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Effects of food texture and head posture on oropharyngeal swallowing

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Tsukada T, Taniguchi H, Ootaki S, Yamada Y, Inoue M. Effects of food texture and head posture on oropharyngeal swallowing. *J Appl Physiol* 106: 1848–1857, 2009. First published March 26, 2009; doi:10.1152/japplphysiol.91295.2008.—This study aimed to describe the electromyographic (EMG) activity patterns of the genioglossus (GG) and suprahyoid (SHy) muscles during swallowing. The effects of changes in food texture/consistency and head posture on transport of the swallowed bolus were also investigated. Participants were 10 normal adults. Test foods consisted of a liquid, a syrup, or 4 ml of paste made from 0.5% or 1.0% agar. Each food was swallowed with the head in one of three positions, and EMGs and videofluorographic (VF) images were recorded. Mean values of onset, peak, and offset times, peak amplitude, area, and duration of the EMG burst were measured. The total swallowing time, oral ejection time, pharyngeal transit time, clearance time, fauces transit time, and upper esophageal sphincter (UES) transit time were measured. The GG muscle burst patterns showed two peaks (GG1 and GG2) during each swallowing. The offset time and duration of the GG1 burst and the onset, peak, and offset times and duration of both the GG2 and SHy bursts were significantly affected by food texture. There were no significant differences in bolus transit time among the different experimental conditions. Regression analyses demonstrated significant linear relationships between the tongue tip touching the palate and the peak of the GG1 burst, between passage of the bolus tail at the fauces and offset of the GG1 burst, between passage of the bolus tail at the UES and peak of the GG2 burst, and between passage of the bolus tail at the UES and offset of the SHy burst. These results demonstrate that the duration, but not the amplitude, of tongue and suprahyoid muscle activity were increased with increasing hardness of food during swallowing and that the bolus transit time can be fixed within a certain range of physical food properties.

swallowing; genioglossus muscle; suprahyoid muscles; food texture; videofluorography

THE TONGUE CONTRIBUTES TO MANY oropharyngeal functions such as chewing, sucking, swallowing, respiration, and speech. During swallowing, the tongue plays a role in the formation, placement, and manipulation of a bolus during the oropharyngeal phase of swallowing, the posterior transfer of the bolus from the oral cavity to the pharyngeal cavity, and retraction against the pharyngeal wall to assist in moving the bolus into the upper esophageal sphincter (UES) (1, 17, 21). The structural characteristics of the tongue allow it to perform a wide range of movements with multiple degrees of freedom. Not only does it provide the anterior and lateral seals necessary for bolus containment, but it also generates pressure for bolus propulsion. The tongue is composed of intrinsic and extrinsic muscles. The longitudinal, transverse, and vertical intrinsic muscles have no bony attachment and determine the tongue's shape, whereas the extrinsic muscles have bony attachments and can control tongue protrusion and retrusion (17). The styloglossus and the hyoglossus are the main retrusor muscles, and the genioglossus (GG) is the main tongue protrudor. The suprahyoid muscles, including the mylohyoid, digastric, and geniohyoid, and the infrahyoid muscles, including the thyrohyoid, work together to fix and elevate the tongue, the hyoid bone, and the thyroid cartilage, while the suprahyoid also produces protrusion of the hyoid bone.

Electromyographic (EMG) activities of the human GG muscle have been recorded in previous studies using needle (18), wire (8, 20, 23, 29, 39, 40), and surface electrodes (5, 20, 22, 36). However, intraoral devices to record tongue muscle EMGs obviously interfere with the dynamic movements of the tongue itself. Although a few studies aimed at clarifying tongue movements and jaw/tongue coordination in humans have reported on the patterns of tongue muscle EMG activity, a quantitative analysis of GG muscle activity during swallowing has not yet been fully evaluated, and its functional role remains unclear. The first aim of the present study was to describe the EMG activity patterns of the GG muscle during swallowing.

Several reports have suggested that the basic neurophysiology of swallowing is fine-tuned in response to peripheral inputs (12, 19). The major effects of high bolus viscosity were a delay in oral and pharyngeal bolus transit, an increase in the duration of pharyngeal peristaltic waves, and prolonged and increased UES opening and esophageal peristalsis (4, 6, 14, 25, 26, 33, 35). It has also been reported that an increase in bolus volume had no effect on oral and pharyngeal bolus transit time and the duration of pharyngeal peristaltic waves but led to prolonged UES opening and laryngeal closure duration and longer swallowing apnea (2–4, 14). These findings suggested that bolus volume and viscosity affected swallowing in different ways. Regarding the effects of the food consistency on muscle activity during swallowing, a few studies have focused on EMG activity patterns. Ruark et al. recorded EMGs from the upper lip, lower lip, the submental area including the suprahyoid muscles, and the laryngeal strap muscles during swallowing boluses of different consistencies in children and adults (26). Only EMG bursts from the submental and laryngeal strap muscles showed significant differences in duration among the different foods. Reimers-Neils et al. also suggested that the duration of swallowing influenced by the submental and infrahyoid muscles increased significantly across the food consistency categories, from liquid to thick paste (25).

The effects of these factors on swallowing behavior are of interest to clinical researchers because restriction of diet consistency and/or volume is a common recommendation for individuals with oropharyngeal dysphagia. Although this strategy may reduce the risk of residue in the pharynx or penetration into the larynx, resulting in aspiration, little empirical

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evidence exists to support or guide the use of texture modification as an intervention for these patients.

The effect of head posture, such as head flexion or head rotation, on swallowing also requires investigation. The head flexed position is a postural technique frequently used as a compensatory treatment to eliminate aspiration (32), and this position has been reported to lead to narrowing of the laryngeal entrance and a posterior shift of the epiglottis, thus increasing airway protection (41). Head rotation, however, will divert material down the opposite pyriform sinus into the esophagus, bypassing the damaged area and allowing more efficient swallowing in patients with dysphagia (16). Although these techniques are now widely accepted by clinicians, the effects of changes in head position on the physiology of swallowing, and in particular on tongue function, have so far not been clarified. The second aim of the present study was to clarify the effects of changes in food texture/consistency and head posture on oropharyngeal swallowing, with emphasis on tongue and sublingual muscle function.

MATERIALS AND METHODS

Participants. Participants were 10 normal adults (eight men, two women) aged from 25 to 29 yr (mean ± SD age 26.6 ± 1.4 yr). All participants were healthy and had complete or almost complete dentition, i.e., except for the third molars. They had no signs of severe malocclusion, or masticating or swallowing problems. They also reported no history of pulmonary disease, neurological disease, structural disorders, language disorders, speech disorders, or voice problems. Informed consent was obtained from all participants, using a written form approved by the Ethics Committee of the Niigata University Faculty of Dentistry.

EMG recordings. A noninvasive bipolar surface electrode assembly was designed in our laboratory for recording GG muscle activity (Fig. 1). This was fabricated on a plaster cast of the lower dentition for each subject. The base was first made by using acrylic resin (Splint-Resin, GC), which was adjusted on the lingual face of the lower dentition and surrounding soft tissue. The lead cable made of polyester-coated silver wire was embedded in the base and exited the mouth between contralateral premolar teeth. At the tip of cable, a ball-type electrode, made of exposed silver with a diameter of 2 mm, was placed on the lateral side of the sublingual caruncle with an interelectrode distance of 10 mm.

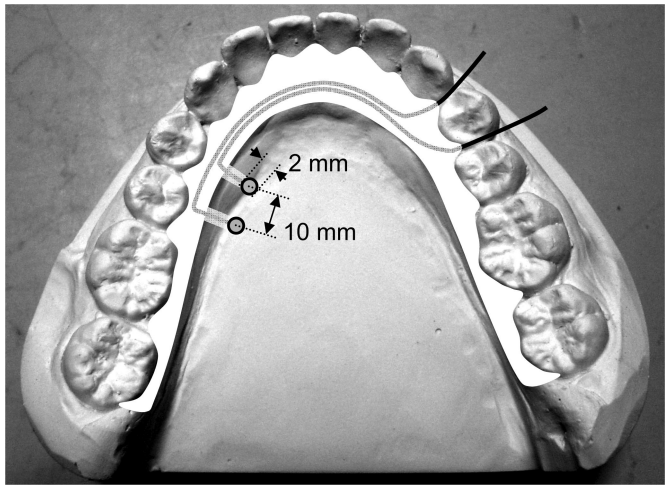

Fig. 1. Electrode unit for electromyographic (EMG) recordings of the genioglossus (GG) muscle.

Pairs of surface electrodes with a diameter of 8 mm (NT-211u or NT-212u, NIHON Kohden, Japan) were used for EMG recordings from the left suprahyoid muscle group (SHy) including the mylohyoid, geniohyoid, and anterior belly of digastric. Two electrodes were attached to the skin over the anterior belly of the digastric muscle with an interelectrode distance of 20 mm. A reference electrode was affixed to the earlobe.

In addition to EMG recordings, laryngeal movements during swallowing were simultaneously recorded using a pulse transducer (MLT1010, ADInstruments, Colorado Springs, CO) placed between the cricoid and thyroid cartilages at the midline. A laryngeal sensor was used to synchronize the EMG and video recordings, as described below (Fig. 2), although this was used only to record the initiation of swallowing, and no quantitative information on the magnitude of movement was obtained. The laryngeal sensor was lightly hit with a spoon before swallowing, with no complaints from the subjects. No EMG activities were evoked by hitting the sensor, and the procedure had no effect on swallowing.

Signals from EMG electrodes were amplified and filtered (low 30 Hz and high 2 kHz) (AB-651J, NIHON Kohden, Tokyo, Japan) to remove movement-related artifacts, and the amplified EMG signals and laryngeal sensor signals were stored on a personal computer. The sampling rate was 10 kHz, and the signals were passed through an interface board (PowerLab, ADInstruments). Data analysis was performed using the PowerLab software package (Chart 5 for Windows, ADInstruments).

Data collection. The experimental procedure has been described in previous studies (34, 35, 37).

Subjects sat on a chair with their heads unsupported. The reliability of the GG and SHy EMG recordings was confirmed by observing stable and repeatable activities of the muscles recorded in corresponding conditions: *1*) at rest, *2*) at maximum jaw opening (jaw opening), *3*) at maximum tongue protrusion (tongue protrusion), and *4*) back to neutral tongue position after tongue protrusion without jaw movement (tongue back). The subject was asked to maintain each position for 3 s.

Test foods with different physical properties were prepared for the swallowing tasks. These were 4-ml boluses of a half-solid nutrient made from agar powder (low gel strength agar, Ina Food Industry, Nagano, Japan) at either 0.5% (thin paste) or 1.0% (thick paste), a syrup (Blueberry syrup, Knott's), and a liquid. These materials were mixed with 40% wt/vol barium sulfate. Hardness, cohesiveness, and adhesiveness of the foods were measured using a creepmeter (RE2-3305, Yamaden, Tokyo, Japan) (Table 1). The order of hardness and adhesiveness was thick paste > thin paste > syrup > liquid. The viscosities of the syrup and liquid were also measured using a viscometer (TV-22, Toki Sangyo, Tokyo, Japan) (Table 1). The specimens were set on the table, and the loading cell was rotated at a speed of 50 revolutions/min. The viscosity of the pastes could not be measured because they were non-Newtonian fluids.

After one of the test foods was inserted into the mouth by the researcher, the subject kept it on the floor of mouth and then swallowed it on cue [dipper-type swallowing (3)]. During swallowing, recordings were made with the head in either the head-neutral position (Neutral), head-flexed position (Flex; head was flexed forward by 30°), or the head-rotated position (Rotation; head rotated left by 30°). The head position was maintained during a single swallowing task.

Three sets of data were collected for each task (i.e., each food type swallowed in each head position) during the recording period, giving a total of 36 recordings for each subject. The order of task completion was randomly determined by the researcher.

In addition to the EMG recordings, movements of the food bolus and the oral and pharyngeal organs of the subjects were observed using videofluorography (VF) equipment (MULTISKOP, Siemens, Munich, Germany) installed at Niigata University Medical and Dental Hospital. VF images were obtained in the sagittal plane at a speed of 25 frames/s. The data were then converted and stored on computer via

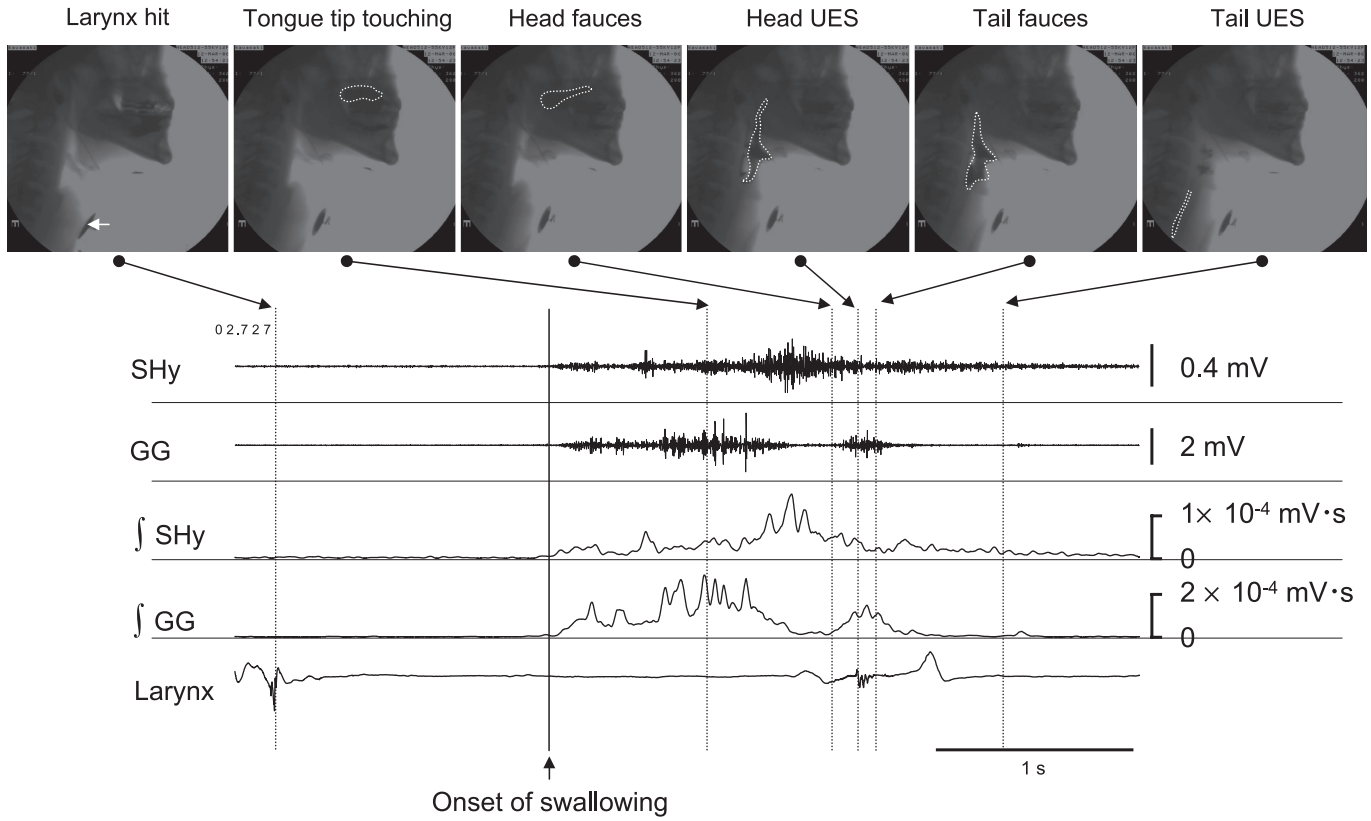

Fig. 2. Combined videofluorographic (VF) images, electromyographic (EMG) recordings of suprahyoid (SHy) and GG muscles, and signals from a laryngeal sensor during swallowing of liquid. EMG signals are shown as raw data of recordings (*top* two lines, GG and SHy) and rectified and smoothed recordings (*bottom* two lines, ∫GG and ∫SHy). A thick vertical line represents the onset of the SHy burst and the start of swallowing. Hitting the laryngeal sensor (Larynx) was used as a temporal reference to temporally align the EMG and VF images. This allowed us to extract and playback video images that corresponded in time with the EMG. Larynx hit, the frame when the larynx was hit; Tongue tip touching, the frame when the tongue tip touched the palate; Head fauces, the frame when the bolus head reached the fauces; Head UES, the frame when the bolus head reached the UES; Tail fauces, the frame when the bolus tail passed the fauces; Tail UES, the frame when the bolus tail passed the UES.

a video recorder (Handycam, Sony, Tokyo, Japan). VF recordings were made once for each task in each subject to minimize the X-ray exposure. Each task took <6 s, and the total X-ray exposure time was therefore limited to <2 min. Total exposure to radiation per session was estimated to be 89.77 mGy; i.e., the equivalent of 10 dental X-ray exposures.

Data analysis. EMG bursts were full-wave rectified and smoothed (time constant of 20 ms). To initially confirm the reliability of the GG and SHy EMG recordings, the mean amplitude of each EMG channel for 2 s was calculated for each task for the first set of recordings, i.e., recordings at rest, during jaw opening, tongue protrusion and tongue back. The values were normalized to those recorded during jaw opening for SHy and during tongue protrusion for GG to allow them to be combined and compared across subjects and conditions.

During the swallowing tasks, times of onset, peak, and offset, as well as the burst duration, were measured for each burst. The thresholds for the onset and offset were defined as follows. The EMGs recorded at rest were rectified for 5 s, and the mean value ± SD was obtained as a control. When the values exceeded the control + 2 SD during the trials, the EMG burst was considered to be active. In the present study, the start of the swallowing event was defined as the appearance of the SHy burst, as reported in previous studies (15, 25). Mean times of onset, peak, and offset of the EMG burst were then measured, as well as the mean value of the duration, peak amplitude, and area of the burst in each task of each subject. Peak amplitude and area were normalized to those recorded during swallowing liquid with the head in a neutral position.

The video recordings were analyzed by single-frame analysis. The time of each event was obtained by direct reading of the digital clock recorded on each video frame. Using this method, the times of the following variables were determined: onset of propulsive tongue tip movement (which represents the tongue tip touching the palate); passage of the bolus head and tail through the fauces; movement of the bolus head through the pharyngoesophageal junction (i.e., the time from the arrival of the bolus head at the level of the UES until passage of the bolus tail through the UES); total swallowing time; oral ejection time (OET; defined as the length of time taken for the bolus to move through the oral cavity from the first frame showing the tongue tip touching the palate until the bolus tail passes the fauces); the pharyngeal transit time (PTT; defined as the time taken for the bolus to move through the pharynx from the point showing the bolus tail passing the fauces until it passes through the UES); the clearance time (CT; defined as the time taken for the bolus to invade the pharynx from the point showing the bolus head passing the fauces until the bolus tail passes the UES); the fauces transit time (FTT; defined as the time

Table 1. *Texture/consistency characteristics of test food*

	Yield Stress, Pa	Cohesion	Adhesion, J/m^3	Viscosity, mPa·s
Liquid	20	0.6	2	3
Syrup	27	0.3	6	828
Thin paste	126	0.5	17	
Thick paste	464	0.4	73	

Note that the syrup had a higher viscosity than the liquid, despite having similar stress, cohesion, and adhesion values.

taken for the bolus to pass the fauces); the UES transit time (UTT; defined as the time taken for the bolus to pass the UES).

To determine the relationship between the timing of events detected by the EMG recordings and bolus transit time obtained from the VF images, EMG activity data were synchronized with the VF recordings at the time when the laryngeal sensor was hit by a spoon. Mean values were calculated for the variables obtained from VF images and EMGs, and regression analyses were performed if the time of bolus passage showed any temporal relationship with that of the EMGs.

Tests for statistical differences among the tasks and comparison tests were performed using statistical software (Sigmastat for windows version 3.11, Systat Software). For statistical analyses, a two-way repeated-measures ANOVA was performed to compare the parameters among the different food types at the three head positions. If the treatment effects were not normally distributed with equal variance, a two-way ANOVA on the ranks was selected. $P < 0.05$ was considered to indicate significance. Mean values were expressed as means ± SE for EMG recordings and means ± SD for VF recordings.

RESULTS

Stable and repeatable EMG recordings from GG and SHy muscles were obtained in all subjects (Fig. 3). Figure 4 shows mean EMG amplitudes recorded from the muscles during the different tasks. As expected, increased activity of the GG muscle was detected during tongue protrusion and increased SHy muscle activity during jaw opening. Although the degree of jaw opening was not measured in the present study, it was apparent that SHy muscle activity was less during tongue protrusion or tongue back than during jaw opening. The SHy burst persisted during tongue protrusion and decreased in amplitude during tongue back, although there were no significant differences among control, tongue protrusion, and tongue back.

Effects of food texture/consistency and head posture on EMG burst pattern. The swallowing event was characterized by SHy and GG bursts, including a small but significant movement of the larynx (Fig. 2). The SHy muscles exhibited a single peak EMG burst pattern during each swallowing event. The small and static burst at the beginning of swallowing increased in amplitude and reached a peak. The GG muscle basically exhibited a double peak EMG burst pattern (GG1 and GG2) during each swallowing event. The GG1 and GG2 bursts normally occurred continuously, i.e., the offset of GG1 and onset of GG2 were coincident.

The onset, peak, and offset times of each burst were measured relative to the onset time of the SHy burst. The GG1 and SHy bursts appeared and the GG2 and SHy bursts disappeared simultaneously. The order of appearance of the peaks was GG1, SHy, and GG2 in all cases, although no statistical analysis was performed.

The onset time of the SHy burst was used as the reference time and was therefore not analyzed. The temporal relationships of each burst pattern were analyzed statistically using a two-way repeated-measures ANOVA or a two-way ANOVA on the ranks (Fig. 5 and Table 2). The offset time and duration of GG1 were significantly delayed and increased, respectively, with increasing hardness of the food; significant differences in offset time were noted between liquid and thin paste vs. thick paste and in duration between liquid, syrup, and thin paste vs. thick paste. The peak time and duration of the GG2 burst were also significantly delayed and increased, respectively, with increasing hardness of the food; significant differences in both peak time and duration were noted between liquid and thin paste vs. thick paste. Regarding the SHy burst, significant differences in peak time and duration were found between liquid vs. thick paste and in offset time between liquid and thin paste vs. thick paste. Interestingly, onset and peak times of the GG1 burst were not dependent on the foods or on the head posture.

Peak amplitude and area of the EMG burst were analyzed using two-way repeated-measures ANOVA or two-way ANOVA on the ranks (Fig. 6 and Table 3). These variables were not significantly affected by food properties and/or head posture.

Effects of food texture/consistency and head posture on bolus transport observed by VF images. Bolus transit time was recorded during swallowing of different foods and with different head positions. As with the analyses of EMGs, two-way repeated-measures ANOVA or two-way ANOVA on the ranks were used to determine the effects of food hardness and head

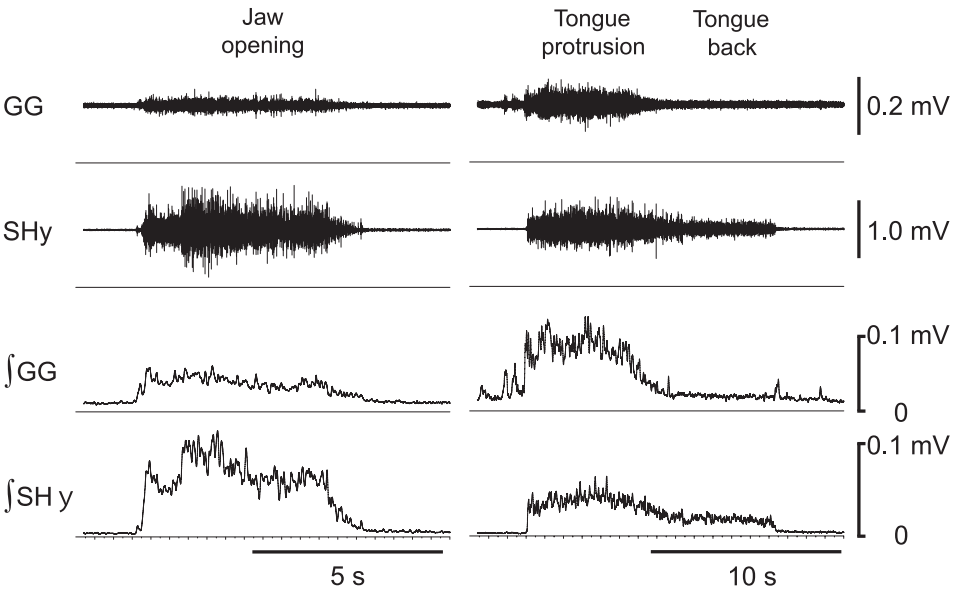

Fig. 3. Typical example of EMG recordings in the GG and SHy muscles during maximum jaw opening, maximum tongue protrusion, and tongue back to neutral position. EMG signals are shown as raw data of recordings (*top* two lines, GG and SHy) as well as rectified and smoothed ones (*bottom* two lines, ∫GG and ∫SHy).

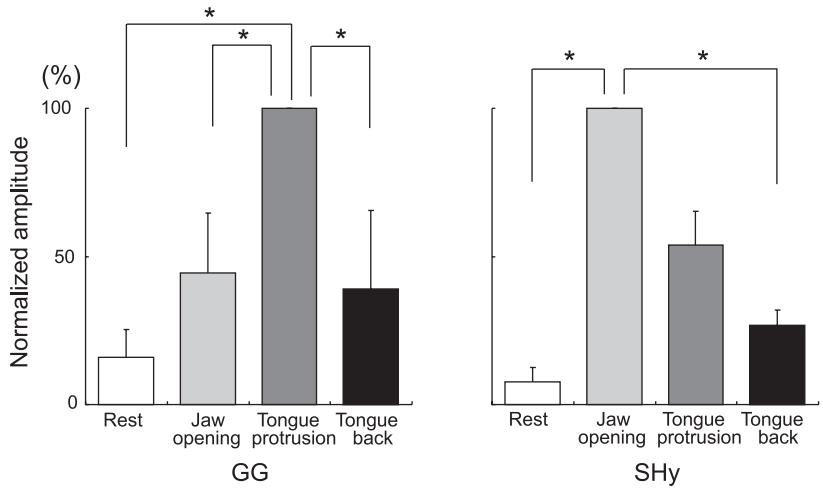

Fig. 4. Mean normalized amplitude of electromyographic burst during each function, i.e., at rest, maximum jaw opening, maximum tongue protrusion, and tongue back. Mean values for GG muscle were 16 ± 9, 44 ± 20, and 39 ± 27% (means ± SD; $n = 10$) at rest, jaw opening, and tongue back, respectively, whereas those for SHy muscles were 8 ± 5, 54 ± 12, and 27 ± 5% (means ± SD; $n = 10$) at rest, tongue protrusion, and tongue back, respectively. *Significant difference ($P < 0.05$).

posture (Table 4). Mean transit times are shown in Fig. 7. There were no significant differences, suggesting that these factors had less effect on bolus transit than on EMG bursts in the present study.

Relationship between EMG and VF recordings. Previous reports have suggested that some time points during the passage of a bolus were virtually coincident with the onset of biomechanical events (3, 37). In the present study, we compared some time points during the passage of a bolus with those of the EMG bursts during swallowing. The tongue tip touching the palate and the peak of the GG1 burst, the passage of the bolus tail at the fauces, the offset of the GG1 burst, the passage of the bolus tail at the UES, and the peak of the GG2 burst occurred within 0–0.2 s of one another. Mean values were 2.6 s for the tongue tip touching the palate vs. 2.8 s for the peak of the GG1 burst; 3.2 s for the passage of the bolus tail at the fauces vs. 3.3 s for offset of the GG1 burst; and 3.6 s for the passage of the bolus tail at the UES vs. 3.6 s for the peak of the GG2 burst. Although the timings of the passage of the bolus tail at the UES and offset of the SHy burst were expected to be coincident with each other, they were significantly different (mean 3.6 s for the former and 4.4 s for the latter). Regression analyses showed significant linear relationships between the time of the tongue tip touching the palate and the peak of the GG1 burst, between the passage of the bolus tail at the fauces and offset of the GG1 burst, between the passage of the bolus tail at the UES and the peak of the GG2 burst, and between the passage of the bolus tail at the UES and offset of the SHy burst (Fig. 8).

Although the onset of the GG burst was statistically identical to that of the SHy burst regardless of the bolus conditions, it is still unclear how these bursts contributed to the start of bolus propulsion and how they were affected by the experimental conditions. The time intervals between the onset of the EMG burst and bolus propulsion were therefore compared among the different boluses (Fig. 9). The time intervals increased with increasing hardness of the bolus, indicating that hard food might lead to a delay in bolus propulsion after activation of the swallowing-related muscles.

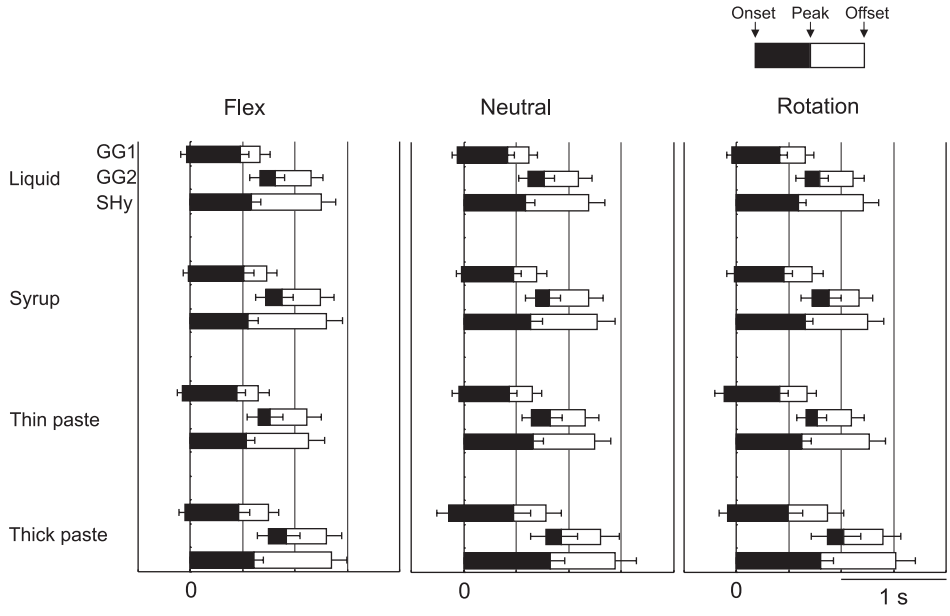

Fig. 5. Effects of food texture/consistency and head posture on the temporal pattern of EMG activity of the muscles. Onset of EMG burst of SHy muscles was defined as *time 0* and means ± SE ($n = 10$) of EMG variables for all the tasks are presented. There were no significant differences in the onset and offset times between the GG1 and SHy bursts, and between the GG2 and SHy bursts, respectively. The order of appearance of the peaks was GG1, SHy, and GG2, regardless of the conditions. All bursts were delayed with increasing food hardness but were unaffected by head posture (see Table 2 for details). Flex, head-flexed position; neutral, head-neutral position; rotation, head-rotated position.

Table 2. *Effects of food texture and head posture on the timing of EMG burst*

GG1	Onset	DF	F	P	Peak	DF	F	P	Offset	DF	F	P
F		3	1.526	0.208		3	0.516	0.672		3	3.442	0.017
P		2	0.227	0.797		2	0.339	0.713		2	0.465	0.629
F × P		6	0.435	0.855		6	0.098	0.997		6	0.228	0.967
Total		287				287				287		
GG2	Onset	DF	F	P	Peak	DF	F	P	Offset	DF	F	P
F		3	3.378	0.019		3	3.634	0.013		3	4.111	0.007
P		2	0.464	0.629		2	0.240	0.786		2	0.038	0.962
F × P		6	0.225	0.969		6	0.311	0.931		6	0.283	0.945
Total		287				287				287		
SHy					Peak	DF	F	P	Offset	DF	F	P
F						3	3.384	0.019		3	3.401	0.018
P						2	3.315	0.038		2	0.304	0.738
F × P						6	0.520	0.793		6	0.379	0.892
Total						287				287		

F, food; P, position; DF, degree of freedom.

DISCUSSION

This study has demonstrated some small but significant differences in the patterns of EMG bursts recorded under different experimental conditions; onset, peak, and offset times of the GG1, GG2, and SHy bursts were delayed, and the duration of the bursts were lengthened, with increasing food hardness. Regarding the bolus transit time, the OET tended to increase with increasing hardness of the food, but there were no significant differences in transit times between foods with different properties. These findings support previous studies (4, 14, 25, 30, 31), which demonstrated that the major effects of food consistency were to extend the duration of lingual peristalsis and delay OET. Differences in head position, however, had no effect on the values. The results suggest that biomechanical features of the bolus can affect the stereotyped pattern generation in terms of the temporal patterns of muscle activities to form the bolus and propel it from the oral cavity through the pharynx and into the esophagus within a fixed time.

Reliability of EMG recordings in the GG muscle. We developed a noninvasive surface electrode for recording from the GG muscle. In our preliminary experiment, we confirmed that the GG activity recorded from this electrode reflected the dynamic movement of the tongue (34). The base of the tongue moves upward and downward during swallowing so that contact between the electrodes and the tongue surface could vary, potentially causing problems in stable measurement of GG activity. To ensure that the electrode tip was stably placed on the floor of mouth and was protected from exposure to saliva, ball electrodes were used and the neck of the electrodes was coated with polyester, allowing the electrodes to move flexibly and to absorb the dynamic movement of the floor of mouth. Thus recordings could be performed consistently and repeatedly using this recording unit.

It is possible that the GG EMGs were not a precise measure of muscle contraction but also included recordings of activity in surrounding muscles because of their close proximity to the surface recording site. Previous studies have shown that increased lingual pressure during effortful swallowing led to an increase in the EMG amplitude of SHy muscles (10, 11). In these studies, the authors suggested that the surface EMG

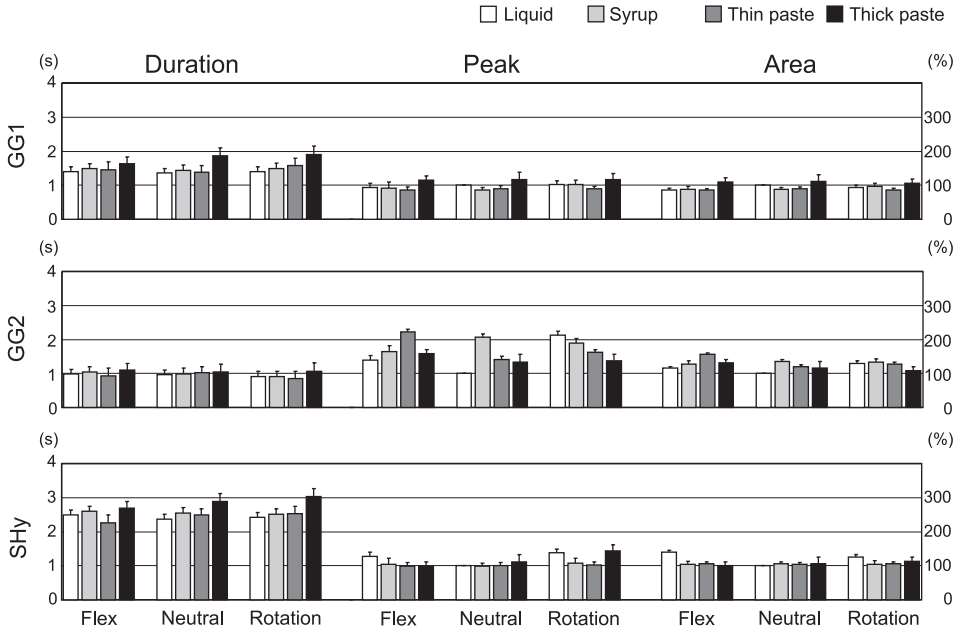

Fig. 6. Effects of food texture/consistency and head posture on the EMG activity of the muscles. Means ± SE (n = 10) of EMG variables for all the tasks are presented. Duration values are given in seconds; peak and area values are given as percentages. There were no significant differences in all the variables among the conditions, except for the duration of the GG1 and SHy bursts, which varied with food hardness (see Table 3 for details).

Table 3. *Effects of food texture and head posture on the duration, peak, and area of EMG burst*

GG1	Duration	DF	F	P	Peak	DF	F	P	Area	DF	F	P
F		3	7.278	<0.001		3	2.618	0.056		3	3.198	0.028
P		2	0.877	0.417		2	0.231	0.794		2	0.233	0.792
F × P		6	0.541	0.777		6	0.116	0.994		6	0.224	0.968
Total		287				287				287		
GG2	Duration	DF	F	P	Peak	DF	F	P	Area	DF	F	P
F		3	2.423	0.066		3	0.253	0.859		3	0.409	0.747
Position (P)		2	1.685	0.187		2	0.209	0.812		2	0.352	0.704
F × P		6	0.451	0.844		6	0.309	0.93		6	0.253	0.957
Total		287				287				287		
SHy	Duration	DF	F	P	Peak	DF	F	P	Area	DF	F	P
F		3	3.401	0.018		3	1.183	0.321		3	1.231	0.304
P		2	0.304	0.738		2	1.686	0.191		2	0.618	0.541
F × P		6	0.379	0.892		6	0.567	0.755		6	0.696	0.654
Total		287				287				287		

amplitude of SHy muscles could reflect increased tongue effort during swallowing of thick food. In this regard, Palmer et al. recorded surface EMGs from SHy muscles, as well as from five individual muscles (mylohyoid, anterior belly of the digastric, geniohyoid, GG, and platysma) during swallowing to investigate the contributions of individual muscles to the surface EMGs (24). These authors found that the contributions of the GG muscle were quite minimal. In the present study, the activity patterns of the GG and SHy muscles were completely different from each other during swallowing, thus excluding the possibility of contamination of these signals.

Sauerland and Harper (28) observed different patterns of EMG activity from the GG muscle. The authors revealed that the motor units in (or the motor nerve fibers proceeding toward) the anterior part of the GG muscle discharged during inspiration, whereas the units or nerve fibers in the posterior part of the GG muscle discharged tonically rather than phasically. This finding has been confirmed in humans (8, 38) and in animals (42), where the GG muscle or its efferent nerve in the direction of the mandible discharged synchronously during inspiratory activity, whereas those in the direction of the tongue discharged not phasically but tonically. Because the placement of electrodes in this study was not near the mandibular bone, we speculated that no phasic involvement in the GG activity was likely. It is reasonable to assume that measurements from the GG muscle were unaffected by respiratory activity because of where the electrodes were placed.

Temporal pattern of EMG activity in the SHy muscle during swallowing. In the present study, different foods resulted in significantly different peak and offset times of the SHy EMG burst as well as in the duration of the burst. SHy muscle activity is involved in the entire swallowing sequence, since it forms a platform and provides support for tongue movements (3, 31). Numerous previous studies have demonstrated that swallowing thick food causes an increase in the duration of the SHy EMG burst (4, 9, 24, 25, 30, 35). It has also been suggested that prolongation of the EMG burst was caused by a decrease in the velocity of lingual peristalsis and greater laryngeal elevation (30, 31). These results support those of our present study and indicate that the duration of the SHy burst was strongly affected by food texture and/or consistency. Hard food may require prolonged bursts in the SHy muscles, as well as the tongue muscles, to anchor the hyoid and transport the hard bolus through the oral and pharyngeal cavities.

Temporal pattern of EMG activity in the GG muscle during swallowing. Oral pressure produced by the tongue against the palate has been reported to increase with food of heavier consistencies and prolonged OET (30, 35, 37). These results suggested that GG muscle activity would be strongly affected by food consistency and that the activity bursts of swallowing-related muscles required to propel a hard food bolus in the oral cavity would also be of longer duration.

Interestingly, the GG burst pattern in this study showed two peaks during each swallowing. Among the few studies that have observed GG activity during swallowing, none have reported a double peak pattern of the GG burst (8, 18, 40, 42), although some raw GG recording data did suggest the existence of double peak patterns (see Refs. 40, 42). Furthermore, it should be noted that the food properties had less effect on the onset and peak times of the GG1 burst than on its offset time and duration. In the present study, the onset of the SHy burst was defined as *time 0*, which indicated that the generation of the SHy burst was centrally controlled by the swallowing pattern generator (7). Since the onset and peak times of the

Table 4. *Effects of food texture and head posture on the bolus transport*

	Total	DF	F	P	OET	DF	F	P	PTT	DF	F	P
F		3	0.507	0.679		3	1.223	0.307		3	2.000	0.120
P		2	0.125	0.883		2	0.065	0.937		2	0.212	0.810
F × P		6	0.870	0.521		6	1.104	0.367		6	1.139	0.347
Total		93				93				93		
	CT	DF	F	P	FTT	DF	F	P	UESTT	DF	F	P
F		3	1.074	0.365		3	0.165	0.920		3	2.271	0.086
P		2	0.382	0.684		2	0.207	0.814		2	1.707	0.188
F × P		6	0.590	0.737		6	0.788	0.582		6	0.921	0.484
Total		93				93				93		

OET, oral transit time; PTT, pharyngeal transit time; CT, clearance time; FTT, fauces transit time; UESTT, upper esophageal transit time.

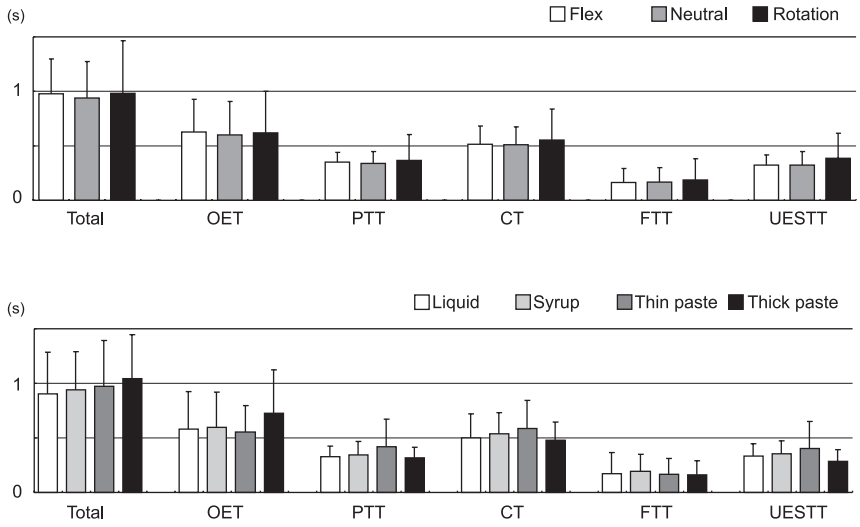

Fig. 7. Effects of food texture/consistency and head posture on bolus transit time. Means ± SDs (n = 10) of bolus transit times are presented for different head postures in the *top* graph and for different foods in the *bottom* graph. There were no significant differences in bolus transit times among the tasks. OET, oral ejection time; PTT, pharyngeal transit time; CT, clearance time; FTT, fauces transit time; UESTT, upper esophageal transit time.

GG1 burst were not modulated by the food properties, and the peak of GG1 was coincident with the tongue tip touching the palate, it seems likely that the GG and SHy muscles activate simultaneously to initiate swallowing. Furthermore, it would be suggested that the GG1 burst mainly plays a role in propelling the bolus in the oral cavity into the pharyngeal cavity because the offset time of the GG1 burst was roughly identical to the bolus tail passing the fauces. The OET was not significantly increased with increasing hardness of the food, unlike the duration of the GG1 burst. It should be noted that the onset of the GG1 burst was not strictly identical to the time of the tongue touching the palate. We also found that the time interval between the onset of the GG1 and SHy bursts and bolus propulsion tended to increase with increasing hardness of the food. In this regard, the contribution of other swallowing-related muscles, including the intrinsic tongue muscle and surrounding muscles, such as palatoglossus, palatopharyngeal, and levator veli palatine, to the propulsion of the bolus should be considered (7). The first three of these are rich in muscle receptors, e.g., muscle spindles, whereas the last one has fewer (13, 27). At the beginning of swallowing, the duration of the GG burst acting to propel the bolus was modulated by the

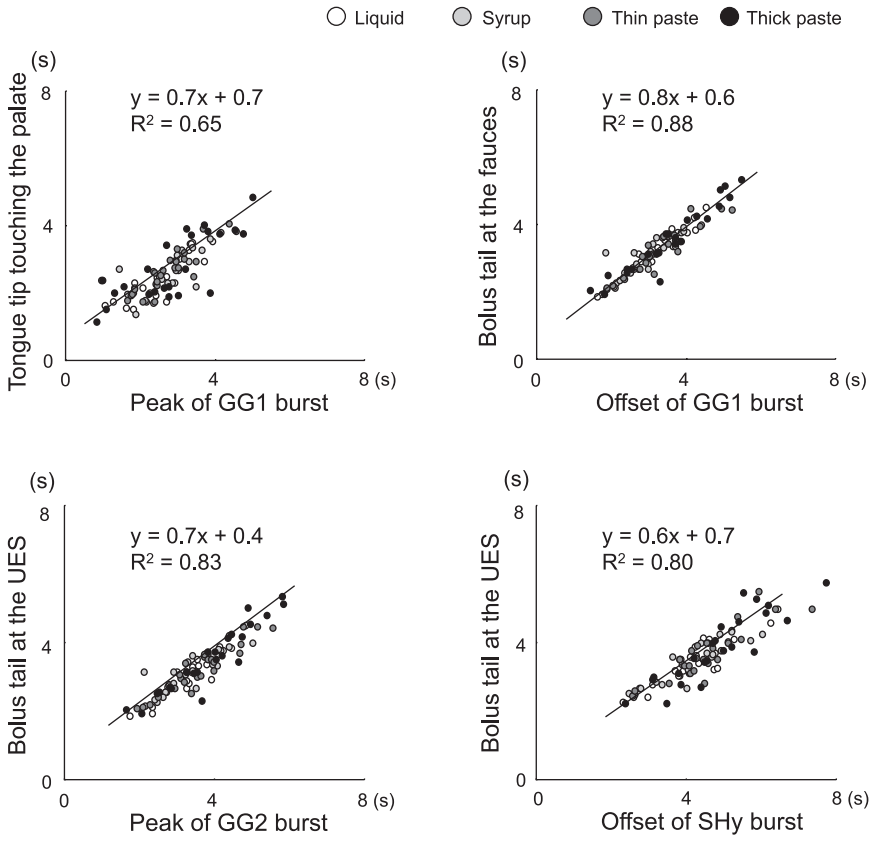

Fig. 8. Scatter plots and linear regressions comparing the variable features of electromyograms with those obtained from videofluorographic images. The time when the larynx was hit was set as zero. All the cases showed significant positive correlations ($P < 0.01$). Note that the offset time for genioglossus (GG) 1 and the time of bolus tail at the fauces are identical. Flex, head-flexed position; neutral, head-neutral position; rotation, head-rotated position; SHy, suprahyoid muscles.

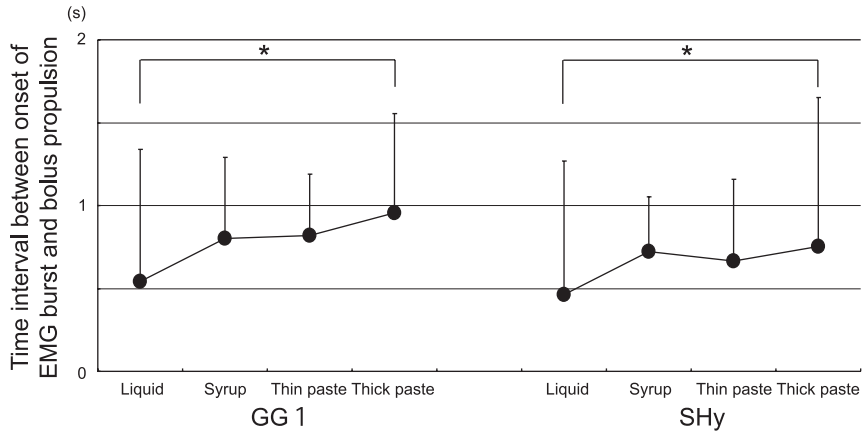

Fig. 9. Time interval between onset of EMG burst and bolus propulsion. Time intervals between the onset of GG1 and bolus propulsion were 0.54 ± 0.80, 0.80 ± 0.49, 0.82 ± 0.37, and 0.95 ± 0.60 s (means ± SD; $n = 10$) for liquid, syrup, thin paste, and thick paste, respectively. Time intervals between the onset of SHy burst and bolus propulsion were 0.46 ± 0.80, 0.72 ± 0.33, 0.67 ± 0.49, and 0.75 ± 0.89 s (means ± SD; $n = 10$) for liquid, syrup, thin paste, and thick paste, respectively. There was a significant difference in the time interval of GG1 and SHy burst only between liquid and thick paste. *$P < 0.05$.

hardness of the bolus, whereas swallowing-related muscles other than the GG and SHy may also contribute to triggering food propulsion, causing minor differences in the changes in the temporal patterns between the muscle activity and bolus transit time.

The offset time of the GG1 burst, which was equivalent to the onset of the GG2 burst, was also coincident with the time at which the bolus tail reached the fauces, and the offset time of the GG2 burst was coincident with the bolus passing the UES. It therefore seems likely that the GG2 burst functions to squeeze the bolus from the pharynx into the esophagus. The results obtained here suggest that onset, peak, and offset of GG2 were delayed with increasing hardness of the food. However, there were no significant differences in the duration of GG2 between the different conditions ($P = 0.06$). Although the offset of GG2 was significantly delayed with harder food, the pharyngeal stage of swallowing might be controlled to propel food into the pharynx within a certain range of time.

Effects of food texture/consistency on the magnitude of EMG activity. The peak amplitude and area of the GG and SHy muscle bursts were not modulated by the experimental conditions in the present study. Reimers-Neils et al. and Sugita et al. both investigated the effects of food viscosity on the swallowing-related muscles but produced inconsistent results. The former demonstrated an effect of food consistency on the magnitude of swallowing-related muscle activity, but the latter did not (4, 9, 24, 25, 30, 35). The inconsistency of these results may be due to the fact that the test foods and/or bolus volumes used differed in the two studies. The former study, which did demonstrate a significant difference, also failed to find any significant differences between the peak and mean EMG amplitudes of the SHy muscle generated by swallowing liquid and thin paste. It is possible that the effects on the magnitude of SHy muscle activity depend on the physical conditions of the bolus and/or volume and that the bolus may not have been large enough to cause significant differences in the EMG burst.

Effects of food texture/consistency on bolus transport. The results obtained by VF recordings in the present study disagreed with previous findings. The bolus transit time was not significantly affected by the bolus properties, in contrast to previous studies, which have reported that bolus transit time was dependent on food consistency (4, 14, 25, 30, 31). The results of our previous study found that total swallowing time and OET were significantly longer during swallowing of a thick paste than a liquid or a syrup, whereas PTT and CT were significantly longer during swallowing of a syrup, which was the same hardness as a liquid but with higher viscosity (37). This discrepancy may be due to a decrease in the volume and/or a difference in the texture of the test foods. Reimers-Neils et al. suggested that food consistency affected the pattern of activity in the swallowing-related muscles, including the SHy muscles (25). The authors, however, found that there were no significant differences in the peak and mean EMG activities of the SHy muscles when liquids and thin pastes were swallowed. It may be that the effects on the magnitude of SHy muscle activity depends on the physical condition of the bolus, and the bolus size in our study may not have been large enough to make a significant difference in the EMG burst. The central pattern generator for swallowing, which organizes the swallowing-related movements in the oral, pharyngeal, laryngeal, and esophageal regions, may control movement of the food bolus from the oral cavity into the esophageal region through the pharyngeal cavity in a set time, regardless of the food conditions.

Effects of head posture on the swallowing movement. There is clinical interest in evaluating the effects of head posture on swallowing function. The bolus formed by the tongue is propelled backward to the valleculae, divides at the valleculae, proceeds through the pyriform sinuses, and finally enters the region of the UES. Logemann et al. examined the effects of head rotation and flexion on the mechanics of swallowing (16). Head rotation to either side increased the UES opening diameter without affecting the period of UES opening or the oropharyngeal transit time. Head rotation can improve swallowing in patients with unilateral oropharyngeal dysphagia. On the other hand, the head-flexed position, clinically called the chin-tuck position, has been widely used in neurogenic patients with dysphagia, especially in individuals in whom delays in triggering reflex pharyngeal swallowing were observed (32). The head-flexed position widens the vallecular space to prevent the bolus from entering the airway, narrows the airway entrance, pushes the tongue base backward toward the pharyngeal wall, and puts the epiglottis in a more protective position. It has, however, been suggested that no manometric changes and no reduction in pharyngeal contraction pressure occur in this position. Thus these clinical techniques used to increase bolus transport can mechanically improve abnormal propulsion but might not alter GG or SHy muscle activity. The

results obtained in the present study indicate the validity of using EMG and VF data to study natural swallowing in normal subjects. It is possible that the situation differs in patients with dysphagia, and further studies are needed to determine the reliability of EMG and VF techniques in these patients.

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