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Coordination in oro-pharyngeal biomechanics during human swallowing

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HIGHLIGHTS

- The oro-pharyngeal swallow related events could be assessed by noninvasive sensors.
- There is exquisite biomechanical coordination during oro-pharyngeal swallowing.
- Tongue pressure generates closely to the hyoid rapid elevation.
- Tongue pressure reaches a peak when the hyoid stabilizes in the highest position.
- Tongue pressure ceases concurrently with the onset of hyoid descent.

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ABSTRACT

In swallowing, the tongue contacts against the hard palate to generate pressure for propelling a bolus from the oral cavity into the pharynx. Meanwhile, the hyoid and larynx move upward and forward to facilitate the bolus from the pharynx into the esophagus. It has been well known that sequential coordination between those actions is critical for safety accomplishment of swallowing. However, the absence of noninvasive assessment for it limits the detection to the physiological symptom of dysphagia. We applied a sensor sheet on the hard palate to measure tongue contact pressure and a bend sensor on the frontal neck to monitor the laryngeal movement, which was synchronized with hyoid motion for assessing the coordination between both actions in 14 healthy male subjects when swallowing 5 ml of water. The sequential order of tongue pressure and hyoid movement was successfully displayed. Tongue pressure was produced after slight movement of the hyoid and closely to the hyoid elevation, then reached a maximum when the hyoid stabilized in the most anterior–superior position, and ceased concurrently with the onset of hyoid descent. Additionally, the synchronized data from both sensors showed positive correlations between identified time points on the laryngeal signal waveform and onset, peak and offset of tongue pressure. Our sensing system successfully showed the coordination between tongue pressure production and hyoid motion, and could be a simple and noninvasive method for clinicians to evaluate the oral and pharyngeal stages of swallowing.

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1. Introduction

Swallowing is the process by which food is transported from the mouth to the stomach. It can be anatomically divided into oral, pharyngeal, and esophageal stages [1], and requires a series of voluntary and involuntary actions of several structures occurring under precise coordination. Once the bolus is formed in the oral cavity, the tip, body and sides of the tongue contact the palate to progressively squeeze the entrapped bolus backward [2] until reaching the isthmus, coinciding with the onset of the pharyngeal phase of swallowing [3], in which the hyoid bone and larynx displace vertically and anteriorly to protect the airway and ensure that the bolus passes through the pharynx into the esophagus safely and efficiently [4,5].

Physically, the tongue and hyoid interact with each other during normal swallowing, with evidences suggesting that hyoid motion is coordinated with tongue movement [6,7], while the tongue–palate contact may yield increased strength in the suprahyoid muscles and provide mechanical stabilization for hyoid elevation [8]. As for the sequential relationship between tongue–palate contact and peak hyoid

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elevation, a videofluoroscopic study showed considerable temporal overlap with widespread individual variability [9]. Studies using ultrasound also considered that the sequential relationship between tongue–palate contact and hyoid motion is intricate, without any fixed coordination between them [10,11]. However, the tongue–palate contact was measured at only one location [10] or integrated across all three tongue-bulbs[11]. In addition, the bolus volume was too large for patients to perform a single swallow [9,10] and the swallowing type (tipper or dipper) was not detailed [9–11]. The studies limit our understanding of the functional coordination between the oral and pharyngeal stages during swallowing. Therefore, simple and noninvasive appliances are urgently needed to facilitate the clinical measurement and evaluation of swallowing.

We previously developed a sensor sheet for measuring tongue pressure at five points on the hard palate [12], and tongue pressure in healthy elderly subjects [13] and stroke patients with dysphagia [14,15] were precisely measured. In addition to a sensor sheet system for assessing the oral stage of swallowing, a bend sensor system that is useful for obtaining the temporal aspects of laryngeal movement synchronized with hyoid motion during swallowing was also established successfully [16]. The objective of the present study was to investigate the sequential coordination between the tongue pressure production and hyoid–laryngeal movement using the two noninvasive sensing systems, which were expected to act as a comprehensive system to evaluate the oral and pharyngeal stages of swallowing.

2. Materials and methods

2.1. Subjects

Fourteen healthy, adult male volunteers (mean ± S.D.: 27.0 ± 2.2 years old) participated in the study. None of the volunteers had any disturbances in mastication and swallowing, abnormality in the number or position of teeth except for the third molar, history of orthodontic treatment and temporomandibular disorder, and abnormality of occlusion. Witten informed consent was obtained from each subject after explanation of the aim and methodology of the study, which was approved by the Ethics Committee of Osaka University Graduate School of Dentistry (No. H21-E32).

2.2. Measuring system and procedure

Tongue pressure was measured by a 0.1-mm-thick sensor sheet (100 Hz, Nitta, Osaka, Japan) with 5 measuring points (Chs.1–5) (Fig. 1A) for recording the tongue pressure production at each point of attachment to the hard palate. The suitable size of the sensor sheet was selected from 3 sizes and attached to the palate with a sheet-type denture adhesive (Touch Correct II, Shionogi, Tokyo, Japan) properly [12,17,18]. As a result, three sensors (Chs.1–3) were placed along the median line of the hard palate. Specifically, Ch.1 was set 5 mm posterior to the incisive papillae locating the anterior-median part, Ch.2 was set at the mid-median part, and Ch.3 was set at the posterior-median part. The other two sensors (Ch.4 and Ch.5) were positioned symmetrically in the left and right posterior-lateral parts of the hard palate (Fig. 1A). We also calibrated the system by applying negative pressure using a vacuum pump through an air duct in the cable of the sensor sheet before measurement.

Hyoid–laryngeal movement was measured by a previously developed bend sensor (73.7 mm × 6.4 mm × 1.0 mm, 1000 Hz, MaP 1783, Nihon Santeku Co. Ltd., Osaka, Japan) (Fig. 1B) which could bend physically with motion [16]. An increasing bend angle is generally associated with increased measured resistance. As a result, the more the sensor bends, the bigger is the output voltage amplitude after converting the input of a resistance to voltage (V) with a dual sided supply operational amplifier. After fixing it along the midline of the frontal neck with its tip at the level of the prominence of the thyroid cartilage when reaching the highest position during swallowing (Fig. 1D), the hyoid activity could be determined noninvasively from the produced signal waveform [16]. The swallowing sound is bilaterally symmetric [19], so we placed one microphone (JM-0116, Ono-Sokki, Tokyo, Japan) (Fig. 1C) over the left lateral border of the trachea immediately inferior to the cricoid cartilage (Fig. 1D) to detect the timing of bolus passage through the entrance of the esophagus [20].

During measurement, the participant was instructed to sit in an upright position with the head supported by a headrest to avoid head retroflexion, and keep the Frankfort plane horizontal and feet touching the floor. 5 ml of water (37 °C) was given via a syringe and held on the mouth floor until swallowed wholly one time upon the verbal command. The participant was asked to relax the tongue to the mouth floor immediately after each trial. Five repetitions were performed for

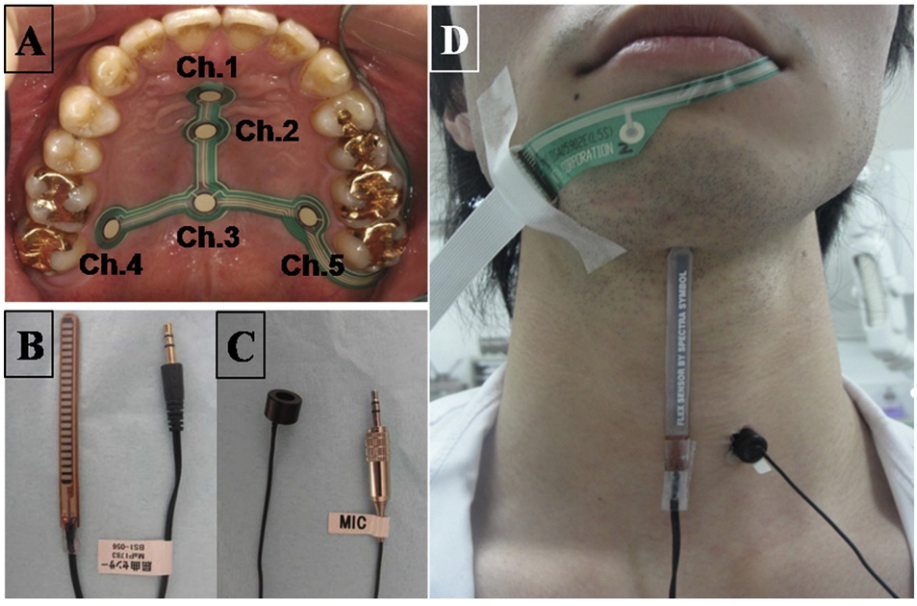

Fig. 1. Schematic representation of sensors and experimental set-up. (A) Location of sensor sheet. The sensor sheet was attached to the hard palate after the suitable selection from three sizes according to the participant's palate form. (B) Overview of bend sensor. (C) Overview of microphone. (D) Image of a subject with sensor sheet, bend sensor and microphone.

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