Sixty-eight food-texture terms (Supplementary Table 1) that were related to the easiness of deglutition were selected from the list of 271 terms reported by Hayakawa et al. [6]. Fifty-four commercially available dysphagia diets (Supplementary Table 2) were used as candidate experimental samples. These included four categories of products (Class 1: easily masticated foods; Class 2: foods that can be mashed by gums; Class 3: foods that can be mashed by the tongue; Class 4: foods that do not need to be masticated and unidentified items). All foods were specified by the Japan Care Food Conference. Class-2 foods were not included as candidates because healthy evaluators found them difficult to eat.

Representative textures and experimental samples

Using the 54 commercially available dysphagia diets (Supplemantary Table 2), a texture perception questionnaire for the 68 textures was answered by five women who are well trained with sensory teste engaged in food-science research. The perception of each texture, such as sticky, was scored on 0 (imperceptible) or 1 (perceptible). The texture with total score more than 3 was selected for further analysis. 51 textures and 54 dysphagia diets were input into the correspondence analysis. To calculate the statistical distance between variables with each texture and diet sample, we transformed the data into a three dimensional scatter plot graph and examined their interrelations. Referring to this scatter plot, 10 representative textures which explain the deglutition comprehensively, were selected. And 10 dysphagia diet samples that were closely plotted to these textures were selected as experimental samples. All statistical analyses were conducted using JMP Pro 11.0.0 (SAS Institute Inc., SAS Campus Drive, Cary, NC, USA).

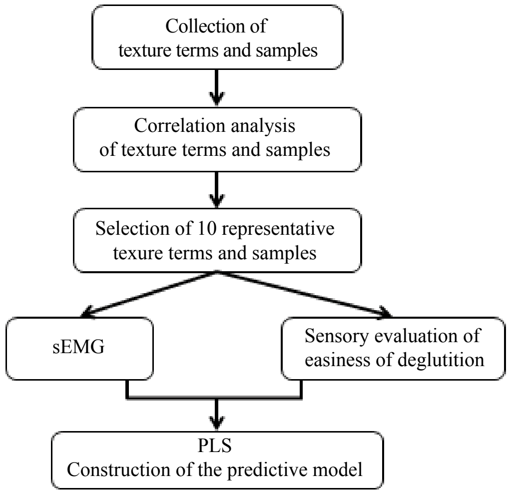

Figure 1: Schematic representation of study protocol.

Sensory evaluation

Using the 10 experimental samples, we conducted a sensory evaluation for the easiness of deglutition. In detail, experimental samples were given random code numbers and independently presented in a random order. The code numbers were attached to white paper cups (3 ounces, 90 ml) and 10 grams of each sample were put into each cup. The samples were tasted using a clear plastic spoon. All samples were provided at room temperature.

The easiness of deglutition was assessed by scoring in a 9-point scale. (-4, imperceptible; -3, very weak; -2, weak; -1, rather weak; 0, flat; 1, rather strong; 2, strong; 3, very strong; 4, extremely strong). Breaks were provided between evaluations, and participants were asked to drink rinse their mouths.

Surface electromyography

sEMGs were recording with a Personal EMG plus 8-channel computer-based EMG unit with Oisaka software (Oisaka Electronic Equipment, Hiroshima, Japan). Wet sensors (BLUE SENSOR, Ambu, Denmark) were taped to the right submental triangle where movements could be clearly detected. To ensure that the sensor was accurately attached, the skin was wiped with cotton dampened with 70% ethanol to remove sebum. The attachment points along the same muscle fiber were searched for during swallowing. Electrodes were taped in tandem at 1 cm distances. As a reference, a sensor was attached to the elbow bone on the opposite side of the dominant hand. Since the data were affected by the position of electrode, one series of test was performed at the same sensor position. The sampling speed was 3 kHz and the signals from the pair of electrodes were amplified 5,000 times. The original EMG was processed with full-wave rectification. Muscle activity was obtained from the integrated EMG wave. The duration of swallowing was defined as the onset of the rapidly increasing peak amplitude until the return of the trace to baseline surrounding the peak signal. The highest peak voltage ($V_{p\text{-}p}$) was obtained from the integrated EMG wave. Power frequency analysis was applied to the original EMG and power spectrum was carried out using the MemCalc/Win program (Suwa Trust, Sapporo, Japan) and the spectral density was obtained. Power spectral density (PSD) was obtained from the whole spectral area of spectral density. The low-frequency components were obtained from the spectrum area between 0.2-10 Hz spectrum area divided by the whole spectrum area, and high-frequency components are the spectrum area greater than 100 Hz divided by whole area (Figure 2).

Development of the predictive model using the cross-validation dataset

To develop a predictive model for the easiness of deglutition, a PLS analysis was conducted using the sEMG measurements as the explanatory variables, and the sensory evaluations as the response variable. NIPALS (Non-linear Interactive Partial Least Squares) and K-fold cross validation (K = 7) was applied to find the combination of the parameters that could precisely explain the objective variable. The precision of the predictive model was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE). PLS-VIP was applied for the selection of the explanatory variables using the variable importance in the projection (VIP) value and weight of the model (W) as the threshold values.

Validation using the test dataset

To verify the predictive model, we selected test samples from the 54 dysphagia diets, excluding the experimental samples used for

Sample ID	Ease of deglutition score	Muscle activity (mV·sec)	$V_{p\text{-}p}$ (mV)	Low-frequency component	High-frequency component	PSD (μV^2/Hz)
1	1.02 ± 2.18	1625.53 ± 174.31	0.62 ± 0.09	0.10 ± 0.02	0.42 ± 0.02	0.04 ± 0.01
2	1.93 ± 1.94	1637.50 ± 155.80	0.64 ± 0.06	0.13 ± 0.02	0.36 ± 0.02	0.04 ± 0.01
3	1.34 ± 1.90	1826.35 ± 164.57	0.72 ± 0.08	0.12 ± 0.02	0.39 ± 0.02	0.05 ± 0.01
4	2.20 ± 1.87	1512.43 ± 164.89	0.68 ± 0.09	0.10 ± 0.01	0.39 ± 0.02	0.04 ± 0.01
5	1.70 ± 2.19	1942.27 ± 189.01	0.76 ± 0.08	0.13 ± 0.02	0.37 ± 0.02	0.05 ± 0.01
6	2.54 ± 1.68	1559.80 ± 195.65	0.70 ± 0.10	0.12 ± 0.01	0.38 ± 0.01	0.04 ± 0.01
7	0.00 ± 1.88	2057.19 ± 175.97	0.80 ± 0.09	0.09 ± 0.02	0.39 ± 0.02	0.05 ± 0.01
8	0.72 ± 2.29	1590.52 ± 160.45	0.69 ± 0.09	0.09 ± 0.01	0.42 ± 0.02	0.04 ± 0.01
9	2.39 ± 1.77	1421.29 ± 156.56	0.67 ± 0.08	0.12 ± 0.01	0.41 ± 0.02	0.04 ± 0.01
10	3.23 ± 0.97	1367.46 ± 158.25	0.66 ± 0.10	0.10 ± 0.01	0.40 ± 0.02	0.04 ± 0.01

Table 1: Mean scores for the ease of deglutition (mean ± SD) was assessed by scoring in a 9-point scale (-4 to +4), muscle activity, $V_{p\text{-}p}$; the highest peak voltage, low-frequency component, high-frequency component, and PSD; power spectral density (mean ± SE) for each sample. Sample IDs refer to Figure 3.

Sample ID	Samples and textures	C1	C2	C3
a'	Smooth	0.64	-0.34	0.07
1'	Carrot paste	0.43	-0.6	0.12
b'	Residual feeling on the tongue; the material is viscous, sticky or piquant	-0.17	-0.16	0.05
2'	Shiso (Japanese basil) and seaweed mousse	0.07	-0.16	0.04
c'	Sticky, elastic, and chewy	-0.71	-0.02	0.52
3'	Rice gruel with vegetables and seaweed	-0.57	-0.04	0.48
d'	Jelly-like	1.03	0.52	0.17
4'	Pineapple-flavored jelly	0.86	0.32	0.15

Table 2: The four texture terms and products that made up the test dataset: texture terms (a'-d') correspond to products (1'-4'). (C1, C2, C3) are the 3D correspondence-analysis coordinates.

the primary examination. The samples which were closely plotted to the representative textures determined in section 2.3 were selected. Furthermore, four samples were collected and used for the predictive model development. Using the experimental samples, we evaluated sensations and sEMG measurements as described above. These resulting values were applied to the predictive model and the precision was evaluated by looking at the R^2 and RMSE values.

Results

Selected representative textures and experimental samples

The following food samples were selected from the correlation analysis: powdery, smooth, residual feeling on the tongue, melting, juicy, creamy, elastic, sticky, smooth, and jelly-like. The following dysphagia diets that best represented these textures were: sweetened green peas paste, macaroni and scallop gratin, rice porridge, pineapple and apple sauce, simmered cod dumplings, corn soup with kernels, meatloaf with brown sauce, bread mousse, strained pork-curry stew, and apple-flavored jelly (Figure 3).

Sensory evaluation

The jack-knife technique was used to detect outliers, which were then removed (upper control limit: UCL, 4.51 at α = 0.05). The mean values ± SD after removing the outliers are shown in Table 1. A Tukey-Kramer HSD test was applied to the sensory evaluation data, and the degrees to which experimental samples easy to swallow were compared. The highest gap was observed between apple-flavored jelly and meatloaf ($p < 0.00001$). This result suggests that jellies, which have high water content and cohesiveness, are perceived to be easy to swallow. In contrast, meatloaf, which feels like it absorbs saliva and clogs the throat, is thought to be difficult to swallow. Next, a sensory evaluation was conducted with dysphagia patients (male, 5; female, 5; aged 57-86 years) with the 4 experimental samples used for the test dataset. A correlation analysis showed that the senses of deglutition for healthy participants correlated significantly with those of dysphagia patients (r = 0.94; $p = 0.02$).

sEMG measurement

The jack-knife technique was used to detect outliers, which were then removed (UCL, 3.38 at α = 0.05). The mean values ± SD after removing the outliers are shown in Table 1. Because the relationship between physical stimuli and perceptions is logarithmic according to the Weber-Fechner law, the sEMG data were transformed to logarithmic values, which were then used in the following PLS-VIP analysis.

Development of the predictive model by PLS-VIP analysis

A predictive model for the easiness of deglutition was generated using a PLS-VIP analysis that incorporated the sEMG data as the explanatory variable. The number of latent variables was three when the cumulative contribution of the response was 87.47% and the cumulative contribution of the explanatory variable was 91.48%. All sEMG factors; muscle activity, low-frequency component, $V_{p\text{-}p}$, PSD and high-frequency component, satisfied the VIP threshold of greater than 0.8 except for high-frequency components. The VIP value obtained via PLS was used to estimate the response variable from the explanatory variables [7]. In general, predictive models using PLS-VIP are conducted by applying factors with VIP values greater than 0.8. However, because the R^2 value of the predictive model was higher when we included all sEMG factors, we included the high-frequency component in the explanatory variables. The weight of the model corresponds to the centralized data (Figure 4). As shown in Figure 4, the VIP value was highest for muscle activity, suggesting that it is most relevant to the easiness of deglutition. The model was applied to the dataset to validate the accuracy of the model. Figure 5 shows the relationship between the measured and predicted easiness of deglutition. The fitting parameters for the cross validation dataset were $R^2 = 0.87$ and RMSE = 0.34.

Validation using the test dataset

Four dysphagia diets, paste-formed carrot, shiso and seaweed mousse, rice gruel with vegetables and seaweed, and pineapple-flavored jelly were selected as experimental samples for obtaining the test dataset. These samples were closely plotted with the following food-textures: smooth, residual feeling on the tongue, sticky, and jelly-like (Table 2). The jack-knife technique was used for outlier detection and outliers were removed (sensory evaluation: UCL, 4.59; α = 0.05; sEMG: UCL, 3.43; α = 0.05). The easiness of deglutition and sEMG data is shown in Table 3. The model was applied to the test dataset to validate the accuracy of the model. Figure 6 shows the relationship between the measured and predicted values of the easiness of deglutition. The fitting parameters for the cross validation dataset were $R^2 = 0.89$ and RMSE = 0.10.

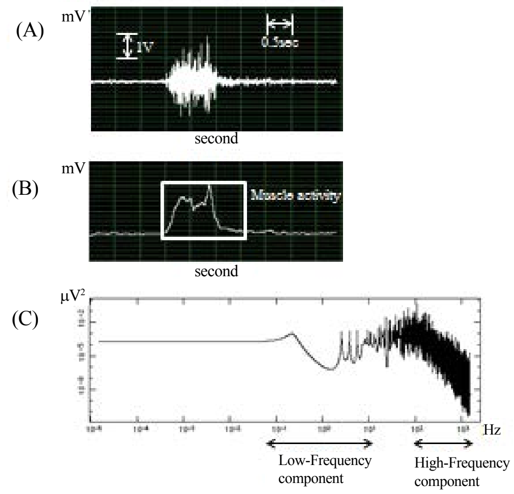

Figure 2: Parameters of surface electromyography (sEMG). (A) Original EMG wave (B) Integrated EMG wave (C) Spectral density.

Discussion

Here, we combined sEMG data recorded from the submental triangle during deglutition with sensory evaluations to determine factors that make swallowing easier. The VIP value obtained from the PLS regression analysis was highest for muscle activity and the correlation coefficient (r) between the easiness of deglutition and muscle activity was -0.86 (p = 0.07). Motor unit recruitment and muscle activity have been reported to be dependent on muscle contraction [8]. When participants feel that swallowing is easy, muscle activity gets likely decreased. Low-frequency components (VIP = 0.97), PSD (VIP = 0.92), and $V_{p\text{-}p}$ (VIP = 0.96) were also sEMG factors that satisfied the criterion of VIP > 0.8 (Figure 4). When muscles are exposed to continuous contraction, the wave of sEMG signals gradually becomes flat. This is thought to result from muscle fatigue, and frequency-spectrum analysis can be used to estimate the degree of fatigue. Although the physiological significance of frequency-spectrum analysis is not yet clear, an increase in low-frequency components (5-30 Hz) has been reported to be the most reliable index of fatigue [9]. PSD has also been reported to decrease with muscle fatigue [10]. sEMG amplitude is known to increase with muscle fatigue, and this is thought to result from an increase of motor units and impulse firing frequency, as well as synchronization of firing activity [11]. Although low-frequency components, PSD, and $V_{p\text{-}p}$ were found to contribute to the easiness of deglutition in our present study, the easiness of deglutition was only found to be significantly correlated with PSD

(A)

Sample ID	Symbol	Samples and textures	C1	C2	C3
a	▲	Powdery	0.05	0.04	0.78
1	●	Sweetened green pea paste	-0.27	-0.25	0.28
b	▲	Smooth	0.64	-0.34	0.07
2	●	Macaroni and scallop gratin	0.56	-0.46	0.19
c	▲	Residual feeling on the tongue; the material is viscous, sticky or piquant	-0.17	-0.16	-0.05
3	●	Rice porridge	0.13	0.06	-0.51
d	▲	Melting	0.32	0.14	-0.16
4	●	Pineapple and apple sauce	0.46	0.32	-0.31
e	▲	Juicy, broth not completely soaked in	0.35	0.79	0.26
5	●	Simmered cod dumplings	0.24	0.72	0.16
f	▲	Creamy	0.40	-1.09	0.20
6	●	Corn soup with kernels	0.28	-0.79	-0.20
g	▲	Elastic, springy	-0.37	0.39	0.40
7	●	Meatloaf with brown sauce	-0.39	0.10	0.51
h	▲	Sticky, elastic, and chewy	-0.71	-0.02	-0.52
8	●	Bread mousse	-0.82	0.15	0.14
i	▲	Smooth, fine	0.20	-0.36	-0.58
9	●	Strained pork-curry stew	0.17	-0.42	0.13
j	▲	Jelly-like	1.03	0.52	-0.17
10	●	Apple-flavored jelly	1.21	0.88	0.05

(B)

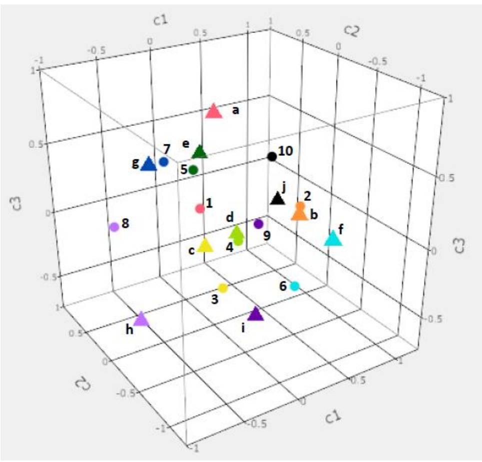

Figure 3: 10 representative food-quality terms and products. (A) List of samples (1-10) and their texture terms (a-j). (B) Three dimensional correspondence analysis scatter plot made from the coordinates (C1, C2 and C3).

Sample ID	Ease of deglutition score	Muscle activity (mV·sec)	$V_{p\text{-}p}$ (mV)	Low-frequency component	High-frequency component	PSD (μV²/Hz)
1'	2.43 ± 1.36	2910.00 ± 183.71	1.40 ± 0.11	0.09 ± 0.03	0.46 ± 0.02	0.10 ± 0.01
2'	0.73 ± 1.63	2890.50 ± 204.99	1.52 ± 0.09	0.07 ± 0.02	0.46 ± 0.01	0.12 ± 0.01
3'	-1.57 ± 1.39	3345.93 ± 280.26	1.69 ± 0.16	0.08 ± 0.03	0.46 ± 0.02	0.13 ± 0.01
4'	2.36 ± 2.04	2551.65 ± 174.79	1.38 ± 0.09	0.06 ± 0.02	0.45 ± 0.01	0.09 ± 0.01

Table 3: Mean scores for the easiness of deglutition (mean ± SD) was assessed by scoring in a 9-point scale (-4 to 4), muscle activity, Vp-p; highest peak voltage, low-frequency component, high-frequency component, PSD: power spectral density (mean ± SE) for each test data sample. Sample IDs refer to Table 2.

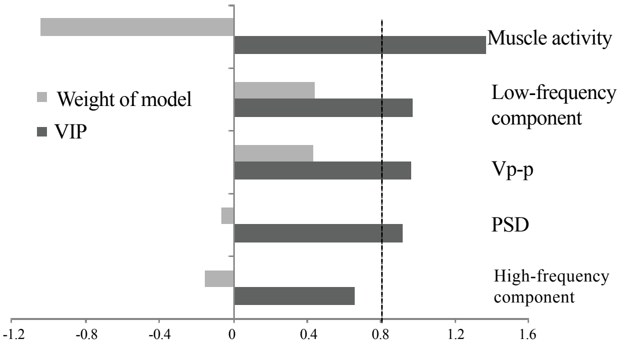

Figure 4: Degree of five sEMG factors contributed to the easiness of deglutition (threshold value; VIP = 0.80). (V_{p-p}: The highest peak voltage; PSD: Power Spectral Density and VIP: Variable Importance in the Projection).

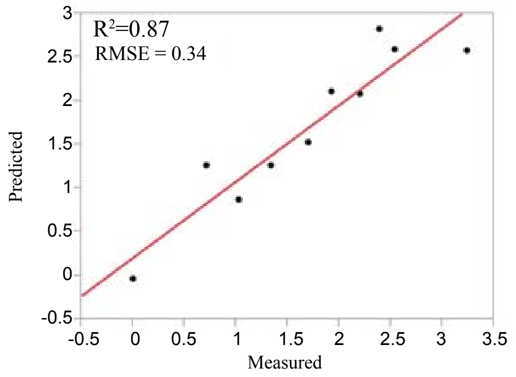

Figure 5: Relationship between the measured and predicted values for the easiness of deglutition using the cross-validation dataset. Red line: linear regression line, each plots were derived from 10 representative samples.

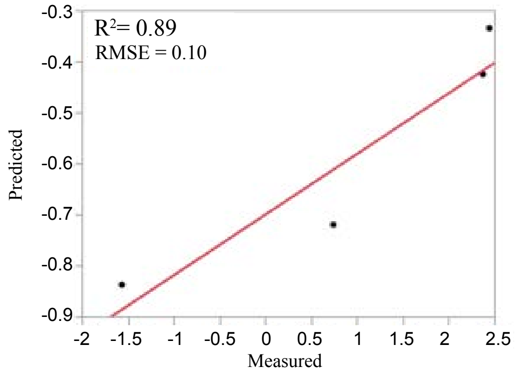

Figure 6: Relationship between the measured and predicted values for the ease of deglutition using the test dataset. Red line: linear regression line, each plots were derived from test samples.

(r = -0.91, p = 0.03) and V_{p-p} (r = -0.99, p = 0.0008). The finding that PSD and V_{p-p} are negatively correlated with the easiness of deglutition suggests that when swallowing becomes difficult, a response similar to muscle fatigue is taking place. The fitting parameters for the cross validation dataset (R^2, 0.87; RMSE, 0.34) and the test dataset (R^2, 0.89; RMSE, 0.10) signify the high accuracy of the predictive model. Thus, the predictive model was able to objectively evaluate the easiness of deglutition in healthy participants. However, to utilize this predictive model for developing dysphagia diets, we first need to determine whether it can be applied as accurately to dysphagia patients who are the primary beneficiary of these products. A sensory evaluation was thus conducted with dysphagia patients with the 4 samples used for the test dataset as a preliminary experiment. A correlation analysis showed that the senses of deglutition for healthy participants correlated significantly with those of some dysphagia patients. This suggests that the easiness of deglutition felt by dysphagia patients might be accurately predicted from sEMG measurements in healthy participants. Further experimentation with sufficient numbers of patients is needed in the future.

We conclude that sEMG measurements can be used for predictive modeling of deglutition ease in dysphagia diets. The procedure can be performed in a shorter time and with a smaller number of participants than are needed for the sensory evaluation, and can contribute to the evaluation and development of dysphagia diets.

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Texture terms	Japanese term	Texture terms	Japanese term
Rough, coarse	*Arai*	High water content	*Mizuke ga ōi*
Loose, primarily for foods consisting of many particles	*Barabara*	Juicy	*Mizumizushii*
Dry and rough, stale, implies the material is not compact	*Basabasa*	Watery	*Mizuppoi*
Sticky, viscous and watery; implies unpleasantness; the area where the material adheres is bigger than *Bechobecho/Bechot*	*Bechabecha*	Sticky, elastic and chewy	*Mocchiri*
Sticky, viscous and watery; implies unpleasantness; the amount of water is slightly larger than *Bechabecha/Bechari/Bechot*	*Bechobecho*	Dry and crumbly, implying a lack of moisture	*Mosomoso*
Sticky, the area where the material adheres is bigger than *Betobeto/Betot/Betotsuku/Bettori*	*Betabeta*	Thick and viscous, resistant to flow	*Mottari*
Sticky, implies a little bit of unpleasantness	*Betobeto*	Smooth	*Nameraka*
Crumbly, not compact and easily crumbled	*Boroboro*	Sticky, viscous and spinnable	*Nebaneba*
Dry, crumbly and not compact; implies staleness	*Bosoboso*	Sticky and viscous, implies wateriness; the area where the material adheres is bigger than *Nechonecho*	*Nechanecha*
Slippery, smooth and wet surface. Sounds and feels like when long thin noodles are slurped	*Churuchuru*	Sticky and viscous, implies wateriness	*Nechonecho*
Cream like	*Cream-jō no*	Pasty, glue-like	*Norijō no*
Creamy	*Creamy*	Slimy, surface covered with slime or mucus	*Numeri ga aru*
Elastic, springy	*Danryoku ga aru*	Slimy and slippery	*Nurunuru*
Thick, heavier than *Taratara*	*Daradara*	Loose, primarily for granular foods or many tiny particles; the particles are smaller and lighter than *Barabara*	*Parapara*
Thick and viscous	*Dorodoro*	Dry, stale	*Pasapasa*
Liquid	*Ekijyō no*	Thick, resistant to flow	*Potteri*
Soft and limp, flexible	*Funyafunya*	Soft elastic and resilient	*Purin*
Mushy; having lost its original shape through cooking, mixing, or mashing	*Guchagucha*	Soft elastic and slightly wobbly	*Purupuru*
Mushy; soft and watery; having lost its original shape through cooking, mixing, or mashing	*Guchogucho*	Light, thin, a state or behavior like flowing powders or thin liquids	*Sarasara*
Crumbly and soft	*Horohoro*	Fibrous	*Sen'ijō no*
Jelly-like	*Jelly-jō no*	Firm, solid	*Shikkari*
Hard, firm, stiff, tough, rigid	*Katai*	Juicy, broth not completely soaked in	*Shiruke ga ōi*
Lumpy, chunky	*Katamarijō no*	Residual feeling on the tongue; the material is viscous, sticky or piquant	*Shita ni nokoru*
Porridge-like	*Kayujō no*	Smooth and slippery	*Suberu*
Smooth, fine	*Kimekomakai*	Fluid, dripping	*Taratara*
Homogeneous	*Kin'itsuna*	Melting	*Torokeru*
Powdery	*Konappoi*	Slightly viscous	*Toromi ga aru*
Feels smooth in the mouth	*Kuchiatari ga yoi*	Smooth and viscous	*Torotoro*
Sticky	*Kuttsuku*	Beady, grainy	*Tsubujō no*
Mellow and soft	*Maroyaka*	Easy to crush or mash	*Tsubureyasui*
Sticky, difficult to remove material that adheres to eating utensils and teeth	*Matowaritsuku*	Beady, grainy, smaller and harder than *Tsubujō no*	*Tsubutsubu*
Thick, viscous and creamy; primarily for cream-like foods	*Mattari*	Smooth surface, slippery	*Tsurutsuru*
Honey-like	*Mitsujō no*	Soft, tender	*Yawarakai*
Dense	*Mitsuna*	Thin, loose, easy to deform	*Yurui*

S1 Table: Textures and their Japanese terms: 68 textures related to the easiness of deglutition extracted from 271 textures [6].

Sample	Classification (Japan Care Food Conference)	Sample	Classification (Japan Care Food Conference)
Strawberry-flavored jelly with pulp	3	Stewed soybean paste	4
Stewed sardines and plum mousse	3	Simmered cod dumplings	1
Sweetened green pea paste	4	Pineapple-flavored jelly	Unknown
Broiled eel in egg soup	3	Fried rice with chicken and ketchup	2
Pineapple-flavored pudding	3	Tuna-and-vegetable paste	4
Creamed shrimp and scallop	2	Corn soup with kernels	Unknown
Rice gruel with vegetables and seaweed	1	Tofu and eggs in starchy sause	2
Rice porridge with salmon	3	Chicken-and-vegetables paste	4
Macaroni and scallop grati	1	Simmered meat and potatoes	3
Rice porridge with crab	3	Meatballs in onion soup	1
Stewed pumpkin mousse	3	Stewed meatloaf	1
Stewed flatfish and Japanese radish	3	Carrot soup	Unknown
Simmered beef and burdock	2	Meatloaf in brown sauce	3
Pumpkin gratin	2	Bread mousse	3
Japanese wheat noodles with vegetables and tofu	2	Vegetable and seaweed mousse	3
Stewed freeze-dried tofu mousse	3	Pumpkin boiled in sugary syrup	3
Rice porridge, wheat, millet, beans and barnyard millet	Unknown	Broccoli mousse	3
Salmon and vegetables in egg sou^5	2	Strained pork-curry stew	4
Salmon mousse	3	Tofu and minced meat in spicy sauce	2
Shiso (Japanese basil) and seaweed mousse	3	Purple sweet potato mousse	3
Rice porridge	Unknown	Melon-flavored jelly	Unknown
Thin beef strips cooked with vegetables, tofu, and eggs	2	Corn paste	4
Pineapple and apple sause	4	Carrot paste	4
Steamed rice with red beans	3	Steamed rice	3
Grape-flavored jelly	4	Yuzu (Japanese citron) flavored jelly	4
Pear-flavored jelly	Unknown	Apple-flavored jelly	4
Japanese radish with minced chicken and starchy sauce	3	Chestnut-flavored mousse	3

S2 Table: Samples and classifications: 54 commercially available food samples. Classifications are based on the Japanese Care Food Conference. All samples were purchased from food companies in Japan.