The Journal of Physiological Sciences (2018) 68:837–846
https://doi.org/10.1007/s12576-018-0601-0

ORIGINAL PAPER

A new flexible piezoelectric pressure sensor array for the noninvasive detection of laryngeal movement during swallowing

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Received: 27 July 2017 / Accepted: 20 February 2018 / Published online: 5 March 2018

Abstract

We tried to develop a new device to detect laryngeal movement noninvasively. We made small piezo pressure sensors (length, 1.5 mm, width, 7.0 mm), and five of these were lined up with 3.0-mm intervals and embedded in the middle of a palm-sized urethane resin sheet. This sheet was lightly attached to the ventral surface of the neck near the laryngeal prominence. The first and second peaks obtained from each sensor should correspond to the period when the larynx moves to the upper and lower positions during swallowing. The mean maximum rising velocities for men and women were about 0.08 and 0.11 m/s, respectively. Similarly, the mean maximum lowering velocities for men and women were about 0.09 and 0.11 m/s, respectively. The swallowing latencies for men and women were about 0.49 and 0.53 s, respectively. In conclusion, we succeeded in developing a new device, which will be useful in evaluating the swallowing function.

Keywords Swallowing · Laryngeal movement · Noninvasive measurement

Introduction

Elevation of the larynx is essential for airway protection during the pharyngeal phase of swallowing. The elevation causes apposition of the arytenoids to the base of the epiglottis and closes the laryngeal vestibule [1, 2]. During normal swallowing, the larynx elevates from 21.1 to 33.9 mm in healthy subjects [3]. Pathologically reduced or delayed laryngeal elevation is the most common cause of aspiration in persons with dysphagia [4–7]. Therefore, precise measurement of the laryngeal movement is useful in evaluating the swallowing function. In the clinical setting, however, laryngeal movement is not routinely measured in dysphagia patients, since there is no simple, easy, and safe way to do this.

In many studies, video fluorography (VF) has been used to measure the laryngeal movement during swallowing [3]. Since X-rays goes through cartilage, it is difficult to take images of the thyroid cartilage itself. Therefore, the elevation of the subglottic air column was usually used as an indirect index of the laryngeal movement [8–11]. Although it is possible to measure the laryngeal movement using VF, VF has several disadvantages. The major disadvantage is the radiation exposure. Video fluoroscopic examination of swallowing (VFS) is regarded as the gold standard in diagnosing and assessing swallowing disorders [12]. In VFS, various foods and liquids are mixed with a contrast medium such as barium and swallowed under VF allowing direct visualization of aspiration. VFS allows clinicians to assess the safety and efficiency of swallowing across various textures and the impact of compensatory maneuvers on swallowing function. The average patient dose has been estimated to be 12.79 mGy per VFS procedure [13]. The effective dose is used to estimate the risk of stochastic effects (e.g., cancer risk), and the regulatory effective dose limit (20 mSv/year averaged over 5 consecutive years, or 100 mSv in 5 years, and 50 mSv in a single year) is used to ensure that the occurrence of stochastic effects is kept within acceptable levels

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[14]. However, the International Commission on Radiological Protection recommended the use of the linear no threshold (LNT) hypothesis for the development of prospective radiation control programs [14]. The LNT hypothesis assumes that for each incremental increase in the radiation dose there is an incremental increase in the probability of cancer, even for low doses. Consequently, any radiation from medical tests must be minimized to comply with the as low as reasonably achievable (ALARA) principle [15].

Based on the aforementioned background, we thought a new noninvasive method for the measurement of the laryngeal movement was necessary. To the best of our knowledge, a few studies exist in which the laryngeal movement was measured with a method other than VF [16, 17]. Burnet et al. [16] measured the movement of the laryngeal prominence using a moving image by photographing the neck from the side. However, this method is only applicable to men with a large and clear laryngeal prominence. A research group at Niigata and Osaka University developed two types of devices for measuring the laryngeal movement [17]. One type had two rows and three columns of piezo pressure sensors with 8-mm distances between them, which were mounted at the anterior region of the neck to record the ascent and descent of the thyroid cartilage [17]. These researchers mentioned that this device should be attached directly and firmly to the anterior region of the neck, and the device exerts considerable pressure in this region. They also stated that this was applicable primarily to men [17]. They further developed another device, in which 12 photo-reflective sensors were aligned with 5-mm distances between them [17]. To avoid interference with the laryngeal movement, these sensors were positioned just above the skin surface at the anterior region of the neck using polyurethane foam and a fixation belt. The photo-reflective sensor is an electronic device combining a light-emitting diode (LED) and a photo-diode, and it can detect the intensity of reflected light in inverse proportion to the square of the distance between the LED and the opposing neck surface. Although this device can track the position of the laryngeal prominence, it is only applicable to subjects with a clear laryngeal prominence. Thus, all of the existing devices cannot be applied to subjects with no apparent laryngeal prominence, such as most women.

During swallowing rehabilitation, speech-language-hearing-therapists (ST) palpate the patient's neck and evaluate the laryngeal movement. Even in subjects with no apparent laryngeal prominence, ST can sense the laryngeal movement. We thought that the development of a highly sensitive small pressure sensor would enable us to create a device that can sense the laryngeal movement with a light touch to the neck and that has sufficient spatial resolution. Thus, the goal of this study was to develop a new device for the noninvasive detection of laryngeal movement during swallowing even in subjects with no apparent laryngeal prominence.

Methods

New small and highly sensitive piezo pressure sensor

Since the commercially available piezo pressure sensor was too large to detect movement of the larynx, we made a small piezo sensor. To minimize electrical noise, the case was made from stainless steel and used as the chassis ground (outer length: 1.5 mm, outer width: 7 mm, depth: 3.5 mm, thickness: 0.2 mm). Polyvinylidene fluoride (PVDF) sheets (thickness: 40 µm, theoretical piezoelectric coefficient d33: 35 pC/N, Kureha Corp., Japan) were used for the piezo pressure sensors. A PVDF sheet was cut into 1.0 × 5.0 mm pieces, and these pieces were integrated into the stainless-steel case with a shield wire (Fig. 1a, b). The shield wire was about 1 mm in diameter. The backside of the stainless-steel case was filled with epoxy resin. A chloroprene rubber sheet (length 1.2 mm, width 6.7 mm, thickness 0.3 mm) was glued onto the side of the sensor. The surface of the chloroprene rubber sheet was about 0.1 mm above the stainless-steel case to sense the pressure. This sensor was made by ELMECH Electronics Industries Co., Ltd. (Japan).

The impedance of the electrical voltage signal obtained from the piezo sensor was converted by an impedance conversion circuit. The total gain was 0.56 and the time constant was 3.0 s.

New piezo sensor array sheet

To suppress interference between adjacent sensors, silicone gel ($\theta - 7$, Asker C hardness: 0, thickness: 1.5 mm, Taica Corp., Japan) was cut to the same size as the side of the stainless-steel case (width 7 mm, length 3.5 mm) and was installed so as to interpose each sensor. As a result, the distance between the centers of the sensors was 3.0 mm. Then, this block of sensors was embedded in the center of a urethane resin sheet (HITOHADA® gel, Asker C hardness: 5, vertical: 80 mm, horizontal: 100 mm, thickness: 8 mm, Exseal Corp, Japan, Fig. 1c). The sensors were aligned in a vertical line, and the surface of the chloroprene rubber sheet of the sensor was set slightly above the surface of the urethane resin sheet. The cables from the sensors were drawn out from the vertical side of the sheet. This piezo sensor array sheet was made by Kouwa Precision Co., Ltd. (Japan).

Subjects

Six men and six women participated in this study. The average age was 32.5 ± 10.5 years (range, 21–49 years) for men and 34.7 ± 11.7 years (range, 21–49 years) for women. Each

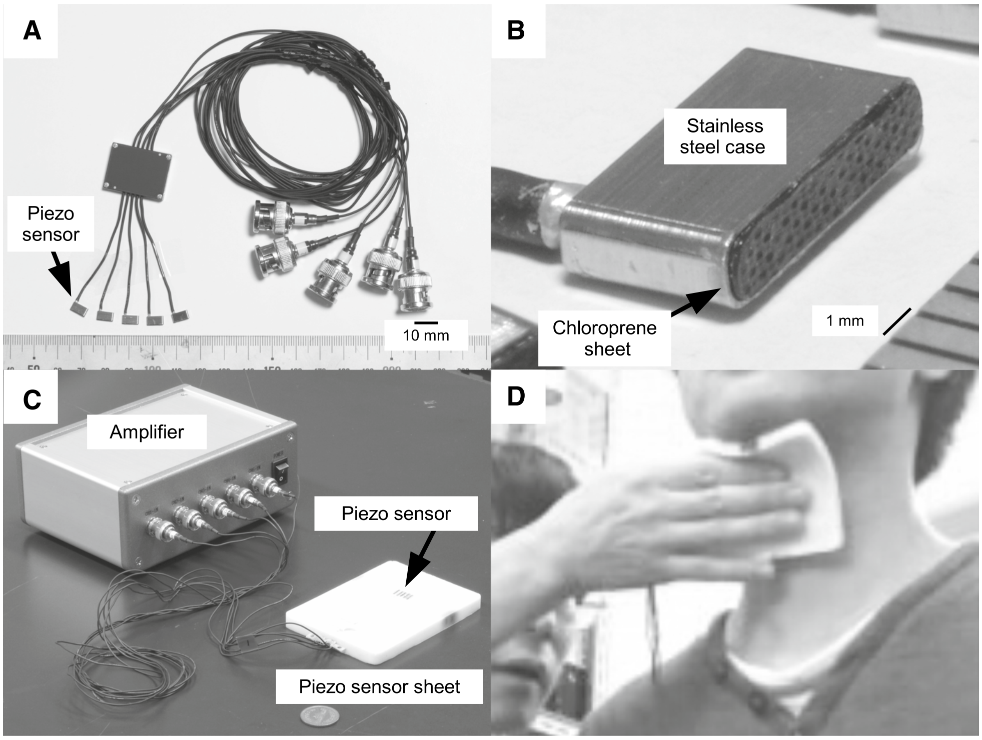

Fig. 1 Photographs of the new piezoelectric pressure sensor array sheet. **a** Five piezo sensors before they are embedded in the urethane resin sheet. **b** High magnification of the piezo sensor. **c** External appearance of the sensor sheet and its amplifier. **d** A still image indicating the way the sensor sheet was attached to the ventral surface of the subject's neck near the laryngeal prominence. This photograph was taken from a movie clip obtained at the beginning of the experiment shown in Fig. 3A

subject was healthy, had no known neurological disorders, and had no history of injury or surgery to the head or neck. The Seirei (Ohkuma) questionnaire for dysphagia screening was used to ensure that none of the subjects had complaints of dysphagia [18, 19].

Experimental procedure

Each subject sat on a backless round chair. Then photographs of the front and side views of the neck were obtained. The subject was instructed to hold 3 ml of mineral water in his or her mouth until instructed to swallow. Each swallow was initiated with the bolus (3 ml mineral water) positioned above the tongue, with the tongue tip touching the upper incisors, for a so-called "tipper'‘-type swallow [20]. The non-sensor side of the sensor sheet was placed on the researcher's palm, and the sensor side of the sensor sheet was lightly attached to the ventral surface of the subject's neck near the laryngeal prominence (Fig. 1d). At this time, the lowest-positioned sensor was placed 0.5–1.0 cm higher than the laryngeal prominence at rest. Within 30 s after the sensor was attached, the researcher instructed the subject to swallow and push the foot switch with his or her foot simultaneously. The subject was instructed to swallow as soon as possible after the instruction to swallow while avoiding any head movement such as nodding. The same procedure was repeated 10–20 times. The signals obtained from the sensors and the foot switch were fed into a personal computer using an analog–digital converter and its software (Power1401-3 and Spike2 version 7, CED, UK). The sampling frequency was set at 1 kHz for each channel. To record the conditions of the subject and the procedure, a video of the subject's neck and environmental sound was captured using the attached software (Spike2 Video Capture Version 1.05) and a USB web camera (UCAM-DLY300TA, ELECOM, Japan) at a resolution of 320 × 240 pixels at 30 frames/s.

Analysis

For each subject, more than eight swallows were used for the analysis. Four swallowing parameters were defined and measured (described in the "Results" section below). All parameters were measured using cursors in the Spike2 software. All data were averaged and expressed as mean ± standard deviation. Statistical comparison was performed with an unpaired t test, and statistical significance was set at $P < 0.05$.

Results

Electrical signals obtained from sensors during swallowing in men and women

As shown in Fig. 2, there was a clear sex difference in the appearance of the laryngeal prominence. In men, only one of six had no clear laryngeal prominence. On the other hand, five out of six women had no clear laryngeal prominence.

During the pharyngeal phase of swallowing, the larynx moves upward to close the trachea with the epiglottis, and the larynx stays in the upper position as the bolus goes through from the pharynx to the esophagus safely. The larynx then goes downward to the resting position. As expected, when the sensors were placed 0.5–1.0 cm higher than the resting position of the laryngeal prominence, two positive peaks were observed in most of the sensors during swallowing. None of the subjects reported discomfort or difficulty in swallowing when the sensor sheet was lightly attached to the ventral surface of the subject's neck near the laryngeal prominence during swallowing. The sensor has a time constant of 3 s. This was too slow, and the slow pressure change evoked by the subject's and researcher's body movement sometimes rendered the swallowing signals inconspicuous. Therefore, the wave was smoothed digitally at a time constant of 0.01 s. This value was best to minimize the slow voltage fluctuation with minimum effects on the swallowing signals. Two representative swallowing trials obtained from a man and a woman are shown in Figs. 3 and 4, respectively. As shown in Fig. 3A, the first peak (arrows, c–f) corresponds to the time when the laryngeal prominence passed and pushed these sensors when moving to the upper position, and the second peak (arrows, g–j) corresponds to the time when the laryngeal prominence passed and pushed the sensors when returning to the resting position. In fact, the first peak in the lower-positioned sensor occurred earlier than the first peak in the upper adjacent sensor (Fig. 3A, arrows c–f). The second peak in the upper-positioned sensor occurred earlier than the second peak in the lower adjacent sensor (Fig. 3A, arrows g–j). In the following, the period when the laryngeal prominence was going up is defined as the rising phase and the period when the laryngeal prominence was going down is defined as the lowering phase. The lowest-positioned sensor, sensor 5, sometimes showed two peaks in the rising phase (Fig. 3A, arrows a and b). The first peak seemed to correspond to the preparatory period during which the larynx moved upward to the position it held

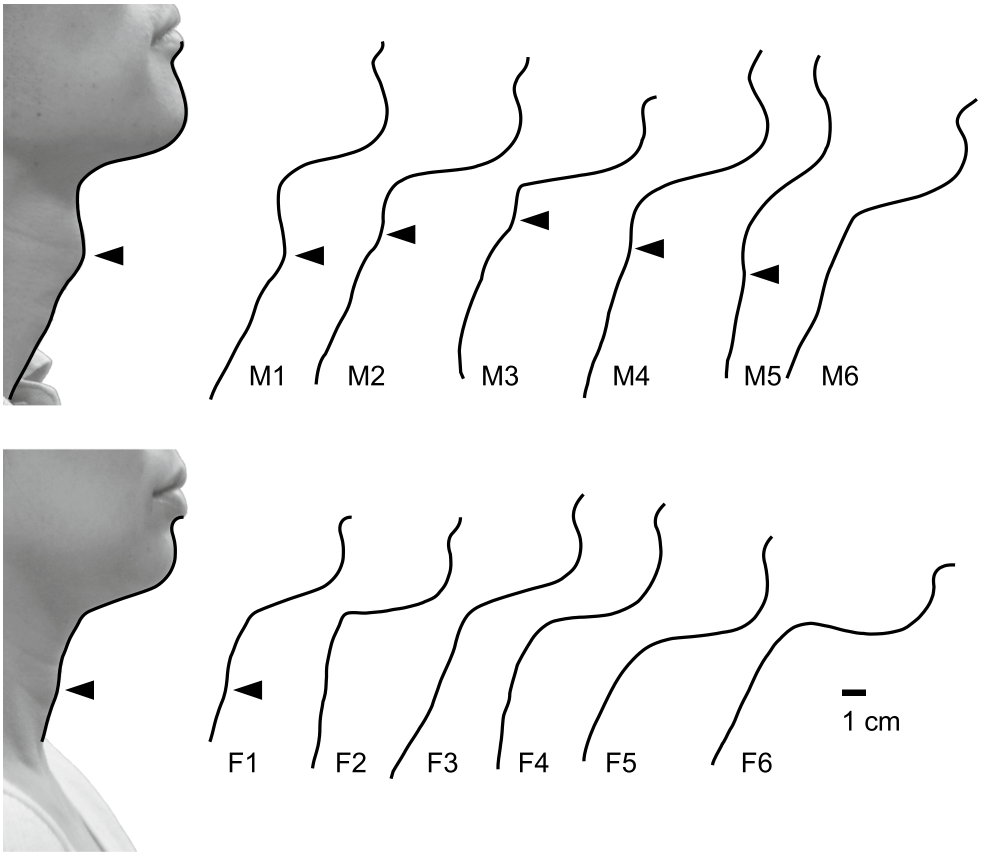

Fig. 2 Side-view profiles of the neck surface in all subjects. The subject number is shown at the bottom right in each trace. The photographs on the left sides of the upper and lower panels show the side view of subjects M1 and F1, respectively. The position of the visible laryngeal prominence is indicated by the *arrowheads*

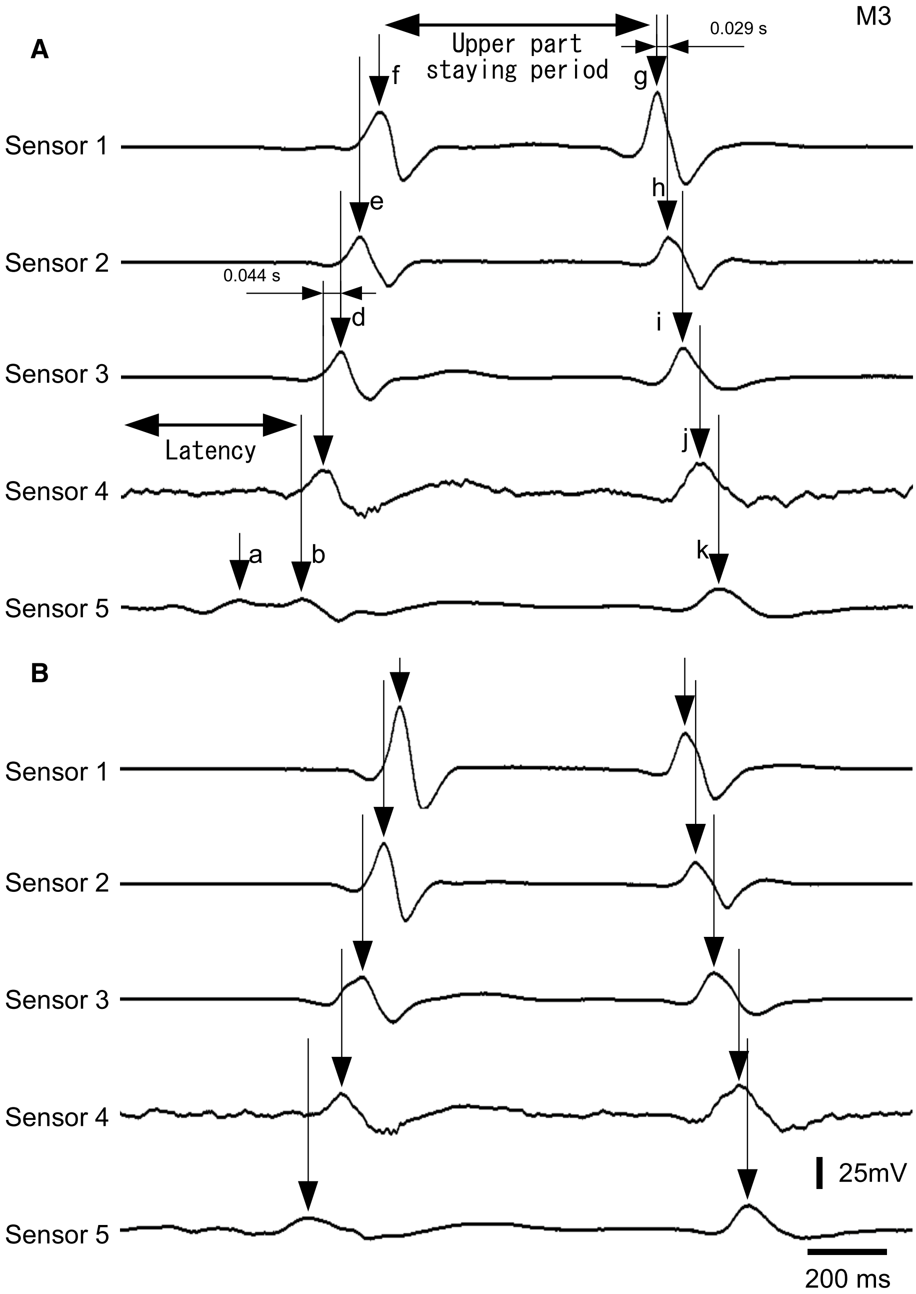

Fig. 3 Representative recordings obtained from a man with a clear laryngeal prominence during swallowing. **A**, **B** The voltage signals obtained from sensors 1–5 simultaneously are listed from the upper to lower position. The sensor sheet, in which sensors 1–5 were embedded in the order of upper to lower, was placed at the surface of the neck. Thus, sensor 5 was positioned lowest and was placed a bit higher than the laryngeal prominence. The traces were recordings lasting 2 s from the instruction to swallow. **A** Arrows a–k indicate positive peaks. **B** Each *arrow* indicates a positive peak evoked during swallowing

when the pharyngeal phase started (Fig. 3A, arrow a). The second peak in the rising phase in sensor 5 corresponds to the starting point of the pharyngeal phase (Fig. 3A, arrow b), since this peak occurred sequentially in sensors 4, 3, 2, and 1 with similar time differences between them (Fig. 3A, arrows c–f). When two peaks occurred in the rising phase, the period from the instruction to swallow to the second peak was treated as the swallowing latency, and was 0.45 s in this example (Fig. 3A). Figure 3B shows another swallowing trial. Although the amplitudes of the signal changed with each swallow (cf. recording of sensor 1 between Fig. 3A, B), the sequential pattern of waves was quite similar between the sensors.

A representative recording obtained from a woman who showed no clear laryngeal prominence is shown in Fig. 4A, B. The pattern of waves was quite similar to that in men. As shown by arrow a in Fig. 4B, when the sensor was assumed to be just on the laryngeal prominence before swallowing, a negative trough was observed at the very beginning of the swallow. This pattern was also observed in subjects with a clear laryngeal prominence (not shown). In these examples in Figs. 4A, B, the

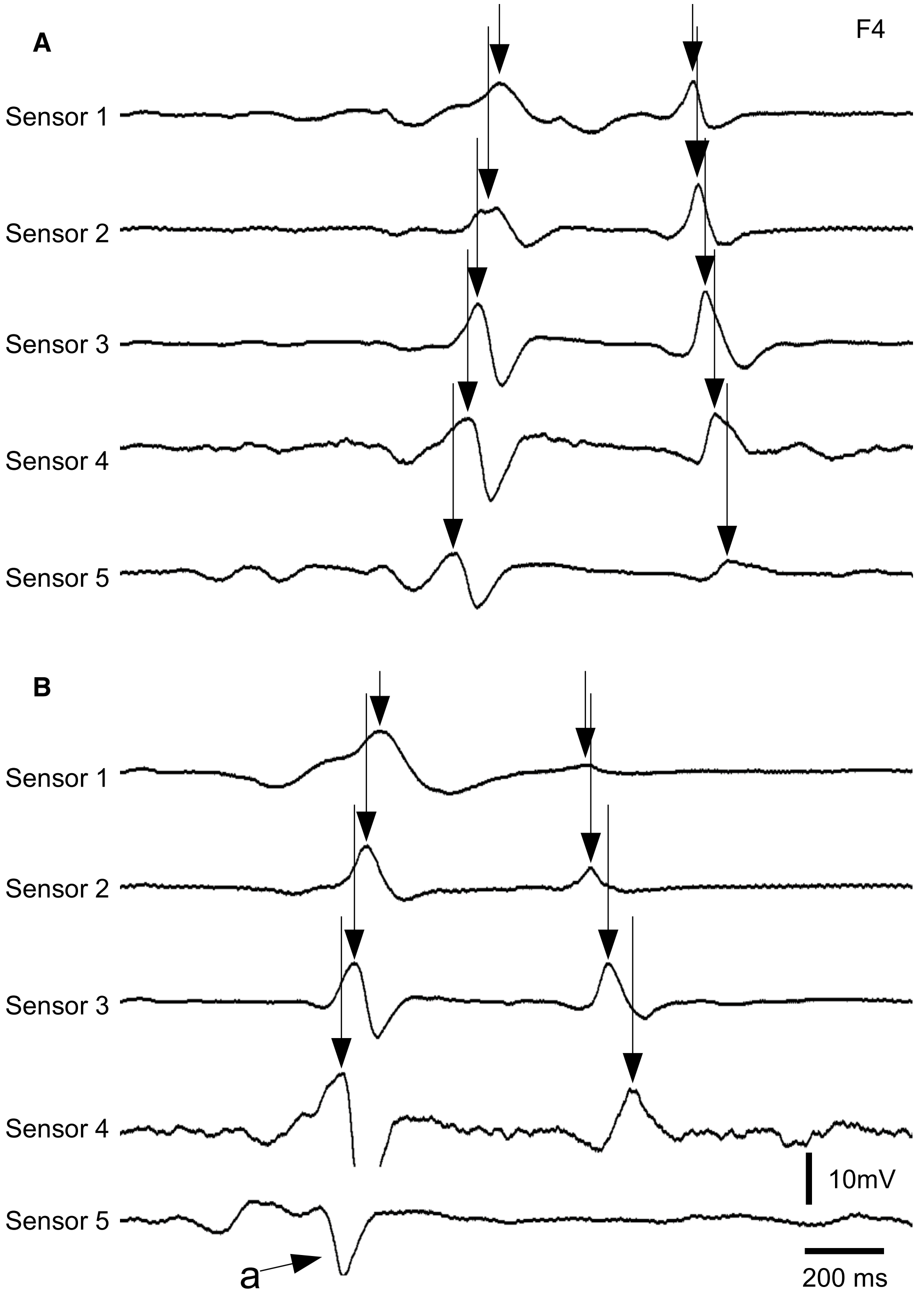

Fig. 4 Representative recordings obtained from a woman with an unclear laryngeal prominence during swallowing. **A**, **B** Same format as in Fig. 3**B**. Since a negative peak in sensor 5 (*arrow a*) occurred at around the same time as the first positive peak in sensor 4, the laryngeal prominence must have been positioned just under sensor 5 at the very beginning of the swallowing and moved in the direction of sensor 4

swallowing latencies were different between trials (0.84 and 0.57 s, respectively). The peak amplitude of the wave was affected by the force exerted when pressing the sensor array against the neck during swallowing. As a result, the amplitude of each wave in the group with a clear laryngeal prominence was 11.4 ± 6.3 mV (M1–M5, F1), and was not significantly different from the amplitude in the group without a clear laryngeal prominence (M6, F2–F6; 7.4 ± 5.1 mV). We measured the root mean square of the recording from 1 s before the instruction to swallow until the instruction to swallow in these 12 subjects, and this value was 0.094 ± 0.053 mV. Therefore, the peak was easy to discriminate from electrical fluctuations caused by body movement or other noises.

In four subjects (F1, F3, F5, M6), two other small peaks were observed between the two large peaks described above in the lower-positioned sensors. Although we did not palpate and determine the position of the cricoid cartilage, these peaks could represent the period when the bump of the cricoid cartilage passed and pushed the sensors above it (not shown).

Swallowing parameters in each subject

As mentioned above, the first peak in the lower-positioned sensor occurred earlier than the first peak in the upper adjacent sensor (Fig. 3A, arrows c–f), and the second peak in the upper-positioned sensor occurred earlier than the second peak in the lower adjacent sensor (Fig. 3A, arrows g–j). Since the distance between sensors was fixed at 3 mm, the velocity of the laryngeal movement could be calculated using the time difference. In a trial shown in Fig. 3A, the time difference was similar between sensors during the rising phase. On the other hand, in a trial shown in Fig. 3B, the time difference between sensor 5 and sensor 4 was longer than the time differences between the other sensors. During the rising phase, the velocity of the laryngeal movement is zero at the very beginning, reaches a maximum, and then becomes zero again at the top. Therefore, 3 mm was divided by the shortest time difference to obtain the velocity, and this velocity was defined as the maximum rising velocity. In this instance, since the time difference was 0.044 s, the maximum rising velocity was 0.0682 m/s. Similarly, during the lowering phase, the velocity is zero at the very beginning and end of the lowering phase. In contrast with the rising phase, the time difference at the pair of upper sensors tended to be short (Fig. 3A, arrows g–j). The maximum lowering velocity was also obtained using the shortest time difference during the lowering phase. In this instance, since the time difference was 0.029 s, the maximum lowering velocity was 0.1034 m/s. The period between the first and second peaks was shortest in sensor 1, the sensor placed at the highest position (Fig. 3A, arrows f and g). Although the highest position that the larynx reached was impossible to determine, the period between the two peaks in sensor 1 corresponds to the period when the larynx was positioned higher than sensor 1. In the present study, this period was defined as 'the upper part staying period', and was 0.697 s in this example (Fig. 3A).

The four parameters, namely, swallowing latency, maximum rising velocity, maximum lowering velocity, and upper part staying period, obtained from each subject, are summarized in Fig. 5. There was no gender difference in any of the four parameters. The mean latency was 0.487 ± 0.111 s for men and 0.531 ± 0.180 s for women. The mean maximum rising velocity was 0.0793 ± 0.0225 m/s for men and 0.1057 ± 0.0215 m/s for women. The mean maximum lowering velocity was 0.0940 ± 0.0288 m/s for men and 0.1098 ± 0.0568 for women. The mean upper part staying period was 0.573 ± 0.177 s for men and 0.670 ± 0.191 s for women.

Discussion

Here, we reported a new flexible piezo sensor sheet that can be fitted to the shape of the neck, even accounting for large individual differences. Using this new sensor sheet, various swallowing parameters could be obtained noninvasively and repeatedly, even in subjects with no clear laryngeal prominence. In the following, we discuss the advantages and disadvantages of this newly developed sensor sheet for use in studying the swallowing physiology and pathophysiology.

Piezo sensors have been used previously for the detection of swallowing [17]. As far as we know, however, this is the first study in which the velocity of the laryngeal movement was measured using an array of piezo sensors. In the present study, we obtained four swallowing parameters, namely, swallowing latency, maximum rising velocity, upper part staying period, and maximum lowering velocity. Unfortunately, since only five sensors were used, and the sensor sheet had a sandwich structure in which a piezo sensor with 1.5-mm outer length was sandwiched by silicone gel with a 1.5-mm thickness, the total length of the sensing range was limited to 13.5 mm. Thus, although we found that the laryngeal prominence moved more than 13.5 mm, we could not obtain the exact distance moved. To cover the whole range of laryngeal prominence movement, a larger number of piezo sensors needed to be incorporated into the sheet. At present, studies in which laryngeal movement was measured relied almost solely on the use of VF (see review for [3]). In most of these studies, the movement of the subglottic air column was used to represent the laryngeal movement [8, 9, 11, 21]. As reviewed by Molfenter et al. [3], the distance moved varied between studies, and ranged from 21.1 mm to 33.9 mm. Therefore, a 40–50 mm length would be a suitable length along which to monitor the whole laryngeal movement, and we are planning to make a new sensor sheet that is more than 50 mm long. Another consideration is spatial resolution. To detect a 1% change in the length of the laryngeal movement, a spatial resolution of 0.2–0.3 mm is needed. This spatial resolution has been difficult to realize and remains a challenge for the future.

As discussed above, we were not able to obtain the exact distance the larynx moved. Therefore, although we measured the time period between the first and second peaks in the uppermost sensor and defined this as the upper part staying period, this period is longer than the actual period of laryngeal closure. As for the distance moved by the laryngeal prominence, this problem will be solved by increasing the number of piezo sensors on the sheet. Since a shortened laryngeal closure time period increases the risk of aspiration, this period has pathophysiological

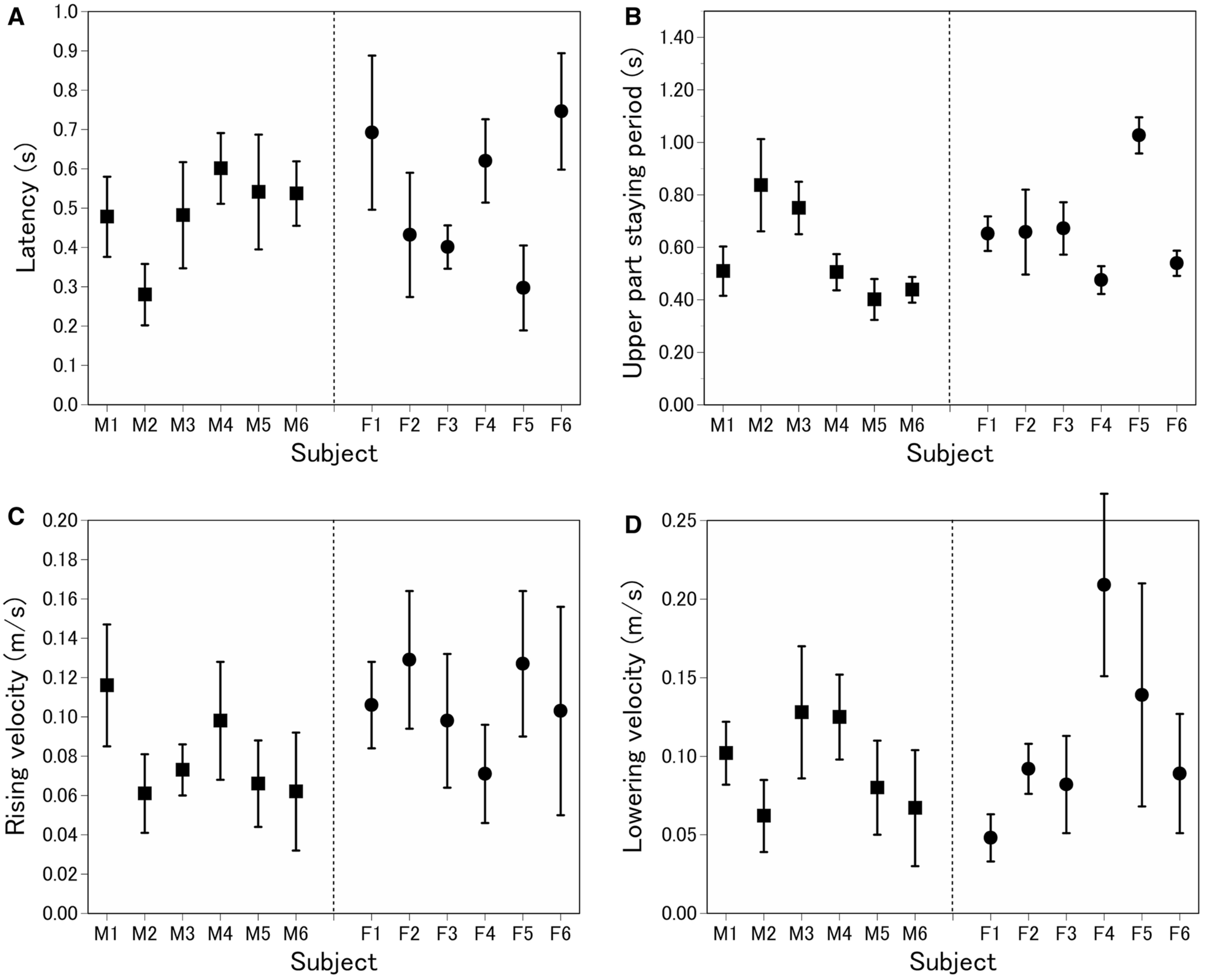

Fig. 5 Summary graph of each parameter. Each data plot indicates the mean value obtained from each subject. *Error bar* indicates standard deviation

importance. The laryngeal closure time period has been measured using VF in many studies [1, 8, 9, 20]. According to Logemann et al. [1], the laryngeal closure time was 0.48 ± 0.05 s with the swallowing of 1 ml of liquid and 0.50 ± 0.02 s with the swallowing of 5 ml of liquid in eight healthy men. The same research group also obtained similar values in younger and older men and women [8, 9]. According to Dantas et al. [20], however, the laryngeal closure time was 0.96 ± 0.05 s with the swallowing of 2 ml of liquid and 0.99 ± 0.11 s with the swallowing of 5 ml of liquid in ten healthy men. These values were much longer than those obtained by Logemann's research group [1, 8, 9]. In the present study, the upper part staying period was 0.573 ± 0.177 s for men and 0.670 ± 0.191 s for women. These times are a bit longer than but in good accordance with Logemann's data. Since the sensor sheet we developed can measure swallows repeatedly, this parameter could be valuable in evaluating the swallowing function.

In the present study, the moving velocity of the laryngeal prominence was measured over the shortest interval. There have been two VF studies in which the moving velocity of the larynx was measured during swallowing [5, 22]. In one study [5], the moving velocity was normalized by the distance separating the arytenoids from the valleculae; therefore, the actual velocity (i.e., measured in m/s) could not be determined. In the other study [22], 48 males who had no pathology and who had an ossified larynx were studied. VF was obtained at a speed of 30 frames/s. The swallowing laryngeal movement was divided into five phases: the slowly ascending phase, the rapidly ascending phase, the pause at the position of maximum rise, the rapidly descending phase, and the slowly descending phase. The mean velocities in the slowly and rapidly ascending phases were 0.0166 and 0.0645 m/s, respectively. Similarly, the velocities in the rapidly and slowly descending phases were 0.0473 and 0.0127 m/s, respectively. In the present study, the mean maximum rising and lowering velocities were 0.0793 and 0.0940 m/s for men. In the previous VF study, the durations of the rapidly ascending phase and the rapidly descending phase were 0.35 ± 0.10 s and 0.37 ± 0.15, and the lengths moved in those phases were 22.6 ± 5.4 and 16.8 ± 5.3 mm [22], respectively. Since the range of measurement was limited to 13.5 mm in the present study, the mean velocity was impossible to measure. Therefore, we could not make a simple comparison. However, the finding that the maximum velocity in the present study was larger than the mean velocity in Furukawa [22] was reasonable. Burnet et al. [16] measured the movement of the laryngeal prominence using a moving image by photographing the neck from the side using male subjects with a large and clear laryngeal prominence. The average maximum rising velocity of the laryngeal prominence movement during the swallowing of 2 ml of water was 72.67 ± 29.98 mm/s in 15 participants, and this value is quite similar to the present results. Since it has been shown that the slowing of the velocity of the laryngeal elevation was proportional to the clinical severity of aspiration during swallowing [5], and this parameter can be obtained using the sensor sheet we developed easily and repeatedly, our sensor sheet can be quite valuable.

VFS is regarded as the gold standard in diagnosing and assessing swallowing disorders [12]. Although VFS is the sole method used to monitor the position of the bolus, and enables the direct visualization of aspiration, the swallowing function is evaluated merely by the presence/absence of aspiration and by its extent. Objective evaluation with numerical values is difficult. In the clinical context, a speech-language-hearing therapist examines the laryngeal movement of the patient by palpation and evaluates the swallowing function subjectively. One of the advantages of this new sensor sheet is the ease with which numerical values for various swallowing parameters can be obtained. These values are essential for performing an objective evaluation. Thus, although it is impossible to monitor the position of the bolus and the presence of aspiration using this new sensor sheet, this sheet provides a new complementary method to evaluate the swallowing function objectively. The developed sensor sheet was a bit too thick for the movement of the larynx to be felt from the outside of the sensor sheet. We are planning to make a new, thinner sensor sheet.

The major weakness of this new flexible piezo sensor sheet is that it is impossible to measure the laryngeal movement along the upper/lower axis and the front/back axis separately. Since the movement of the larynx to the front side is important for opening the esophagus, evaluating the movement along the front/back axis is also functionally important. A previous study using VF showed that the larynx moves about 8.0 ± 2.1 mm anteriorly during swallowing in adult men [22]. Our developed sensor sheet is flexible and can fit the various neck shapes. If the extent of the bending of the sensor sheet before swallowing is monitored, it would be possible to differentiate the laryngeal movement into upper/lower and front/back components. In the present study, the sensor sheet was placed by hand. When the sensor sheet is placed using a fixed apparatus, however, it is possible to sense the difference in the amplitude of the pushing force in each sensor during swallowing. Using this difference in the pushing force, it might be possible to evaluate the extent of the laryngeal movement along the front/back axis.

In summary, we succeeded in developing a new sensor sheet for the noninvasive detection of larynx movement during swallowing, even in subjects with no apparent laryngeal prominence. Using this sensor sheet, four parameters, namely, the swallowing latency, the maximum rising velocity, the maximum lowering velocity and the upper part staying period, can be obtained easily and repeatedly. This makes possible a new method of studying the physiology and pathophysiology of swallowing, including the efficacy of swallowing rehabilitation.

Acknowledgements This work was supported by JSPS KAKENHI Grant Number 26350663.

Author contributions MI1 and MI2 designed the research; MI1, MK, YH, KT, and RT performed the experiments; MI1, MK and YH analyzed the data; MI1, KT, RT and MI2 interpreted the results of the experiments; MK and YH prepared the figures; MI1 drafted the manuscript; KT, RT and MI2 edited and revised the manuscript.

Compliance with ethical standards

Conflict of interest M Iizuka is employed at Showa University and has filed a patent application for the swallowing function evaluation instrument (Japanese patent application No. 2017-24592). The authors have no conflicts of interest directly relevant to the content of the present study.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. All procedures were approved by the Ethical Committee of Showa University (Approval No. 2000) and the Ethical Committee of Ibaraki Prefectural University of Health Sciences (Approval No. 697).

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