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The challenges of developing a textile-based device for recognizing swallowing movements during different swallowing tasks

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Abstract

Swallowing difficulty, also known as dysphagia, is a fairly common symptom that may lead to malnutrition, dehydration, pulmonary complications, and a reduced quality of life. Currently, a swallowing evaluation requires a hospital environment, skilled personnel, and expensive devices. Thus, it is important to develop a successful method for evaluating swallowing in an everyday environment. This study developed a textile-based solution that resembles a neck gaiter. Wireless accelerometer and gyroscope sensors embedded inside the gaiter were used to detect swallowing movements. The recognition of swallows was achieved through cervical auscultation and video footage, and this data was subsequently compared with the information obtained from wireless accelerometer and gyroscope sensors. Based on the measurement results for 17 adults without dysphagia, the developed neck gaiter can identify individual swallows of 5 sips of water (with a 97 % identification success rate) and consecutive swallows of 100 ml of water (98 % identification success rate). However, we were not able to recognize swallowing movements from speaking, chewing and head movements. Future research is now needed to develop a prototype to differentiate swallowing movements from other movements, such as chewing and speaking.

Keywords: deglutition, motor functions, wearable technology

Introduction

We eat and drink every day and usually don't think about what is happening in our mouth, pharynx, and esophagus during eating and swallowing. However, swallowing is a complex phenomenon that requires seamless cooperation and the precise timing of several brain areas, cranial nerves and muscles [1,2]. If an individual has difficulties swallowing, the medical term, dysphagia, is used to describe that condition. Dysphagia is a fairly common symptom. In a large population-based survey completed in the United States, every sixth adult surveyed reported experiencing swallowing difficulties [3]. Dysphagia can be caused by various diseases or injuries such as neurological disease or injury (e.g. cerebrovascular accident, brain injury or a progressive neurological disease such as Parkinson's disease) or head and neck cancers [4]. It is important to diagnose dysphagia as early as possible in order to prevent related complications, such as malnutrition, dehydration, pulmonary complications, and a reduced quality of life [5-8].

Evaluation of the swallowing process usually begins with a clinical evaluation by a speech therapist. The evaluation is done so that the examinee is in an upright position either in a chair or in bed. In clinical evaluation, the speech therapist evaluates the swallowing visually by watching the movements of the mouth and larynx, palpating the movement of the larynx with fingers [9], and possibly also listening to the sounds of swallowing and breathing with a stethoscope placed on the side of the neck [10]. This clinical evaluation can be supplemented, if necessary, by an instrumental evaluation using a videofluoroscopic swallowing study (VFSS) [11], a fiberoptic endoscopic evaluation of swallowing (FEES) [12] and/or high-resolution manometry [13]. However, these studies require expensive research equipment and skilled personnel, so they are generally performed in a hospital environment. Currently, there are no easy-to-use instrumental swallowing evaluation methods that can be used outside the hospital environment.

In recent years, certain studies have presented different swallowing evaluation devices that can be placed around the neck and face (e.g. [14-16]). Researchers are interested in studying the movement of the neck area during swallowing, listening to the sounds associated with swallowing and breathing, as well as monitoring the airflow coming from the nose. For example, dual-axis accelerometers, force-sensing resistors, and sEMG electrode pads (surface electromyography) have been used to study the movements of the neck area during swallowing [15,17,18]. Various microphones, such as throat microphones and in-ear microphones, have been used to listen to swallowing and breathing sounds [19,20]. Some researchers have also used nasal airflow cannula to study the existence and timing of the cessation of breathing during swallowing [18,21-24]. Most of these technical solutions are complex electronic equipment with wires and the device is attached to the neck with skin tape, thereby compromising both comfort and wearability. Research has been done both on healthy participants [15] and participants with dysphagia [25]; however, so far, no technical solution purposeful intended for practical use has been developed that can distinguish between normal swallowing and abnormal swallowing based on swallowing movements.

The area of the larynx is sensitive, and any swallowing assessment device placed around the neck must not interfere with the actual swallowing. In addition, if the device is intended for long-term use in a person's everyday environment, it is essential to consider comfort of use and the appearance of the device. In our earlier study [26], we tested whether a swallowing phenomenon could be recognized with a textile-based device having eight sensors made of accelerometers and gyroscopes. We had only two healthy participants, and we used a simple swallowing task; the participants were asked to swallow 10 sips of water. The results were promising, since when we reviewed the data for all the sensors attached to the front of the neck, the swallows of these participants could be visually recognized. Thus, a textile-based device with accelerometers and gyroscopes seemed worthy of further investigation to identify swallowing movements. For this reason, we developed a new prototype for a textile-based solution in such a way that it resembles a neck gaiter with wireless sensors hidden inside the textile. The developed prototype uses accelerometers and gyroscopes and consists of seven small sensors, six of which measure swallowing movements from the front of the neck. The seventh sensor is attached to the back piece of the gaiter to monitor non-swallowing movements, such as head turning. The goal of this study was to learn if the swallow phenomenon in different swallowing tasks could be recognized from gathering the data of six sensors attached to the front piece of a neck gaiter.

Methods

Participants

The study participants consisted of 17 adults (8 males, 9 females), who did not have subjectively perceived or diagnosed dysphagia. The mean age of these participants was 23,9 years (median 21, min. 20–max. 54). A written informed consent was obtained from all the participants, and they were all given a notice of research privacy.

A textile-based neck gaiter prototype

The textile-based prototype, which resembles a neck gaiter, consisted of two parts-- front piece and a back piece, which were attached by Velcro tape straps to both sides of the neck (see Figure 1). The fabric used was rib jersey and a mixture of 65% cotton, 30% polyester, and 5% elastane. The front piece had two fabric layers to hide the sensors, and its shape was supported by thin silicon cords. The silicon cords and sensors were placed in pockets sewn to the front piece. On the left side of the front piece was an opening for a stethoscope. The actual design of the neck gaiter will be described in detail in a future article.

Six sensors were designated to measure the swallowing movements from the front of the neck and were thus placed in the front piece. The sensors were attached as illustrated in Figure 1 A: one sensor under the chin (1), one sensor on the thyroid notch (2), two sensors on the level of the hyoid bone, one on the left and one on the right (3, 4), and two sensors below the level of the thyroid notch, one on the left and one on the right (5, 6). In addition, one sensor (7) was attached to the back piece to track non-swallowing related movements, such as head turning. The neck gaiter was designed to be modular, which meant that all sensors could be vertically adjusted to the right locations and be removed easily from the cloth, if needed.

The sensor modules were designed specifically for this particular purpose. Each sensor module (dimensions 14 mm x 33 mm x 25 mm, sensor weight 7.8 grams, battery weight 3 grams) consisted of three separate submodules: 1) an inertial measurement unit (IMU), based on the Invensense MPU-6050 MEMS microchip, containing three orthogonal accelerometers and three orthogonal angular velocity gyroscopes that measured acceleration and angular velocity on the X, Y and Z axes; 2) a microcontroller unit and a Microchip ATMega4808 microcontroller; and 3)a unit for the wireless link, a Nordic Semiconductor NRF24L01 intelligent transceiver chip that had an integral trace antenna on the circuit board.

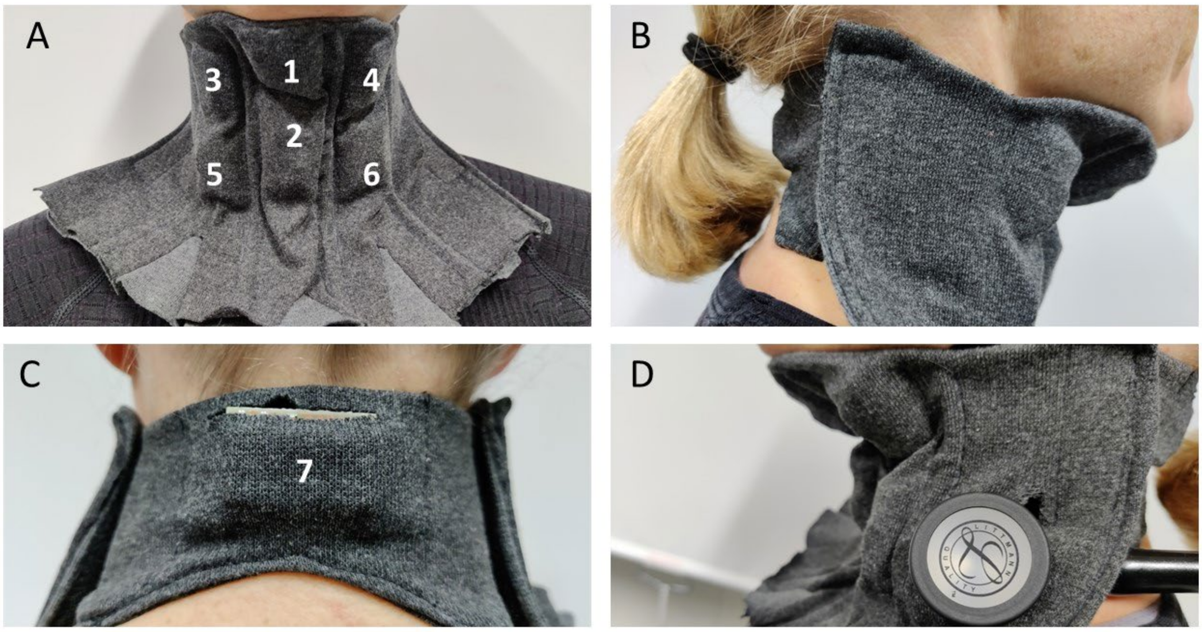

Figure 1. Textile-based neck gaiter prototype: A. the front piece with six sensors, B. the right side, C. a back piece with one sensor, D. the left side with an opening for a stethoscope. The picture is published with permission.

Study protocol

The participant was asked to sit at the table, and the researcher would then fit the neck gaiter individually around participant’s neck. The sensors on the level of the larynx and under the chin were placed individually according to the participant’s anatomical structures. The sensors on both sides were placed vertically as accurately as possible; the upper sensors were placed at the level of the hyoid bone, and the lower sensors were placed below the level of the larynx. Before starting the study, the participant was asked if the neck gaiter was placed comfortably. One researcher had been trained by an experienced speech therapist to listen to swallows with a stethoscope. A stethoscope was placed through an opening in the fabric slightly below the level of the larynx toward the left side (see Figure 1D). All occurred swallows verified by auscultation were recorded to the same file as the data acquired from the sensors. The entire research situation was videotaped. The camera was placed on the participant’s right side, and the participant was filmed from the middle of the body upwards. The video footage was reviewed afterwards to confirm that all swallows were recognized and recorded. The data was stored in a folder exclusively designated for use by the research group within the university's cloud service, which necessitates two-step verification.

The participants were asked to do the following swallowing tasks: First, they were asked to do two speaking-related tasks, reading aloud and speaking spontaneously for two minutes each. Next, they performed three swallowing- related tasks. These were drinking five sips of water, drinking 100 ml of water, and eating an oat biscuit (15 grams). Then, they undertook a task that included speaking, chewing, and swallowing, where they ate an oat cookie and spoke spontaneously at the same time. Finally, the participants were asked to take five sips of water, while pressing their chin to the chest and rotating their heads to the left and the right. These, postural techniques are compensatory strategies that aim to increase the efficiency and safety of swallowing in people with dysphagia [9].

Data analysis

MathWorks MATLAB was used for the data analysis. First, a preliminary identifying of swallows was accomplished by visually inspecting the data from each orthogonal angular velocity gyroscopes sensor. An example of that data can be seen in Figure 2. One researcher examined the graphs of each sensor separately and marked each visually recognized swallow. It was noticed that data from one participant with five sips of water was corrupted for an unknown reason, so that part was excluded from the analysis. Next, the swallows marked with the data were compared to the swallows recognized using cervical auscultation and video footage. Based on this preliminary analysis, it was learned that less than 50% of the swallows could be visually identified from the data for all other tasks except for the tasks where participants were asked to drink 5 sips of water and 100 ml of water.

We wanted to find thresholds to identify the swallows from the orthogonal angular velocity gyroscopes data on the level of the thyroid notch. Thus, at first, the following threshold for an identified swallow was set:

1) the baseline had to be 0.00
2) the amplitude had to reach ±0.03
3) the data had to reach the baseline (0.00) after reaching ± within a second

A limit of one second was set because during a swallow, a bolus of food travels through the pharynx in less than 1 second [27]. The threshold of ±0.03 amplitudes was set based on a visual inspection with the goal to determine a threshold that would work for as many participants as possible. In addition, we adjusted the threshold manually ±0.03 by either lowering it to ±0.015 or raising it to ±0.045 amplitudes, if needed, based on individual differences. Thus, the duration of swallowing and the movement of the larynx varied individually based on the bolus size and individual anatomical structures. All swallows were identified using this threshold and the gyroscope data on the X-, Y- and Z-axis. If even one signal from the different gyroscopes (on the X, Y, or Z axis) triggered hit the threshold conditions, then it was recognized as a swallow. Further, if even one sensor detected swallowing, it was marked as detected in the "all sensors" section. With the manually adjusted thresholds, there were no false positives.

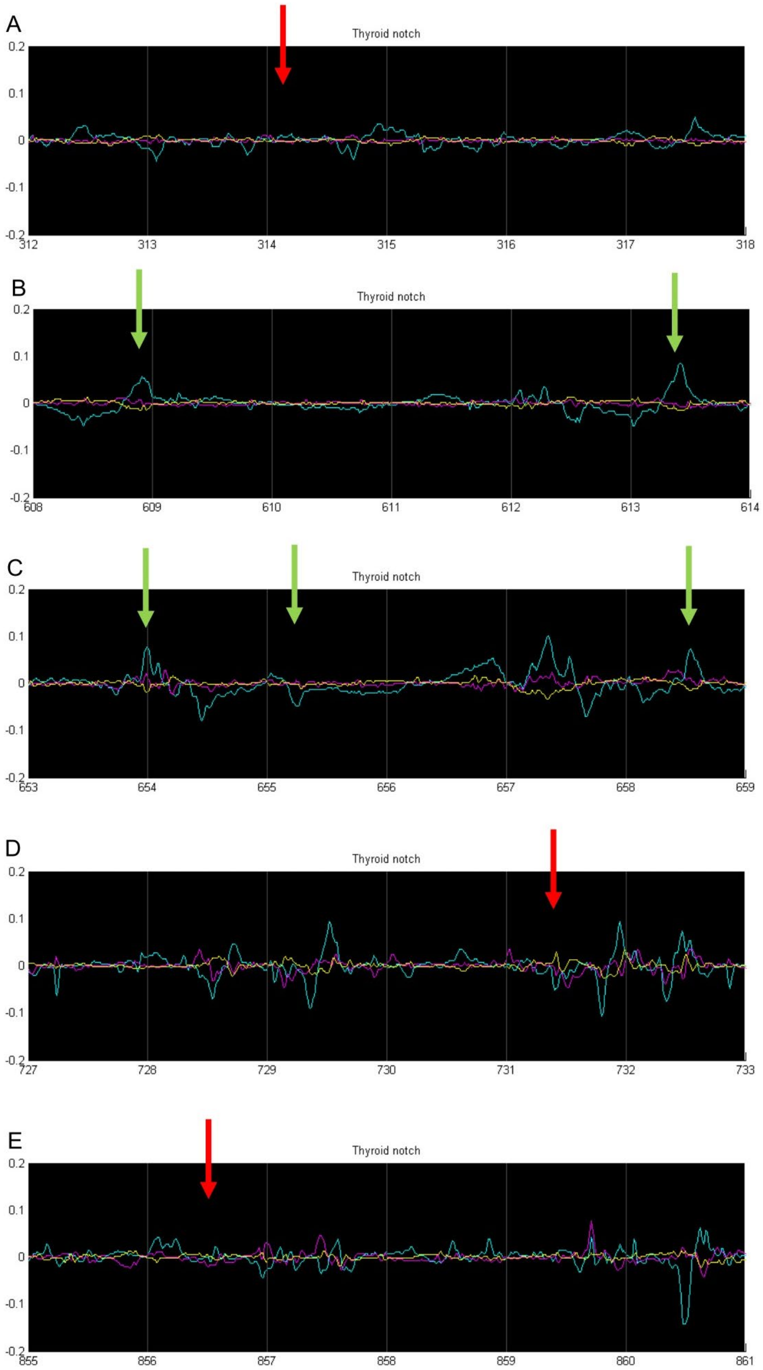

Figure 2. Data from the orthogonal angular velocity gyroscopes on the level of the thyroid notch. All examples are from a same participant and a sample duration is six seconds. Swallows confirmed by cervical auscultation and manually adjusted thresholds are marked with green arrows. Swallows confirmed with cervical auscultation but not with manually adjusted thresholds are marked with red arrows. A. reading aloud with spontaneous swallows, B. drinking 5 sips of water, C. drinking 100 ml of water (a head movement between 657–658 seconds), D. eating an oat biscuit and E. eating an oat biscuit and talking. The X-axis shows the time in seconds, and the Y-axis shows the fetched data values. Acceleration is marked red (X-axis), green (Y-axis), and blue (Z axis). Angular velocity on the X axis is marked cyan (X-axis), magenta (Y-axis), and yellow (Z-axis).

Results

Visual inspection

In total, the participants swallowed 95 times during the task by taking 5 sips of water (n=16) and 93 times during the task by drinking 100 ml of water (n=17). Further, it was noticed that these swallows could be visually identified most precisely from the data from the sensor placed on the thyroid notch (sensor Number 2 in Figure 1A). Thus, it was decided to undertake a more detailed analysis of the data by looking at the data from this sensor while drinking 5 sips of water and drinking 100 ml of water. Based on that visual inspection of all six sensors (Figure 1A), 97 % of the swallows while drinking 5 sips of water and 98 % of the swallows while drinking 100 ml of water could be identified from the gathered data (Table 1).

The set thresholds

The sensor placed on the thyroid notch was chosen for a closer examination with the set thresholds. Using the set thresholds, 97 % of the swallows in the five sips task and 95 % of the swallows in the 100 ml water drinking task could be identified from the data (see Table 1). The thresholds were slightly more accurate at recognizing swallows from the women than for the men during both tasks.

Table 1. The top of the table shows the percentage of the swallows recognized from the data of the orthogonal angular velocity gyroscopes compared to the swallows recognized using cervical auscultation. At the bottom of the table, the percentage of the swallows identified with set thresholds (±0.03, and those manually adjusted ±0.015 or ±0.045 amplitudes) from the data gathered from the orthogonal angular velocity gyroscopes on the level of the thyroid notch is shown.

Sensor location and number	5 sips of water			100 ml of water		
Visual inspection	Men (n = 7)	Female (n = 9)	All (n = 16)	Men (n = 8)	Female (n = 9)	All (n = 17)
under the chin (1)	68 %	75 %	72 %	54 %	83 %	71 %
hyoid bone level, left side (4)	84 %	80 %	82 %	59 %	81 %	72 %
hyoid bone level, right side (3)	91 %	73 %	81 %	77 %	74 %	75 %
thyroid notch (2)	95 %	86 %	91 %	85 %	93 %	89 %
below thyroid notch level, left side (6)	59 %	8 %	32 %	90 %	20 %	49 %
below thyroid notch level, right side (5)	59 %	2 %	28 %	41 %	0 %	17 %
all sensors (1–6)	98 %	96 %	97 %	100 %	96 %	98 %
Set thresholds						
thyroid notch (2)	93 %	95 %	95 %	95 %	98 %	97 %

Discussion

In this study, the sensors embedded in the fabric and placed on the neck best identify individual swallows of 5 sips of water and consecutive swallows of 100 ml of water based on visual inspection and the data gathered from the orthogonal angular velocity gyroscopes. These swallows were easy to identify visually from the data since the swallow produced a peak in the graph. However, there are other elements related to eating and drinking in everyday life than swallowing individual or consecutive sips of liquid. We chew and often also talk during eating situations. During chewing and speaking, there is movement in the neck area, and based on this study, it seems that the movement related to swallowing cannot be reliably separated from the movements related to the actual chewing and speaking using just visual inspection.

The success of visual inspection is important, as it will allow the neck gaiter user to receive feedback on his or her own swallowing and thus could be used, for example, for swallowing rehabilitation. Another use could be that the speech therapist, nursing staff or family members could monitor the user's swallowing by looking at the visual data. For example, counting the number of swallows during a meal would provide objective information about the efficiency of the swallowing process. When evaluating and rehabilitating swallowing, it would be important to know how many swallows are needed to eat a meal and whether the amount of food eaten is relative to the number of swallows. The prototype we tested in this study is not yet capable of this aspect. Once we have successfully distinguished a normal swallowing event amidst various scenarios involving individuals consuming different liquid and food consistencies, engaging in conversation, and moving naturally during eating situations, we can proceed with advancing the neck gaiter's development to identify abnormal swallowing patterns with different patient groups with dysphagia.

Sazonov and colleagues [14] were able to reliably distinguish bites, chewing, and swallowing with their non-invasive monitoring system, but their system utilized four microphones and a piezoelectric strain sensor, thereby likely limiting its comfortability for the individual user. In addition, Olubanjo and colleagues [19] could satisfactorily distinguish events such as speech, chewing, coughing, clearing the throat, and swallowing different liquids by using a throat microphone placed over the suprasternal notch of the trachea. Although these aforementioned studies have been able to separate the swallowing event from other events, these technical solutions are not yet available to consumers. Thus, easy-to-use solutions suitable for consumer use are still needed. In our study, we asked our participants' opinions about the neck gaiter and published these results in another article [28]. Briefly, the neck gaiter was felt relatively comfortable and soft; although the used Velcros were uncomfortable, and the gaiter disturbed turning the head.

Further still, in our study, the sensor placed at the level of the thyroid notch was the most reliable. In previous studies, the swallowing movements mostly were observed by placing the sensor at the level of the thyroid notch [18,24] or just below the thyroid notch [25,29]. We also tried using manual thresholds for the sensor placed at the level of the thyroid notch. With the help of manually adjusted thresholds, swallows of 5 sips of water and consecutive swallows of 100 ml of water were reliably identified. However, this is a laborious method and not suitable for use in an everyday environment. In addition, we were not able to distinguish swallowing movements from the movements related to chewing and speaking using the set thresholds.

The next step in developing a sensor system is create an algorithm that will automatically recognize the swallows from the results of the gyroscope without any human intervention at that stage of the process. That would make the neck gaiter easy to use on anybody, and no special skills would be needed by the individual person or that person's caretakers. Further still, in the future, the neck gaiter system could automatically send the analysed data to speech therapists or doctors, this way helps in the timely identification and treatment of swallowing difficulties and the prevention of complications. After these stages, when the neck gaiter has gained the needed functionalities, the size of the sensors can be minimized. There are many ways to minimize the size of electronics, and doing so would make the neck gaiter even more comfortable.

Conclusion

Based on our results, the developed neck gaiter with embedded orthogonal angular velocity gyroscopes can identify individual swallows of 5 sips of water and consecutive swallows of 100 ml of water. Unfortunately, we were not able to recognize swallowing movements from speaking, chewing and head movements. The next step in the process is to develop an algorithm that will recognize the swallows from the data and study the recognition of solid bolus swallowing. Overall, the neck gaiter presented in this study is clearly worth further development. We envision that in the future, a textile-based neck gaiter can be worn during normal daily life, and no hospital circumstances nor will any trained professionals be needed to perform the measurement of swallows. Overcoming the challenges noted in this study and this article – the laborious way of setting manual thresholds and the issues noted for differentiating swallowing movements from other movements – should be the focus of that algorithm development.

Conflict of interest statement

Authors confirm there are no conflicts of interest.

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