Evaluation of Tongue-, Jaw-, and Swallowing-Related Muscle Coordination During Voluntarily Triggered Swallowing

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Purpose: The prosthodontic treatment of dysphagic patients may preclude favorable treatment outcomes due to uncoordinated or discordant oral and pharyngeal functions. Since optimal treatment requires a full understanding of the mechanism of oropharyngeal swallowing, this study seeks to describe the normal temporal pattern of tongue-, jaw-, and swallowing-related muscle coordination during voluntarily triggered swallows in healthy patients. ***Materials and Methods:*** Tongue pressure against the hard palate at seven measuring points, swallowing sounds, and surface electromyography (EMG) activity of the masseter, anterior digastric, and infrahyoid muscles during voluntarily triggered swallowing were recorded in seven healthy male volunteers. The order of onset and offset of these parameters was analyzed by repeated-measures two-way analysis of variance. ***Results:*** The onset of anterior digastric muscle activity occurred first and was significantly earlier than the onset of the masseter or infrahyoid muscles and tongue pressure. The onset of masseter muscle activity was also significantly earlier than that of the infrahyoid muscle and tongue pressure. Offset of masseter activity was almost simultaneous with the swallowing sound and was significantly earlier than the offset of the anterior digastric and infrahyoid muscles as well as tongue pressure. The EMG burst of the anterior digastric muscle continued until the offset of tongue pressure, and was followed by the offset of infrahyoid muscle activity. ***Conclusions:*** The temporal coordination patterns of the tongue, jaw, and oropharyngeal muscles during voluntarily triggered swallowing appear to agree with known safe management of a bolus and offer criteria for evaluating the function of oropharyngeal swallowing. *Int J Prosthodont 2009;22:493–498.*

The steep growth of the elderly population in the late 20th century has resulted in an increasing number of aged people who are losing the ability to feed themselves. This problem results from age-related diseases such as cerebrovascular accidents and sensory-motor disorders associated with neurologic disease. Dysphagia in such patients can cause life-threatening pneumonia as well as a decrease in daily living activities and quality of life.[1,2] Dentists will begin to treat dysphagic aging patients more frequently and will have to select optimal treatment options based on a full understanding of the function of swallowing. Although a qualitative observatory evaluation of dysphagia using videofluorography is widespread in the medical field,[3,4] a quantitative and noninvasive evaluation of the entire sequence of the oropharyngeal swallowing process remains to be established.

Swallowing can be initiated both consciously and unconsciously. Although the prepharyngeal stage of swallowing is controlled voluntarily in the command swallow, the pharyngeal and esophageal stages are controlled by means of reflexes. Many muscles in the oropharyngeal region are coordinated sequentially by

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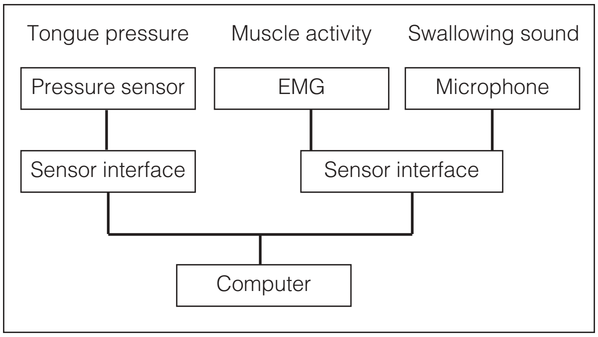


Fig 1a Experiment setup and instrumentation.

Fig 1b *(right)* Masseter, anterior digastric, and infrahyoid muscle locations of EMG electrodes on a subject fit with an experimental palatal plate with seven pressure sensors on the maxilla and a microphone beside the cricoid cartilage.

the medulla oblongata, even though muscle activity is initiated voluntarily.[5–7] Electromyography (EMG) and other sensing methods are used to investigate the pathologic mechanism of dysphagia in patients suffering from strokes,[8,9] myasthenia gravis,[10] amyotrophic lateral sclerosis,[11] and Parkinson disease.[12] However, these methods focus mainly on laryngeal elevation and cricopharyngeal opening during the swallowing reflex. Even though the tongue plays a series of important roles during mastication and swallowing (food comminution, bolus formation, bolus transport, and generation of swallowing pressure[13]), previous studies on the coordination of tongue movement and oropharyngeal muscle activity were limited to mainly animal experiments[14–18] and human study through observations using videofluorography.[19–28] These limitations might be due to difficulties recording EMGs of the tongue or quantitatively measuring tongue movement because of the absence of adequate protocols or devices.

Recently, advanced technology has made it possible to evaluate tongue activity through the production of tongue pressure against the hard palate by using pressure sensors installed in a palatal plate or maxillary denture.[29–34] Previous authors described the normal pattern of tongue pressure production at seven measuring points on the hard palate during the swallowing of water,[33] and elucidated the coordination pattern between tongue and jaw movement during mastication and the swallowing of solid food.[34] Based on these results, the present study seeks to describe the normal temporal pattern of coordination between tongue pressure production and jaw- and swallowing-related muscle activity during voluntarily triggered swallowing to develop quantitative criteria for evaluating the oropharyngeal swallowing function. Such baseline information can then be compared to similar evaluative data in elderly patients and those with a different functional status.

Materials and Methods

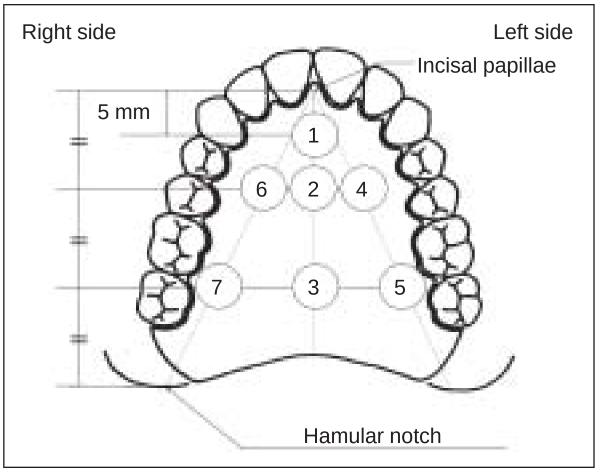
Subjects

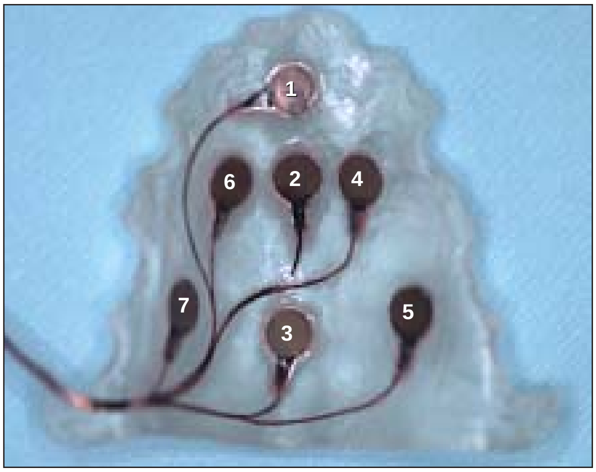
Seven healthy males (mean age: 28.1 years) without a history of compromised mastication or swallowing, any occlusal abnormalities, or a history of orthodontic treatment or temporomandibular disorder participated in this study. Written informed consent was obtained from each subject after an explanation of the aim and methodology of the study, which received approval from the ethics committee at the Osaka University Graduate School of Dentistry, Osaka, Japan.

Measuring System and Procedure

The authors used a previously developed palatal plate technique with seven pressure sensors to measure tongue pressure during mastication and swallowing,[33,34] which also allowed for the simultaneous recording of muscle activity and the sound of swallowing using an EMG and a microphone, respectively (Figs 1a and 1b). Tongue pressure against the hard palate was measured using seven disk-shaped pressure sensors (6 mm in diameter, 0.6 mm thick; PS-2KA, Kyowa Electric Instruments) installed in a palatal plate fabricated from acrylic resin (1.2 mm thick). The location of the sensors in relation to oral structures is shown in Figs 2a and 2b. Cables from each sensor were passed through a vinyl tube (1 mm in diameter) to exit the oral cavity via the oral vestibule. Data were recorded on a personal computer via the sensor interface (PCD-300A, Kyowa Electric Instruments).

Among the many muscles involved in swallowing, the submental and infrahyoid muscles contribute to positioning the hyoid bone and larynx, and jaw-closing muscles contribute to bringing the jaw into the swallowing position.[29,35–37] In the present study, EMG





Figs 2a and 2b Location of pressure sensors on a constructed plate. Sensor 1: 5 mm posterior to the incisive papillae, sensor 2: one-third of the way anteriorly between the incisive papillae and posterior edge of the palate, sensor 3: one-third of the way posteriorly between the incisive papillae and posterior edge of the palate, sensor 4: one-third of the way anteriorly between the incisive papillae and hamular notch on the left side, sensor 5: one-third of the way posteriorly between the incisive papillae and hamular notch on the left side, sensor 6: one-third of the way anteriorly between the incisive papillae and hamular notch on the right side, sensor 7: one-third of the way posteriorly between the incisive papillae and hamular notch on the right side.

activity was monitored at three surface electrode placement sites: the masseter muscle, the anterior belly of digastric muscle representing the submental muscles, and the sternohyoid muscle representing the infrahyoid muscles. Surface electrodes (interelectrode difference 19.5 mm; Duo-Trode, Myo-Tronics) were applied to the belly of each muscle on the left side, since no side-to-side difference was found in the EMG of muscles involved in swallowing in healthy subjects.[38] EMG data were amplified using an amplifier (BA-1008, TEA) and then recorded on a personal computer via a sensor interface (PCD-320A, Kyowa Electric Instruments). To detect the timing of the opening of the esophageal entrance,[37] swallowing sound was monitored by a microphone (JM-0116, Ono Sokki) placed 10 mm beside the cricoid cartilage[39,40] and recorded on a personal computer via a sensor interface. Data were integrated on the personal computer and differences in the order of the onset and offset of tongue pressure and muscle activity, as well as signal to swallow and the sound of swallowing, were analyzed statistically.

Two identically shaped palatal plates were fabricated for each subject, one to be worn for a week before the experiment for adaptation and the other to be equipped with pressure sensors to obtain experimental data. All experiments were performed in a sealed room with the subjects sitting in an upright position. The subject's head was kept steady by the headrest of the chair so that the Frankfort plane was parallel to the floor. Recording started when the subject was given the signal to swallow 15 mL of water that was held in the mouth for a brief period of time. This was performed three times per day for 3 days.

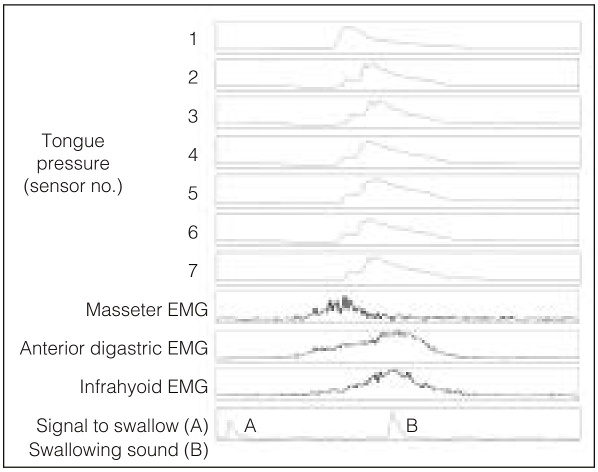


Fig 3 A representative recording of tongue pressure at sensors 1 through 7; integrated EMG of the masseter, anterior digastric, and infrahyoid muscles; signal to swallow; and swallowing sound from which coordination of tongue and oropharyngeal muscle activity was analyzed.

Statistical Analysis

Figure 3 shows an example of the temporal pattern of tongue pressure production (sensors 1 through 7); integrated EMG bursts of the masseter muscle, anterior digastric muscle, and infrahyoid muscle; the signal to swallow; and swallowing sound. The onset and offset times of tongue pressure and EMG bursts of each muscle and the detection of swallowing sound were analyzed over the time course where the onset time of tongue pressure at sensor 1 was set to 0 seconds. The onset time of each EMG burst was the time when it was

Table 1 Onset and Offset Times (Mean ± SD) of Tongue Pressure at Sensors 1 Through 7; EMG Activity of Masseter, Anterior Digastric, and Infrahyoid Muscles; and the Detected Time of Signal to Swallow and Sound During Swallowing

	Onset (s)	Offset (s)
Signal to swallow	–0.84 ± 0.29	
Tongue pressure		
Sensor 1	0*	0.91 ± 0.09
Sensor 2	0.16 ± 0.07	0.91 ± 0.09
Sensor 3	0.24 ± 0.10	0.92 ± 0.09
Sensor 4	0.15 ± 0.08	0.91 ± 0.09
Sensor 5	0.19 ± 0.09	0.92 ± 0.09
Sensor 6	0.15 ± 0.07	0.91 ± 0.09
Sensor 7	0.18 ± 0.09	0.92 ± 0.09
Masseter EMG	–0.15 ± 0.11	0.42 ± 0.13
Anterior digastric EMG	–0.31 ± 0.16	0.92 ± 0.12
Infrahyoid EMG	–0.05 ± 0.19	1.03 ± 0.14
Swallowing sound	0.41 ± 0.12	

*The onset of tongue pressure at sensor 1 was set to 0 seconds.

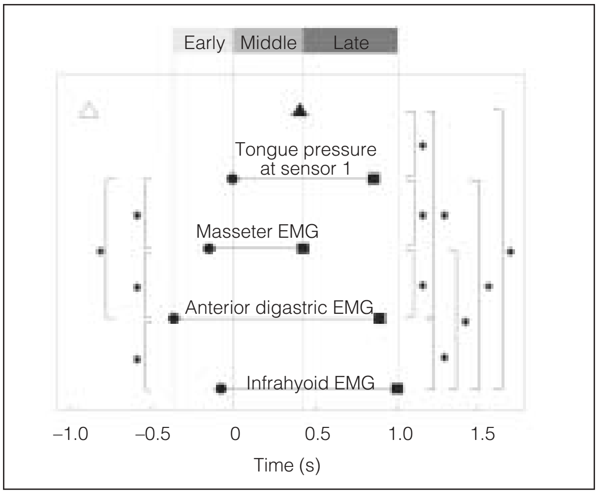


Fig 4 The coordination of tongue pressure produced at sensor 1; activity of masseter, anterior digastric, and infrahyoid muscles; and sound during swallowing. The onset of tongue pressure at sensor 1 was set to 0 seconds. △ = Signal to swallow, ▲ = swallowing sound, • = onset, ■ = offset, and * = $P < .05$.

beyond 2 standard deviations (SDs) of baseline activity; offset time was when it was below 2 SDs.[38] To examine the differences in order of onset and offset times between tongue pressure at sensor 1, EMG bursts of each muscle, and detection time of swallowing sound, uniformity of variance was determined using the Bartlett test. When uniform variance was found, significant differences were determined by repeated-measures two-way analysis of variance and comparison testing was performed using the Tukey test. Statistical analysis was completed using SPSS 12.0 for Windows and a P value of $< .05$ was considered statistically significant.

Results

Table 1 shows the means and SDs of onset and offset times of tongue pressure at each sensor, the EMG burst of each muscle, and the detection of swallowing sound. Tongue pressure at sensor 1 was generated 0.84 ± 0.29 seconds after the signal to swallow, then at sensors 6, 4, 2, 7, 5, and finally at sensor 3. Offset times of tongue pressure did not differ significantly between the various sensors. Among the three sensors installed on the median line of the palatal plate, tongue pressure at sensor 1 was generated significantly earlier than at sensor 3. The order of tongue pressure onset was sensor 1, then sensor 2, and finally sensor 3. This sequence of tongue pressure production in the initial stage of voluntarily triggered swallowing indicates the significance of an anterior to posterior order of tongue contact with the hard palate for transporting the bolus into the pharynx. Thus, the authors established the time course where onset time of tongue pressure at sensor 1 was set to 0 seconds for evaluating myofunctional coordination during the entire sequence of swallowing water. The EMG burst was generated at –0.31 ± 0.16 seconds and ceased at 0.92 ± 0.12 seconds in the anterior digastric muscle, generated at –0.15 ± 0.11 seconds and ceased at 0.42 ± 0.13 seconds in the masseter, and generated at –0.05 ± 0.19 seconds and ceased at 1.03 ± 0.14 seconds in the infrahyoid muscle. Swallowing sound was detected at 0.41 ± 0.12 seconds following the signal to swallow.

Figure 4 shows the order for tongue pressure at sensor 1, EMG burst of each muscle, and swallowing sound among the muscles. Onset time of the anterior digastric muscle was significantly earlier than both the masseter and infrahyoid muscles and that of tongue pressure at sensor 1 ($P < .05$). The onset time of the masseter muscle was significantly earlier than that of tongue pressure at sensor 1 ($P < .05$). Offset time of the masseter muscle was almost simultaneous with swallowing sound, and was significantly earlier than that of tongue pressure at sensor 1 and both the anterior digastric and infrahyoid muscles ($P < .05$). Although no difference was found between offset time of tongue pressure at sensor 1 and the anterior digastric muscle, the offset time of the infrahyoid muscle was significantly later than that of tongue pressure at sensor 1, the masseter and anterior digastric muscles, and the swallowing sound ($P < .05$).

Discussion

This study describes a clear temporal coordination of the tongue-, jaw-, and swallowing-related muscles during the entire sequence of a voluntarily triggered swallow. Although electrophysiologic coordination of the oropharyngeal muscles was highly variable,[5] statistically significant trends could be identified in a small number of subjects by using strict criteria for subject selection and design of the measuring system and task. The recording of tongue pressure under near-natural conditions was possible because of the great care taken in fabricating each subject's experimental palatal plate from a standardized design, as well as the use of an adaptation period prior to the experiment.

On the other hand, considerable costs and time for fabricating this type of experimental palatal plate precluded the enrollment of a larger number of study subjects. Although a sensor sheet system for measuring tongue pressure was developed as an alternative to the experimental palatal plate,[41,42] the plate was used in this study because of the importance assigned to a standardized approach for each subject. The sequential order of muscle activation, which might be more reliable than an analysis of the amplitude of each muscle due to limitations in surface EMG, was analyzed. Given these advantages in the protocol as well as the limitations of this study, it was considered that the findings reflect the physiology of the oropharyngeal swallow.

The onset of tongue pressure at sensor 1 can be interpreted as the initiation of bolus transformation from the oral cavity into the pharynx based on studies on the biomechanics of oropharyngeal swallowing using manofluorography.[29] Accurate timing and sufficient intensity of EMG activity of the anterior digastric muscle is critical for the elevation of the larynx during swallowing.[5–12] The onset of the EMG burst of the anterior digastric muscle was significantly earlier than those of the masseter and infrahyoid muscles and tongue pressure at sensor 1. This is consistent with the ultrasonographic findings by Stone and Shawker,[35] that elevation of the hyoid bone starts before the dorsum of the tongue contacts the palate during swallowing. Early activation of the anterior digastric muscle may contribute to the stabilization of contact between the tongue and palate during bolus transport.[29,37]

The onset of the EMG burst of the masseter muscle was significantly later than that of the anterior digastric muscle but also significantly earlier than that of tongue pressure at sensor 1, suggesting that the jaw tended to be in occlusion before beginning bolus transportation from the oral cavity to the pharynx. Furuya[43] found the same order in onset of the anterior digastric and masseter muscles during swallowing and reported that onset of the masseter muscle was delayed when there was no occlusal support. Therefore, it appears that the current findings of the sequential order of the activities of the anterior digastric and masseter muscles and onset of tongue pressure in the initial stage of a voluntarily triggered swallow (from the onset of the anterior digastric muscle to the onset of tongue pressure, Fig 4) provide data important for preventing the bolus from entering the larynx. The entrance of the airway should be reduced to prevent the bolus from reaching the larynx and jaw position should be stabilized in order to generate and maintain tongue pressure against the palate. This observation also suggests the possible importance of a prosthetic restoration for occlusal support.

Subsequent events in the middle stage of a voluntarily triggered swallow occurred such that the offset of the EMG burst of the masseter muscle was significantly earlier than that of the anterior digastric and infrahyoid muscles and was noted almost simultaneous with the swallowing sound (Fig 4). These findings suggest that activation of the masseter muscle for positioning the jaw in occlusion ceased when the bolus passed through the entrance of the esophagus. This can be claimed based on the assumption that the sound of swallowing reflects the bolus passage into the esophagus. Since there is a possibility that swallowing sound reflects other events, such as the opening of the eustachian tube, improvement in the acoustic analysis of swallowing sound is recommended.

In the late stage of a voluntarily triggered swallow (from the offset of masseter muscle activity to that of infrahyoid muscle activity, Fig 4), the offset time of tongue pressure was significantly later than the hypopharyngeal transit of the bolus and was almost simultaneous with that of the anterior digastric muscle, which was followed by the offset of the infrahyoid muscle. These sequential orders may contribute to the continued elevation of the larynx and maintenance of swallowing pressure by keeping the tongue in contact with the palate until the bolus enters the esophagus. It was reported that the onset of an EMG burst of the infrahyoid muscle, which contributes to the stabilization of the hyoid bone and pulls down the larynx, reflects the beginning of the pharyngeal phase of swallowing and its offset reflects the end of swallowing.[37] Simultaneous EMG activity of the anterior digastric and infrahyoid muscles was also recorded, even though both onset and offset of the infrahyoid muscle were significantly later than the anterior digastric muscle, which suggests that these two muscles may act in competition with one another.

Conclusion

The temporal coordination patterns of the tongue and oropharyngeal muscles during a voluntarily triggered swallow as clarified in this study appeared to agree well with the established safe management of a bolus. These findings could be useful in developing criteria for evaluating the oropharyngeal swallowing function. However, they should also be compared with those established for elderly subjects in future studies.

Acknowledgments

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