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Effect of body posture on involuntary swallow in healthy volunteers

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HIGHLIGHTS

- Swallowing was recorded during pharyngeal water infusion/chewing at four postures.
- Reclining changed the location of bolus head at start of swallow.
- Muscle burst duration and whiteout time significantly increased with reclining.
- Body reclining may prolong pharyngeal swallow during involuntary swallow.

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ABSTRACT

Clinically, reclining posture has been reported to reduce risk of aspiration. However, during involuntary swallow in reclining posture, changes in orofacial and pharyngeal movement before and during pharyngeal swallow should be considered. Further, the mechanisms underlying the effect of body posture on involuntary swallow remain unclear. The aim of the present study was to determine the effect of body posture on activity patterns of the suprahyoid muscles and on patterns of bolus transport during a natural involuntary swallow. Thirteen healthy male adults participated in a water infusion test and a chewing test. In the water infusion test, thickened water was delivered into the pharynx at a very slow rate until the first involuntary swallow was evoked. In the chewing test, subjects were asked to eat 10 g of gruel rice. In both tests, the recording was performed at four body postures between upright and supine positions. Results showed that reclining changed the location of the bolus head at the start of swallow and prolonged onset latency of the swallowing initiation. Muscle burst duration and whiteout time measured by videoendoscopy significantly increased with body reclining and prolongation of the falling time. In the chewing test, reclining changed the location of the bolus head at the start of swallow, and the frequency of bolus residue after the first swallow increased. Duration and area of EMG burst and whiteout time significantly increased with body reclining. These data suggest that body reclining may result in prolongation of pharyngeal swallow during involuntary swallow.

1. Introduction

Swallowing, an early stage of the eating process, involves complex sensorimotor neural components. The basic motor patterns involved in swallowing are programmed by the central pattern generator (CPG) in the medulla oblongata [1,2]. Because the swallowing CPG receives both peripheral and central inputs, such inputs determine the threshold for initiation of swallow and the activity pattern of swallow-related muscles [1,3].

Numerous studies have shown that sensory inputs arising from a food bolus affect the patterns of swallowing movement [4–13]. Most studies have focused on the effect of bolus properties such as hardness, adhesiveness, cohesiveness, or viscosity on voluntary swallowing parameters. Voluntary swallowing can be triggered by convergence of central and peripheral inputs into the swallowing CPG, while involuntary swallowing can be triggered by mechanical or chemical stimulation in the oropharynx or larynx. As such, during involuntary swallowing the brainstem neural network may be a dominant component for initiation and determination of movement patterns, although cortical and/or subcortical regions are also involved in involuntary swallowing [14–16].

There is also evidence that body posture may influence swallowing performance, including bolus transport and muscle activity during swallowing [6–8,17–21]. Lund et al. [22] demonstrated that digastric electromyographic (EMG) activity was larger in the upright position than in the supine position. Inagaki et al. [6,18] showed that lying

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down shortened the EMG burst duration of suprahyoid muscles, which was due to the properties of the bolus, as the toughness and adhesiveness of the food could alter the gravitational force in the oral cavity. Moller et al. [20] also evaluated effect of body posture on saliva swallowing, and found that in reclined and supine positions, onset of lateral pterygoid and digastric muscle bursts were advanced in relation to the temporal muscle when compared with the upright position, which may result in shortening of the oral phase of swallowing. Further, Johnsson et al. [19] demonstrated that hypopharyngeal pressure and diameter of the maximal opening of the upper esophageal sphincter (UES) during pharyngeal swallow increased, and the duration of UES opening was shorter in a supine position compared with an upright position. By contrast, Dejaeger et al. reported that the amplitude, duration, and propagation velocity of pharyngeal contraction were not affected by body posture [17]. Most studies that have evaluated EMG activity of the suprahyoid muscle group or in healthy subjects showed no difference in muscle activity during swallowing among various postures [6,20,21]. In addition, Barkmeier et al. [23] reported that the timing, amplitude, and duration of the thyroartenoid muscle did not vary relative to the suprahyoid muscles in healthy subjects. Thus, differences in bolus conditions may have contributed to these contrasting findings.

Clinically, reclining posture was reported to reduce risk of aspiration when compared with an upright or supine posture in dysphagic patients [24–26]. In this posture, the bolus is likely propelled through the posterior wall of pharynx into the upper esophageal sphincter, but not into the larynx. Park et al. [25] found that a 45° reclining position reduced the rate of penetration/aspiration and decreased the residue in valleculae, but increased the residue in the pyriform sinuses, in dysphagic patients. Umeda et al. [26] also reported that reclining position posture can aid oral transit and readily prevent aspiration and laryngeal penetration; in patients with post operation of oral tumors, laryngeal penetration and aspiration were less likely to occur in the reclining position, while the mean oral transit time of the bolus was significantly shorter than when sitting. However, changes in body posture may affect other functions such as respiration [25,27]. Indeed, Park et al. [25] found that the residue in the pyriform sinuses was significantly increased when at a 45° reclining position versus at an upright position.

Although previous studies have examined the effect of body posture on voluntary swallowing, the underlying mechanisms for involuntary swallow remain unclear. Most normal swallowing, such as saliva swallowing and swallowing following chewing during a meal, is initiated involuntarily. The position of the leading edge of the bolus may be different between normal and volitional swallowing following chewing [28]. In particular, during involuntary swallow in the reclining position, there may be a reduction of involvement of orofacial movement before pharyngeal swallow, a decrease in the speed of bolus transport, and an increase of pharyngeal transit time due to changes in the angle of the pharyngeal walls with respect to the perpendicular direction. Further, if the bolus is propelled on the posterior wall of the pharynx before swallowing, the time of initiation of swallowing may be delayed because the posterior wall of the pharynx is poorly innervated [29,30].

Assuming that gravitational effects on oral and pharyngeal bolus transport differ among the postures, a bolus could be predicted to move more slowly in the posterior wall of the pharynx in the reclined position than in the upright position. As a result, a pharyngeal transit time and swallow-related EMG could be larger in the reclined position. Thus, the aim of the present study was to determine the effect of body posture on (1) activity patterns of the suprahyoid muscles and (2) patterns of bolus transport in the pharynx during involuntary saliva swallowing and swallowing following chewing, and (3) to evaluate the relationship of modulation between muscle activity and bolus transport in natural swallow.

2. Materials and methods

2.1. Participants

Thirteen healthy male adults (mean age ± SD: 29.8 ± 6.0 years; age range: 21–39 years) participated in this study. We did not recruited female participants because anatomical and functional differences between men and women have been described in numerous studies [31–35]. Informed consent was obtained from all participants, and no subject had a history of alimentary disease, pulmonary disease, neurological disease, musculoskeletal disorders, speech disorders, voice problems, or masticating or swallowing problems. The experiments were approved by the Ethics Committee of the Faculty of Dentistry, Niigata University (27-R3-5-25).

2.2. Physiological recordings

To identify and evaluate swallowing function, EMG, electroglottography (EGG), and respiratory airflow were recorded, as previously reported [36]. In brief, bipolar surface EMG electrodes (ZB-150H; Nihon Kohden, Tokyo, Japan) were attached to the skin over the anterior surface of the digastric muscle on the left side, and EMG signals were detected in the suprahyoid muscle group. Signals were filtered and amplified (low cut, 30 Hz and high cut, 2 KHz) (WEB-1000; Nihon Kohden) to remove movement-related artifacts. Bipolar surface EGG electrodes were positioned on both the right and left sides of the thyroid cartilage and the signals were amplified (EGG-D200; Laryngograph, London, UK). For recording expiratory and inspiratory airflow via thermocouples, thermal electrodes (ZB-153H; Nihon Kohden) were attached just below the external nostril on either side. The signal was filtered and amplified (high cut, 100 Hz). Flexible endoscopy was performed to observe bolus transport in the mid and hypo-pharynx. A fiber optic endoscope (FNL-10RP3; Pentax, Tokyo, Japan) was inserted through the nasal passage and into the midpharynx. All signals were stored through an interface board (PowerLab; ADInstruments, Colorado Springs, CO, USA) on a personal computer. The sampling rate was 10 kHz for all physiological variables and 30 Hz for VE images. Data analysis was performed using the PowerLab software package (LabChart6; ADInstruments).

2.3. Data collection

Prior to each experiment, the subject was not allowed to eat and drink for at least 1 h. Individual subjects were instructed to lie comfortably on the chair with a head support. We performed two recording sessions involving a water infusion test and a chewing test, which were performed on separate days with an interval of at least two days.

For the water infusion test, thickened water (Oishi-mizu; Asahi Soft Drinks, Ibaraki, Japan) was prepared at 1% thickening agent (Toromi Up Perfect; The Nissin Oilio Group, Ltd., Tokyo, Japan). Following setup of the recording device, a thin tube (2.7 mm outer diameter; NIPRO, Osaka, Japan) was inserted into the posterior tongue transorally. The tip of the tube was positioned at the vallate papilla. The portion of the tube outside the mouth was taped below the lower lip. Prior to experimentation, the subject was asked to swallow his own saliva for a few seconds before recording to clear the saliva in the oral and/or pharyngeal cavity. The liquid was then delivered through the tube using an infusion pump (KDS-100; Muromachi, Tokyo, Japan). The start of infusion was determined at the end of the expiratory phase. To minimize the mechanical effect of the infused solution, it was infused at a very slow rate (0.05 mL/s) until the first involuntary swallow was evoked. The subjects were blinded to the start of water infusion.

For the chewing test, a 10 g portion of gruel rice (Eiyo Shien Okayu; Foricafoods Corp., Niigata, Japan) was prepared. As with the water infusion test, the subject was asked to swallow his own saliva for a few seconds before recording. The food samples were placed on a dish in front of the subjects, who were asked to put the food into their mouths using a spoon and eat in their usual manner.

In both tests, the recording was performed at four body postures: upright (R90), 60° (R60), 30° (R30), and 0° supine (R0) positions. The order of posture was randomly determined by the experimenter. The water infusion test consisted of three trials in each of the four postures, whereas the chewing test consisted of one trial in each of the postures to avoid satiation. In either test, the time interval between the trials was at least 1 min, and subjects were able to rinse their mouths with distilled water whenever they wished between the trials.

2.4. Data analysis

The EMG bursts were full-wave rectified for data analysis. The thresholds for the onset and offset were defined as follows after smoothing of the rectified EMGs (time constant 20 ms). 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 + 3 SDs during the trials, the EMG burst was considered to be active. However, in the chewing test, because the EMGs often exhibited increased tonic activity superimposed with swallow-related activity, and as they were always more than the control + 3 SDs, the onset and offset times could not be determined by these criteria. Thus, we determined the onset and offset of EMG burst as the points at which EMG bursts rapidly built up from the tonic or stable lines (Fig. 1). A swallowing event could be detected as an EMG burst, EGG burst, and by VE images.

The following variables were obtained in each trial of each posture for the water infusion test. The onset latency of the first involuntary swallow was measured by calculating the time interval between the start of infusion and onset of EMG burst of the first swallow. Burst duration and rising and falling time (defined as the time interval between onset and peak and between peak and offset of EMG burst, respectively), peak amplitude, and area of EMG burst of the swallow were measured. Using VE images, the onset lag time (defined as the time interval between onset of EMG burst and start of pharyngeal swallow; i.e., whiteout), the peak lag time (defined as the time interval between start of whiteout and peak of EMG burst), and the whiteout time (defined as the time interval between onset and offset of whiteout) were measured. For the water infusion test, an individual mean value for each subject was obtained from three trials at each posture. Next, the

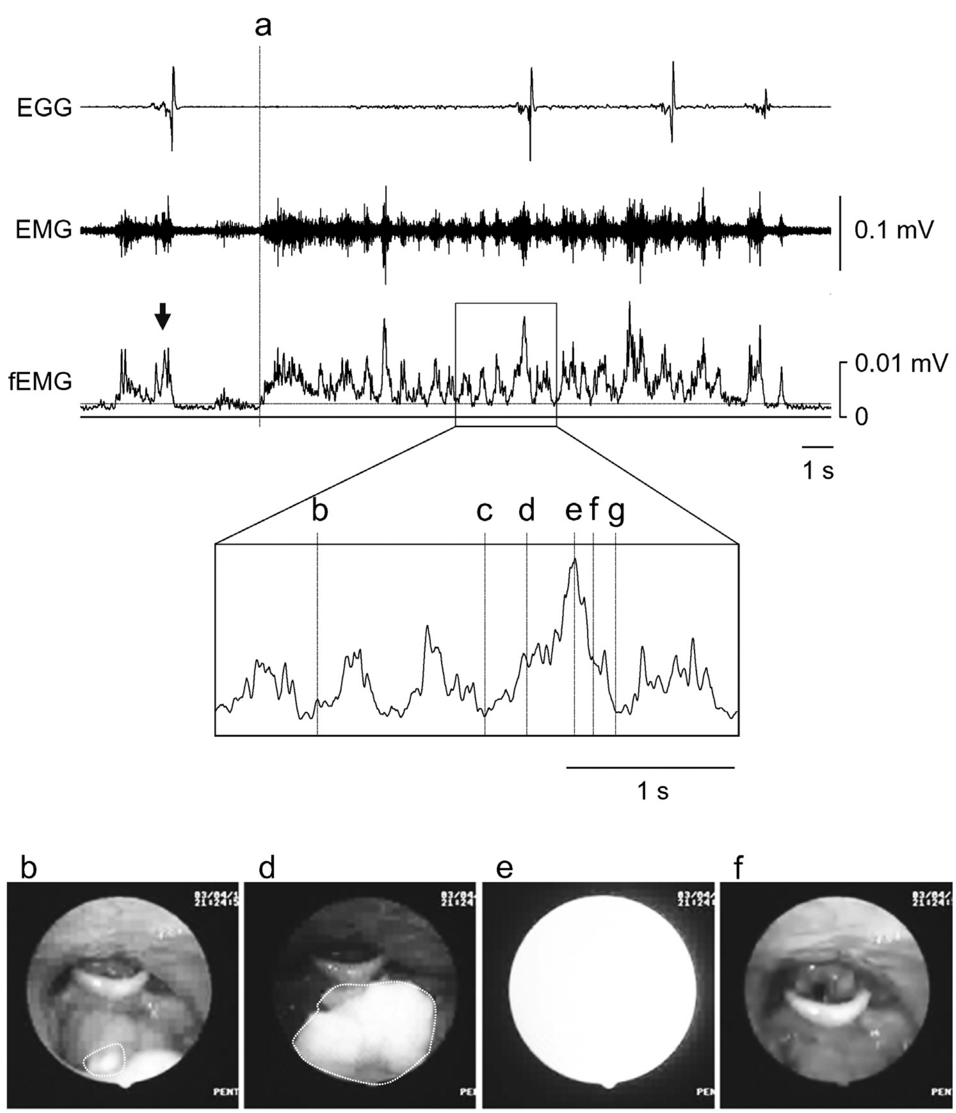

Fig. 1. Example of combined VE images and EGG and EMG recordings at R60 in the chewing test. Top: EGG and raw and filtered EMG signals are shown. Vertical dotted lines represent the start time of chewing (a). Horizontal dotted line on fEMG represents the threshold of EMG burst. Note that once chewing started, the EMGs exhibited increased tonic activity. Duration of EMG burst of voluntary saliva swallow before chewing (arrow) was much longer than that following involuntary swallow. Middle: fEMG signals during swallowing are shown on the expanded time base. Vertical dotted lines represent the time of onset of Stage II transport (b), onset of EMG burst (c), just before whiteout (d), peak of EMG burst (e), offset of whiteout (f), and offset of EMG burst (g). Bottom: VE images as for (b–f) above. Area surrounded by dotted line in (b) and (d) represent the bolus.

Table 1
EMG variables and ANOVA results of water infusion test.

	Prior to swallow	Swallow				
	Latency of first swallow	Burst duration	Rising time	Falling time	Peak amplitude	Area
df	3	3	3	3	3	3
F value	7.043	8.538	0.723	7.058	0.312	2.061
P value	<0.001	<0.001	0.545	<0.001	0.816	0.149

portion of the bolus head at the start of whiteout was determined. In this procedure, pharyngeal and laryngeal regions were divided into the posterior tongue, epiglottic valleculae, pyriform sinus, entrance of the UES, lateral or posterior wall of the midpharynx, lateral or posterior wall of the hypopharynx, and inside of the larynx.

For the chewing test data, the same variables as for the water infusion test were measured, including burst duration, rising time, falling time, peak amplitude, and area of EMG burst of the first swallow. From the VE images, the time interval between the occurrence of bolus in the pharynx and start of pharyngeal swallow (i.e., whiteout), termed the stage II transport time, was measured. In addition, as for the water infusion test, the onset lag time, peak lag time, and whiteout time were measured. Finally, the portion of the bolus head at the start of pharyngeal swallow and the existence of pharyngeal residues after the first swallow were evaluated.

All the variables obtained in the present study are shown in Tables 1–3. The individual mean values of the EMG data were compared among the body postures by using one-way repeated-measures analysis of variance (ANOVA) and Tukey's honest significant difference (HSD) post-hoc test. The portion of the bolus head at the start of pharyngeal swallow and existence of pharyngeal residues after the first swallow in the chewing test were compared among the body postures by using the chi-squared test. Tests for statistical differences and comparison tests were performed using statistical software (SigmaPlot 12; Systat Software Inc., CA, USA). Statistical significance was set at $P < 0.05$. All values were expressed as mean ± SE ($n = 13$) for the water infusion test and mean ± SD ($n = 13$) for the chewing test.

3. Results

Swallowing was clearly detected by the whiteout event of VE and the EGG burst. In addition, because all swallows were evoked involuntarily (i.e., reflexively), the EMG waveform exhibited a single peak and was distinguishable from that of voluntary swallowing (Fig. 1). Out of 156 data points obtained from the water infusion test, 41 points were excluded for analysis as EMG or VE data were lacking owing to technical errors.

3.1. EMG findings in the water infusion test

Variables obtained from the EMGs of the first swallow were compared among the body postures (Table 1, Fig. 2). A significant difference among the postures was observed for latency of the first swallow, EMG burst duration, and falling time. Latency was significantly longer for R0 than for R90 and R60 and for R30 than R90. Duration of the EMG burst was significantly longer for R30 and R0 than for R90 and R60. Falling time of the EMG burst was also shorter for R90 than for R30 and R0 and for R60 than for R0. These results indicate that the greater the recline, the longer the latency, burst duration, and falling time. By contrast, there were no changes in other EMG variables such as rising time, peak amplitude, and area.

Table 2
Variables obtained from VE image and ANOVA results.

		Onset lag time	Peak lag time	Whiteout time
	df	3	3	3
Water infusion test	F value	1.724	0.751	10.132
	P value	0.179	0.529	<0.001
Chewing test	F value	1.912	0.228	13.183
	P value	0.145	0.876	<0.001

Table 3
EMG variables and ANOVA results of chewing test.

	Prior to swallow	Swallow				
	Stage II transport time	Burst duration	Rising time	Falling time	Peak amplitude	Area
df	3	3	3	3	3	3
F value	1.550	47.327	1.931	2.301	0.712	17.810
P value	0.218	<0.001	0.142	0.094	0.551	<0.001

3.2. VE findings in the water infusion test

Data obtained from VE images indicated body posture-dependent changes. For example, the portion of the head of the bolus at the start of whiteout was significantly dependent on body posture (Fig. 3A). At R90, most swallows were evoked when the bolus head reached the posterior tongue, epiglottic valleculae, or pyriform sinus while it spread over the entrance of the UES or lateral or posterior wall of the midpharynx with reclining. At R0, all swallows were evoked when the bolus head was located in the lateral or posterior wall of the pharynx. The onset lag time and peak lag time were not affected by body posture, whereas the whiteout time was significantly shorter for R90 than R30 and R0 and for R60 than R0 (Table 2, Fig. 4).

3.3. EMG findings in the chewing test

As we did not record any masticatory behaviors using masseter EMGs or jaw movement trajectories, we could not perform systematic evaluation of chewing behaviors before swallowing. However, using the stage II transport time, we found no significant difference among the body postures (Table 3, Fig. 5). Rising time and falling time of the EMG burst were not affected by body posture, while the burst duration was significantly different among the postures; the more the body reclined, the longer the EMG burst duration (Table 3, Fig. 5). The peak amplitude was not different between the body postures, while the area was significantly larger for R90 than for R30 and R0 and for R60 than R0 (Table 3, Fig. 5). These data suggest that the reclined posture may predominantly increase the EMG burst duration, which leads to an overall increase of EMG activity.

3.4. VE findings in the chewing test

It is likely that both body posture and bolus processing or location in the oral cavity and pharynx are important determinants of the pattern of swallowing movement. The portion of the head of the bolus at the start of whiteout was significantly dependent on body posture (Fig. 3B). At R90, most swallows were evoked when the bolus head reached the posterior tongue or epiglottic valleculae while it spread over the lateral or posterior wall of the pharynx with the body reclining. The ratio of the presence of bolus residue in the pharynx after the first swallow increased with body reclining (Fig. 3C). The onset lag time and peak lag time were not affected by the body posture, while the whiteout time was significantly longer for R0 and R30 than for R60 and R90 (Table 2, Fig. 6).

3.5. Correlation between EMG and VE variables

The temporal pattern of EMG burst and whiteout are summarized in Fig. 7. As described, while the temporal relationship between the onset of EMG burst and that of whiteout was not affected by reclining, both

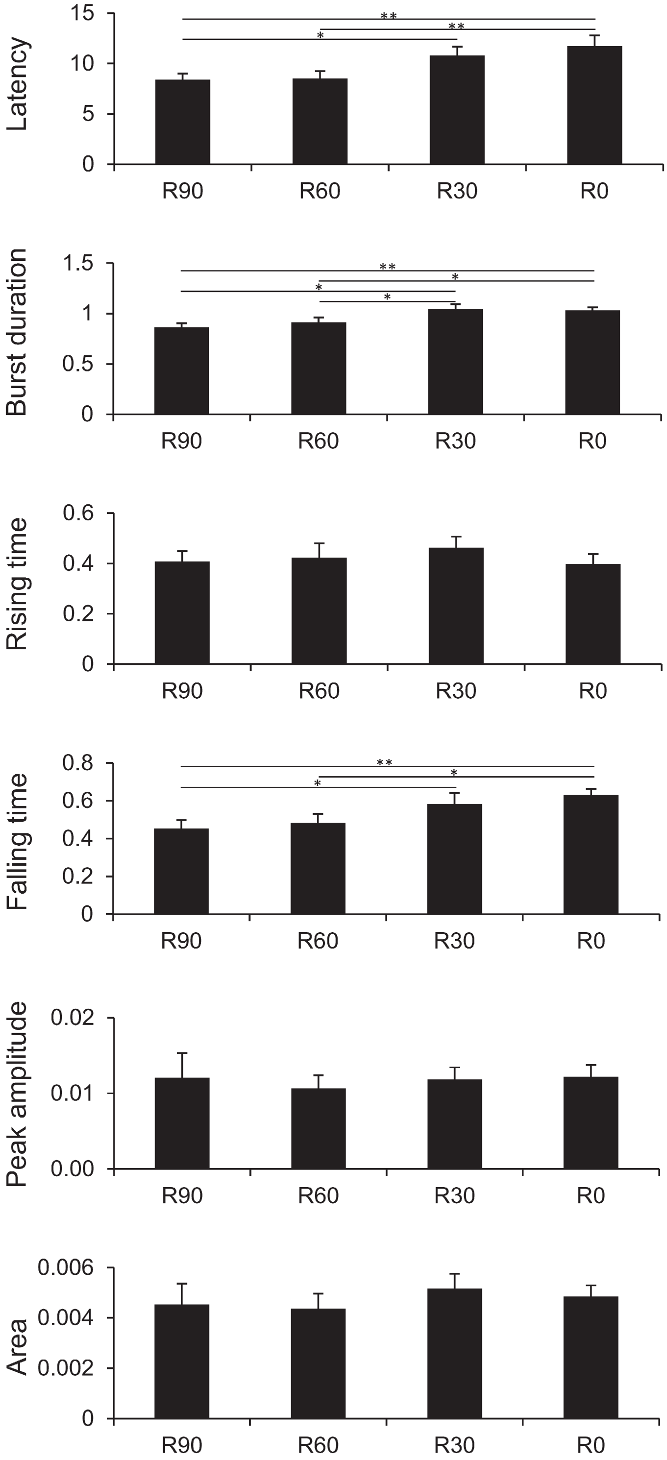

Fig. 2. Effect of body position on EMG burst in the water infusion test. Latency was 8.4 ± 0.6 s for R90, 8.5 ± 0.7 s for R60, 10.8 ± 0.8 s for R30, and 11.7 ± 1.1 s for R0. There was a significant difference between R90 and R0 and between R60 and R0. Burst duration was 0.86 ± 0.04 s for R90, 0.91 ± 0.05 s for R60, 1.04 ± 0.05 s for R30, and 1.03 ± 0.03 s for R0. There was a significant difference between R90 and R30, R90 and R0, R60 and R30, and R60 and R0. Rising time was 0.41 ± 0.04 s for R90, 0.42 ± 0.06 s for R60, 0.46 ± 0.04 s for R30, and 0.40 ± 0.04 s for R0, with no differences between the postures. By contrast, falling time exhibited posture-dependent changes: 0.45 ± 0.04 s for R90, 0.49 ± 0.04 s for R60, 0.58 ± 0.06 s for R30, and 0.63 ± 0.03 s for R0. There was a significant difference between R90 and R30, R90 and R0, and R60 and R0. Peak amplitude was 0.012 ± 0.003 mV for R90, 0.011 ± 0.002 mV for R60, 0.012 ± 0.002 mV for R30, and 0.012 ± 0.002 mV for R0. Area was 0.0045 ± 0.0008 mV·s for R90, 0.0043 ± 0.0005 mV·s for R60, 0.0052 ± 0.0006 mV·s for R30, and 0.0048 ± 0.0004 mV·s for R0. There was no significant difference between the positions. $^{**}P < 0.01$, $^{*}P < 0.05$.

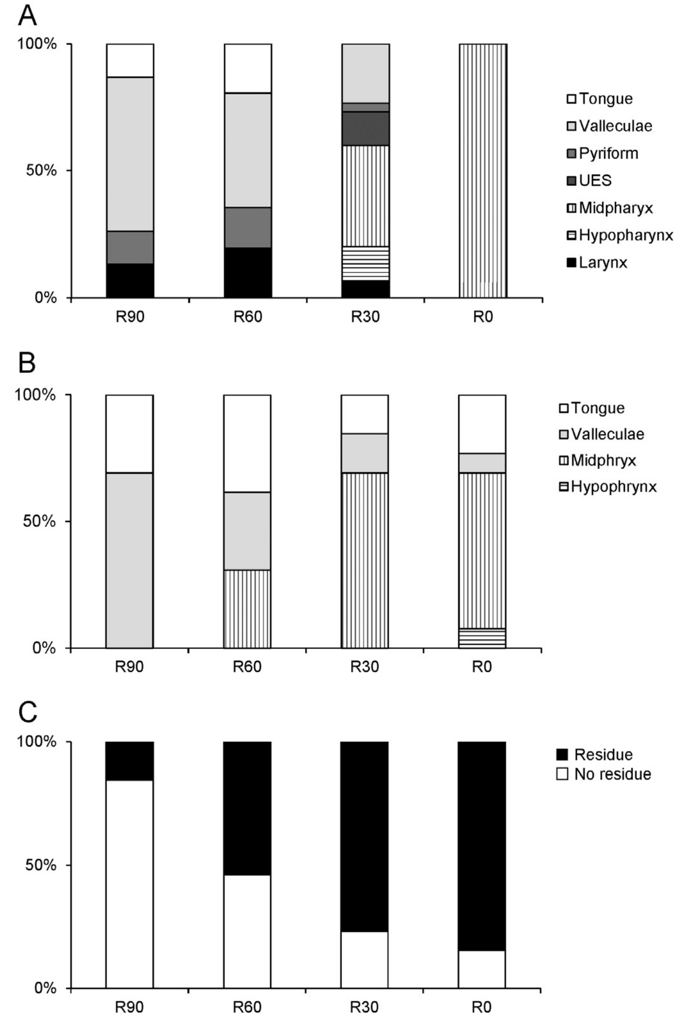

Fig. 3. The portion of the head of the bolus at the start of pharyngeal swallow in the water infusion test (A) and chewing test (B), and ratio of pharyngeal residue after the first swallow in the chewing test (C). (A) At R60 and R90, most swallows were evoked when the bolus head was located in the posterior tongue, epiglottic valleculae, or pyriform sinus. The bolus head spread over the entrance of the UES or the lateral or posterior wall of the midpharynx at R30. At R0, all the swallows were evoked when the bolus head was located in the lateral or posterior wall of the midpharynx. DF = 18, Chi-squared = 97.922, $P < 0.001$. (B) At R90, most swallows were evoked when the bolus head was located in the posterior tongue or epiglottic valleculae while it spread over the lateral or posterior wall of the midpharynx or hypopharynx at reclined postures. DF = 9, Chi-squared = 23.595, $P < 0.01$. (C) The ratio of the bolus residue in the pharynx after the first swallow increased at reclined position. DF = 3, Chi-squared = 15.442, $P = 0.001$.

the duration of the EMG burst and whiteout time increased with reclining. In particular, in the water infusion test, changes in burst duration were likely a result of increase of falling time. Thus, we investigated the correlation between these variables by regression analysis. For this purpose, we measured normalized burst duration, falling time, and whiteout time to those at R0. There was a positive correlation between falling time and EMG burst duration and between EMG burst duration and whiteout time in the water infusion test (Fig. 8). Although similar findings were observed in the chewing test, the correlations were weaker than that for the water infusion test (Fig. 8). Finally, we found a positive correlation between falling time and EMG burst duration in the water infusion test (Fig. 8).

4. Discussion

In the present study, we investigated the effect of body posture on suprahyoid EMG activity and bolus transport in the pharynx during spontaneous saliva swallowing and swallowing following mastication.

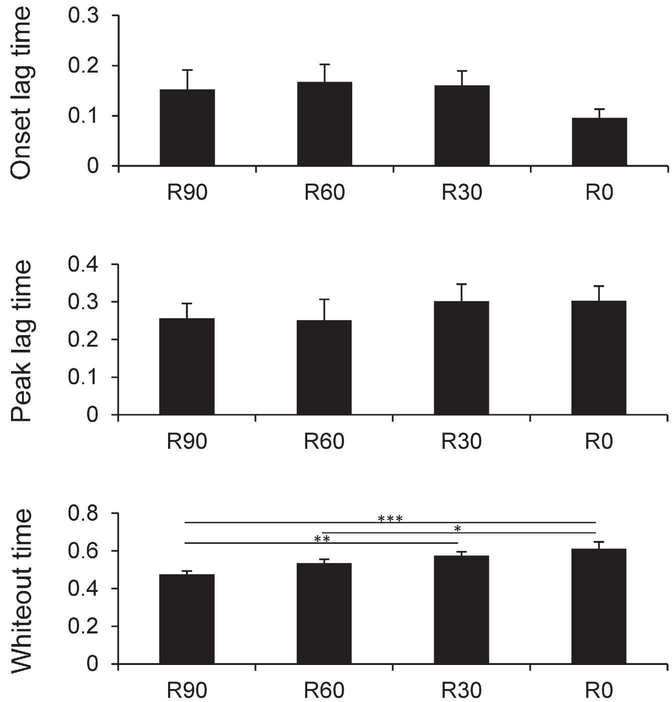

Fig. 4. Effect of body position on onset lag time, peak lag time, and whiteout time in the water infusion test. Onset lag time was 0.15 ± 0.04 s for R90, 0.17 ± 0.03 s for R60, 0.16 ± 0.03 s for R30, and 0.09 ± 0.02 s for R0. Peak lag time was 0.26 ± 0.04 s for R90, 0.26 ± 0.05 s for R60, 0.30 ± 0.05 s for R30, and 0.30 ± 0.04 s for R0. There was no significant difference between the positions. The whiteout time was 0.48 ± 0.02 s for R90, 0.54 ± 0.02 s for R60, 0.57 ± 0.02 s for R30, and 0.61 ± 0.04 s for R0. There was a significant difference between R90 and R30, R90 and R0, and R60 and R0. Whiteout time for R90 was significantly shorter than that for any other posture. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

In the water infusion test, reclining changed the location of the bolus head at the start of swallow and prolonged the onset latency of the swallowing initiation. EMG burst duration and whiteout time representing the duration of pharyngeal swallow significantly increased with body reclining, and the falling time also increased. In the chewing test, reclining changed the location of the bolus head at the start of swallow, and the frequency of bolus residue after the first swallow increased. The duration and area of the EMG burst and whiteout time significantly increased with body reclining. By contrast, the temporal relationships between the onset of EMG burst and whiteout and between the onset of whiteout and peak of EMG burst were not affected by body posture in either test. Functional consideration of the effect of body posture on involuntary swallowing performance is discussed below.

4.1. Effect of reclining posture in the water infusion test

In the water infusion test, the mean latency of swallowing initiation ranged from 8.4 to 11.4 s, while the estimated bolus volume per swallow ranged from 0.42 to 0.57 ml. Although the body posture significantly affected the latency of swallowing initiation, the difference in the estimated bolus volume was only 0.15 ml. Rudney et al. [37] reported that the estimated volume of saliva that evokes spontaneous swallow was 0.46 ml in a normal subject. In that study the subjects were instructed to sit, the same posture as upright in the present study, suggesting that our condition represented the natural situation of spontaneous saliva swallow.

Although we did not clarify whether such a small volume between 0.42–0.57 ml was large enough to stimulate mechanoreceptors responsible for the swallowing initiation, it would be reasonable to consider that water-sensitive receptors in the pharynx were involved in swallowing initiation. Water-sensitive fibers in the pharynx can initiate

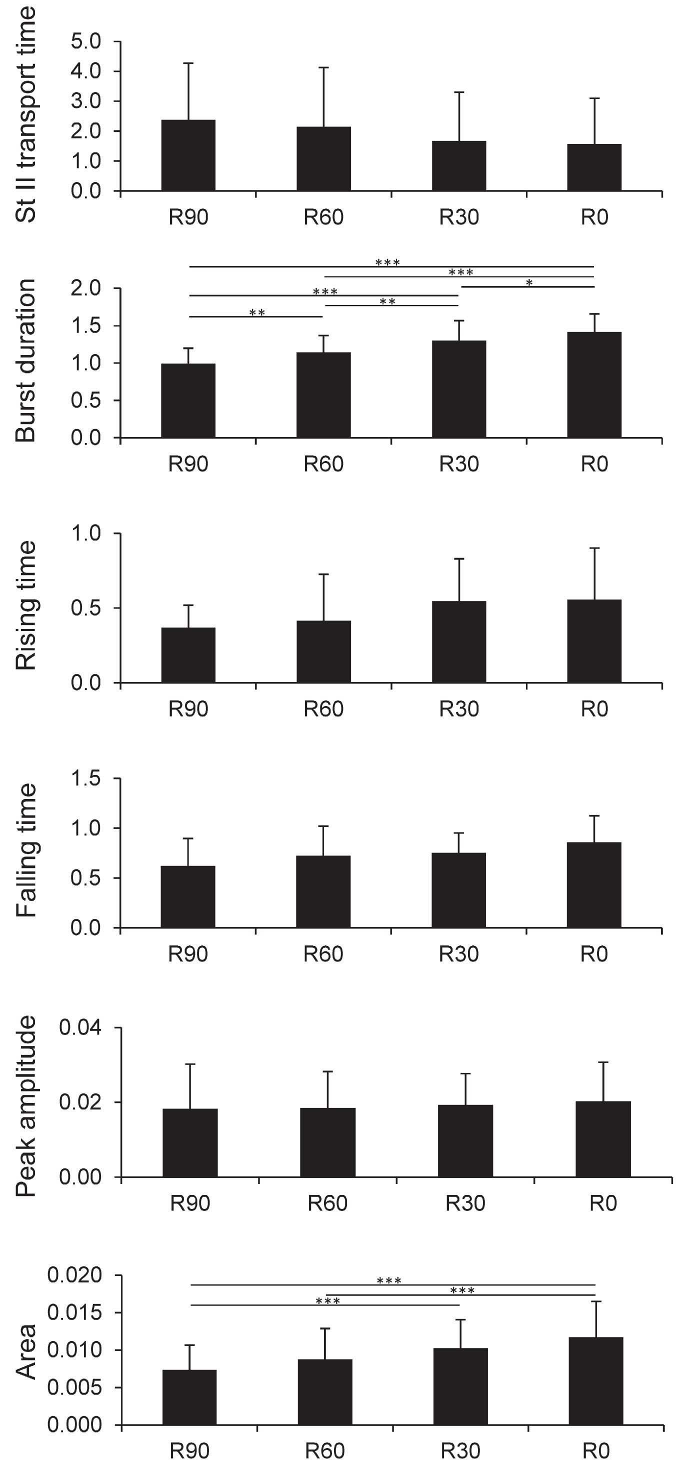

Fig. 5. Effect of body position on EMG burst in the chewing test. The stage II transport time was 2.38 ± 1.89 s for R90, 2.15 ± 1.98 s for R60, 1.67 ± 1.62 for R30, and 1.57 ± 1.53 s for R0. Burst duration was 0.99 ± 0.21 s for R90, 1.14 ± 0.23 s for R60, 1.30 ± 0.26 s for R30, and 1.42 ± 0.24 s for R0. There was a significant difference between each body position, indicating body posture-dependent changes. Rising time was 0.37 ± 0.15 s for R90, 0.42 ± 0.31 s for R60, 0.55 ± 0.28 s for R30, and 0.56 ± 0.35 s for R0. Falling time was 0.62 ± 0.27 s for R90, 0.73 ± 0.29 s for R60, 0.75 ± 0.20 s for R30, and 0.86 ± 0.27 s for R0. There were no significant differences among the body postures. Peak amplitude was 0.018 ± 0.012 mV for R90, 0.018 ± 0.010 mV for R60, 0.019 ± 0.008 mV for R30, and 0.020 ± 0.010 mV for R0, with no significant differences among the positions. Area was 0.0074 ± 0.0032 mV·s for R90, 0.0088 ± 0.0041 mV·s for R60, 0.0102 ± 0.0038 mV·s for R30, and 0.0112 ± 0.0048 mV·s for R0. There was a significant difference between R90 and R30, R90 and R0, R60 and R30, and R60 and R0. ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$.

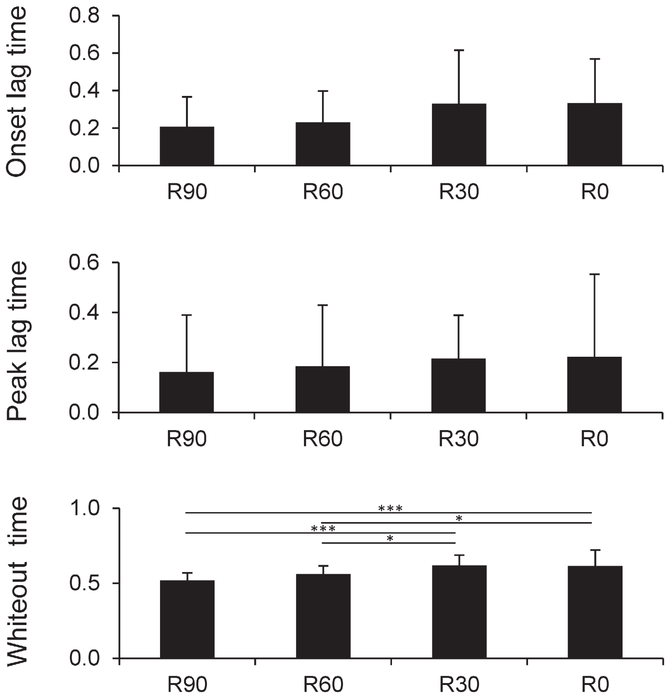

Fig. 6. Effect of body position on onset lag time, peak lag time, and whiteout time in the chewing test. Onset lag time was 0.21 ± 0.16 s for R90, 0.23 ± 0.17 s for R60, 0.33 ± 0.28 s for R30, and 0.33 ± 0.23 s for R0. Peak lag time was 0.16 ± 0.23 s for R90, 0.19 ± 0.24 s for R60, 0.22 ± 0.17 s for R30, and 0.22 ± 0.33 s for R0. There were no significant differences among the body positions. The whiteout time was 0.52 ± 0.05 s for R90, 0.56 ± 0.05 s for R60, 0.62 ± 0.07 s for R30, and 0.62 ± 0.10 s for R0. Significant differences were observed between R90 and R30, R90 and R0, R60 and R30, R60 and R0. ***$P < 0.001$, *$P < 0.05$.

the swallowing reflex in humans [38–40]. Facilitatory effects of water application at a very slow rate to the pharynx on the initiation of swallowing have also been shown [41,42]. In the present study, the differences in the latency between the body postures may reflect differences in the stimulated region and how the water-sensitive receptors responded at each site, as peripheral endings are densely distributed at the piriform sinus or entrance of the upper esophageal sphincter beside the arytenoideus, but sparse on the posterior pharyngeal wall [29]. Our data suggest that the differences in swallowing initiation among the body postures in the water infusion test may relate to the stimulus site, which changed from the anterior to posterior wall in the pharynx with body reclining, rather than by bolus volume. Thus, the swallowing evoked in this test can be regarded as swallowing reflex evoked purely by the peripheral afferents arising from the water-sensitive receptors.

Our findings raise the question of how the reclined posture affected swallowing movements. We found that the temporal relationship between onset and peak of EMG burst and onset of whiteout was not affected by body posture. During swallowing, the hyoid bone first moves upwards and then forwards, before returning to the starting position. By recording jaw and hyoid movements, Ishida et al. [43] demonstrated that upward and forward displacement of the hyoid in swallowing was primarily related to events in the oral cavity and pharynx, respectively. Wheeler-Hegland et al. [44] recorded hyoid movements and suprahyoid EMGs, and found that the hyoid sequence generally occurred at the peak of EMG burst, followed by maximum elevation of the hyoid and then maximum anterior displacement of the hyoid in normal swallow. The maximum elevation during a normal swallowing task remains constant among healthy humans, indicating that a specific amount of elevation relative to the hyoid starting point at onset of pharyngeal swallow is associated with a healthy swallow. This condition supports our finding that the motor sequence before the peak of EMG burst, possibly including upward movement of the

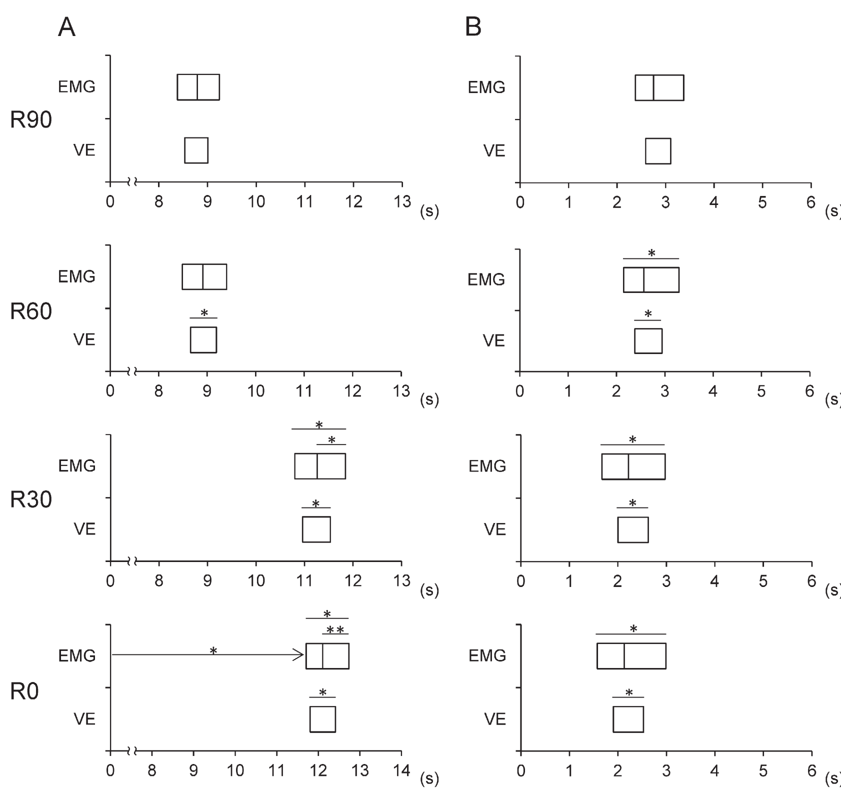

Fig. 7. Temporal pattern of EMG burst and whiteout observed in VE. EMG bar represents mean time of EMG burst. VE bar represents mean time of whiteout. Data from the water infusion test and chewing test are shown in (A) and (B), respectively. Left, middle, and right vertical lines of EMG bar indicate onset, and peak and offset of EMG burst, respectively. Left and right vertical lines of VE bar indicate onset and offset of whiteout, respectively. Time zero indicates the start of water infusion for water infusion test (A) and the time of appearance of bolus in the pharynx (i.e., start of stage II transport) (B). * $P < 0.05$, **$P < 0.01$, significantly different from R90.

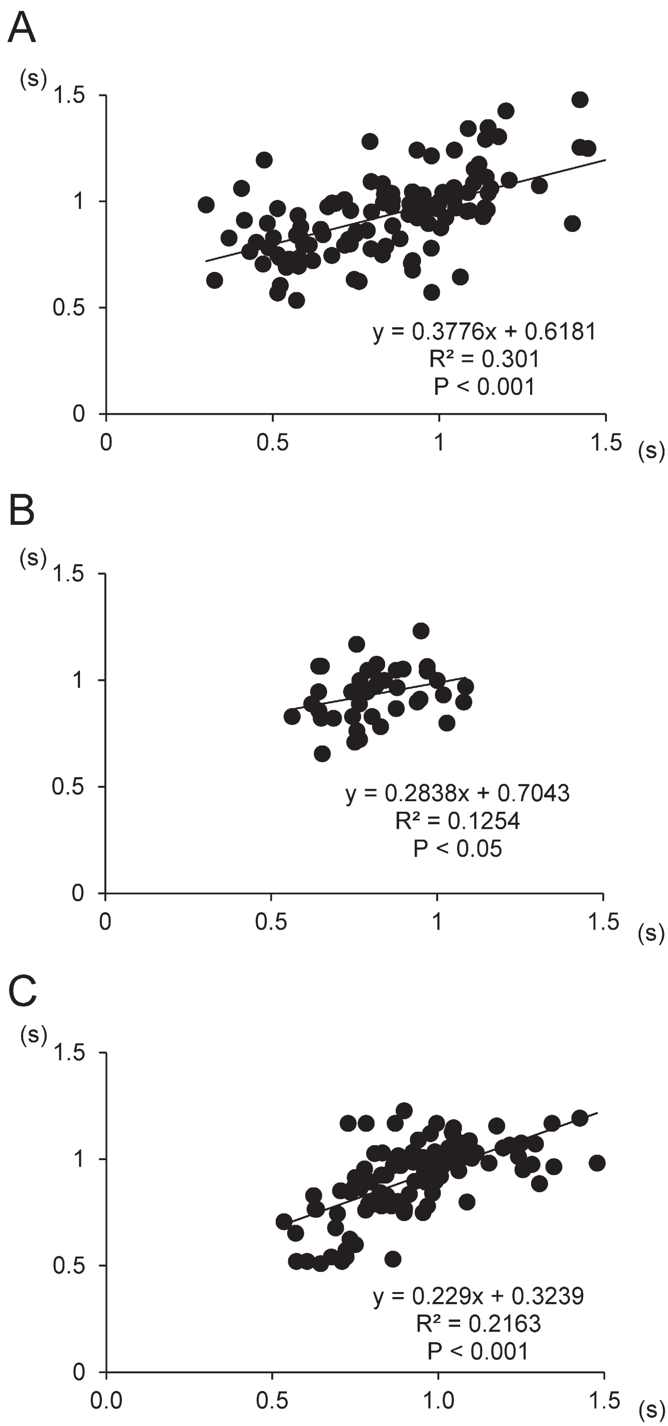

Fig. 8. Temporal relationship between the EMG burst and whiteout. Correlation between duration of EMG burst and whiteout time in the water infusion test (A) and the chewing test (B), and that between the falling time and duration of EMG burst in the water infusion test (C). Regression line, R^2 value, and P value were $y = 0.3776x + 0.6181$, $R^2 = 0.301$, $P < 0.001$ for A, $y = 0.2838x + 0.7043$, $R^2 = 0.1254$, $P < 0.05$ for B, and $y = 0.229x + 0.3239$, $R^2 = 0.2163$, $P < 0.001$ for C. There was a significant correlation in all cases.

hyoid, was not affected by body posture, as there was no bolus in the oral cavity in this situation.

Reclined posture may require antigravitational movement of the hyoid, corresponding to the forward movement in an upright posture. As the suprahyoid musculature plays an important role in the movements of the hyolaryngeal complex, its burst duration could be prolonged when such antigravitational movement is required, without any changes in rising time and peak amplitude. Wheeler-Helgland et al. [44] found no difference in anterior displacement of the hyoid during swallowing among several tasks, suggesting that the muscles contractile and temporal relationships between biomechanical events may be altered by various postures, thus preserving the maximum anterior displacement of the hyoid bone. In support, it was reported that vertical motion of the hyoid bone is primarily related to oral bolus manipulation, while forward movement is associated with the pharyngeal swallow [43].

Taken together, our data suggest that the EMG burst before its peak corresponds to the upward movements of hyoid, and is not affected by body posture. By contrast, the falling time and whiteout time, corresponding to the late part of the EMG burst after its peak, are associated with pharyngeal swallow, and are strongly affected by body posture because of the difference in the direction in forward movement of the hyoid among the body postures.

4.2. Effect of reclining posture in the chewing test

In the chewing test, the stage II transport time was minimally affected by body posture. Palmer [45] examined whether bolus aggregation in the oropharynx during chewing was dependent on gravity, and reported that transport of chewed solid food from the oral cavity to the pharynx (i.e., stage II transport) typically started several seconds before onset of pharyngeal swallow. Thus, it was concluded that regardless of head position, transport of chewed solid food from the oral cavity to the pharynx did not depend on gravity. Our findings were largely identical, in that the stage II transport time was not affected by body posture.

The location of the bolus head at the start of swallow and the frequency of the bolus residue after the first swallow were significantly different among the conditions. In a reclined posture (e.g., R30 or R0), the bolus was propelled onto the posterior wall of the pharynx, while it was mainly located on the anterior wall such as the posterior tongue or epiglottic valleculae in R90. In addition, the change in the body posture affected EMG activity and the pharyngeal swallow, with a significant increase in duration and area of EMG burst and whiteout time with body reclining. As the rising time and peak amplitude of the EMG burst, and the temporal relationship between onset and peak of EMG burst and onset of whiteout, were not affected by the body posture, the bolus transport in the oral cavity is unlikely to be changed by reclining, while that in the pharynx would change. Such changes may be attributed to the effect of body posture on the movement of the hyolaryngeal complex and on bolus transport in the pharyngeal cavity.

Inagaki et al. [18] recorded suprahyoid EMGs during voluntary swallowing of 1 g test food over a range of upright to supine positions, and found that the average rising time of the EMG burst decreased with body reclining. Of note, in that study the task was voluntary swallowing, and swallow-related EMGs included voluntary and involuntary (possibly reflexive) components. Interestingly, our data show a difference in the rising time compared to that reported by Inagaki et al. [18]. In the present study, the mean rising time varied from 0.40 to 0.42 s in the water infusion test and from 0.37 to 0.52 s in the chewing test, which was shorter than that of 0.5–0.8 s by Inagaki et al. [18]. This difference in the duration may be attributed to the involvement of the voluntary component of EMG activity. During voluntary swallowing, the first stage of swallowing starts with voluntary oral transition of the bolus in the oral cavity. The reclined posture will likely shorten the oral transit time because of the gravitational force in the oral cavity, and hence provide easy oral transport. Lying down may start the pharyngeal swallow earlier by causing significant changes in the duration of the EMGs. In other words, reclining posture may affect the duration of the suprahyoid EMG by modifying the timing of the start of the pharyngeal swallow during voluntary swallowing.

The majority of studies investigating the effect of body posture on EMG have reported no effect of body posture [6,17,19,21,46,47]. Thus, it is possible that differences in the task and food materials may cause such differences. First, in all these studies the subjects were instructed to swallow voluntarily. Dejaeger et al. [17] examined the effect of body posture on voluntary swallow in upright, supine, and upside down postures, and found that tongue force and oropharyngeal propulsion pump increased and hypopharyngeal suction pump decreased with body reclining, while other parameters such as pharyngeal transit time and pharyngeal contraction were unaffected. Jonsson et al. [19] investigated the effect of body posture on pharyngeal bolus transport during voluntary swallow, and demonstrated that hypopharyngeal intrabolus pressure and maximum upper esophageal sphincter diameters increased in reclining, while the duration of sphincter opening decreased, with no changes in other parameters such as total swallowing duration, oral and pharyngeal transit time, pharyngeal peristaltic amplitude and duration, the length of the bolus in the pharynx, and excursions of the hyoid and larynx. These data suggest that intrabolus pressure in the oral cavity produced by the tongue and that in the hypopharynx controlled by the UES opening are important determinants, and that gravity does not significantly affect pharyngeal bolus transport. These changes may compensate for the changes in the body posture at least during voluntary swallowing, although activity patterns may be different between voluntary and involuntary swallowing [48]. The differences in function between involuntary and voluntary swallowing remain unknown.

Second, differences in the test material should be considered. We used a gruel rice as a test food, which requires chewing, whereas thickened agent, water, or saliva swallowing were employed in all previous studies [6–8,17–19,21,46,47]. Although we did not measure the textural property of our bolus, previous reports suggest that the adhesiveness and cohesiveness of gruel rice are higher and lower than those of thickened agent or water, respectively [6,49]. As gruel rice is originally made of steamed rice and water, it easily breaks into pieces during swallowing. When the body is reclined, the gravitational force in the pharynx is inhibited. In this case, the physical properties of the bolus can directly affect bolus flow in the pharynx. The high adhesiveness and low cohesiveness of gruel rice may affect the bolus transport during pharyngeal swallow, thus causing an increase in the frequency of pharyngeal residue after the first swallow with body reclining.

4.3. Limitations

There are several potential limitations in our study. First, the subjects were instructed to chew freely in a natural manner and we did not assess any chewing behaviors other than stage II transport. No systematic studies have been performed to evaluate the effect of body posture on the chewing performance. Oral processing and bolus transport in the oral and midpharyngeal cavities might be affected by the body posture. Second, we recorded only VE images to observe bolus propulsion in the pharynx, and thus were unable to evaluate changes in the oral and pharyngeal transit time, manometry, or bolus flow during swallowing. Finally, we recruited only thirteen males as our subjects and used only gruel rice as a test food. Future studies are required to compare the effects of body posture on chewing and swallowing behaviors using a large sample size of both sexes and using several foods to increase the external validity of the results.

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Disclosure

The authors declare that they have no conflicts of interest.

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