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Classification of healthy and abnormal swallows based on accelerometry and nasal airflow signals

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ABSTRACT

Background: Dysphagia assessment involves diagnosis of individual swallows in terms of the depth of airway invasion and degree of bolus clearance. The videofluoroscopic swallowing study is the current gold standard for dysphagia assessment but is time-consuming and costly. An ideal alternative would be an automated abnormal swallow detection methodology based on non-invasive signals.
Objective: Building upon promising results from single-axis cervical accelerometry, the objective of this study was to investigate the combination of dual-axis accelerometry and nasal airflow for classification of healthy and abnormal swallows in a patient population with dysphagia.
Methods: Signals were acquired from 24 adult patients with dysphagia (17.8 ± 8.8 swallows per patient). The abnormality of each swallow was quantified using 4-point videofluoroscopic rating scales for its depth of airway invasion, bolus clearance from the valleculae, and bolus clearance from the pyriform sinuses. For each scale, we endeavored to automatically discriminate between the 2 extreme ratings, yielding 3 separate binary classification problems. Various time, frequency, and time-frequency domain features were extracted. A genetic algorithm was deployed for feature selection. Smoothed bootstrapping was utilized to balance the two classes and provide sufficient training data for a multidimensional feature space.
Results: A Euclidean linear discriminant classifier resulted in a mean adjusted accuracy of 74.7% for the depth of airway invasion rating, whereas Mahalanobis linear discriminant classifiers yielded mean adjusted accuracies of 83.7% and 84.2% for bolus clearance from the valleculae and pyriform sinuses, respectively. The bolus clearance from the valleculae problem required the lowest feature space dimensionality. Wavelet features were found to be most discriminatory.
Conclusions: This exploratory study confirms that dual-axis accelerometry and nasal airflow signals can be used to discriminate healthy and abnormal swallows from patients with dysphagia. The fact that features from all signal channels contributed discriminatory information suggests that multi-sensor fusion is promising in abnormal swallow detection.

1. Introduction

The current gold standard in dysphagia (swallowing disorder) assessment is the videofluoroscopic swallowing study (VFSS) [1]. In this imaging technique, diagnostic and treatment planning decisions are based on analysis of a pharyngeal X-ray video captured during stimulus (i.e., food or liquid) intake. In particular, VFSS can gauge the abnormality of each swallow in terms of the depth of airway invasion and degree of bolus clearance after the swallow. However, VFSS involves radiation exposure, requires specially trained personnel (speech-language pathologists and radiologists), is not available in all hospitals, and often involves long wait times. For these reasons, it is not practical to use VFSS for regular monitoring of dysphagia. A valid, noninvasive tool for detecting and monitoring dysphagia would, therefore, be a valuable addition to swallow assessment methodologies. However, development of such a tool must start with VFSS as a gold standard in swallow segmentation and assessment.

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Examples of noninvasive approaches to swallowing evaluation include cervical auscultation [2], pulse oximetry [3], and electrophysiological methods [4]. This study focused on two such signal modalities, namely dual-axis cervical accelerometry and nasal airflow. The following two paragraphs briefly describe the two signal modalities in the context of swallow analysis.

Swallowing accelerometry refers to the collection and analysis of cervical vibration signals acquired via an accelerometer. This technique originally stemmed from the belief that any differences between healthy and abnormal swallows that are perceivable using cervical auscultation with a stethoscope or microphone must also be discernible from a signal standpoint. Given that subjective perceptual judgments arising from cervical auscultation are susceptible to error [2], it is also reasonable to assume that signal-processing can provide a more objective means of detecting abnormal features in cervical vibrations collected during swallowing. Recent swallowing accelerometry studies have utilized digital signal processing and pattern recognition techniques in an effort to automate swallow evaluation (e.g. [5,6]). Physiologically, it has been shown that peak neck vibration in the anterior–posterior (A–P) direction is associated with maximum hyolaryngeal excursion [7]. Although single-axis accelerometry in the A–P direction has dominated this field, a recent study on dual-axis accelerometry showed that the superior–inferior (S–I) direction contains swallowing information that is not captured by the A–P direction [8].

Because the pharynx is a shared passageway for both air and bolus transport, respiration is a vital physiological function that needs to be precisely coordinated with swallowing for the prevention of airway invasion [9]. The existence and timing of the cessation of breathing during swallowing, termed swallowing apnea, is a critical piece of information in determining the integrity of airway protection [10,11], and can be identified in nasal airflow signals. Since the recording of oral respiration is not feasible during swallowing, nasal respiration is used for airflow monitoring in swallowing research.

With this motivation, the objective of this study was to investigate automated discrimination between healthy and abnormal swallows based on various time, frequency, and time-frequency domain features extracted from dual-axis cervical accelerometry and nasal airflow signals. The underlying hypothesis was that simultaneous consideration of multiple signal modalities can improve upon previously reported classification accuracies based solely on single-axis accelerometry. Such a multi-sensor fusion approach is novel in the field of computational swallow classification.

The ultimate user of a swallow classifier is a patient with dysphagia, as only patients with dysphagia undergo VFSS. Hence, this study compared swallows with and without abnormalities from patients with dysphagia. Swallows from healthy individuals without dysphagia would not form the appropriate control population since they could be substantially different from "normal" swallows from patients with dysphagia. In this paper, "healthy" and "abnormal" swallows are defined as swallows that were found to be physiologically normal (henceforth termed "healthy") on videofluoroscopy and those that were abnormal, i.e., displaying either penetration–aspiration or pharyngeal residues, respectively.

2. Methods

2.1. Signal acquisition

Dual-axis accelerometry and nasal airflow signals were acquired from 24 (22 males) adult patients with dysphagia during routine VFSS sessions. All patients had suffered either stroke or acquired brain injury and underwent VFSS to investigate their swallowing function. The average age of the patients was 64.8 ± 18.6 years. Corresponding X-ray videos were recorded as well. The presiding speech-language pathologists determined the number of swallows and stimulus types for each patient, although a standardized approach, beginning with a thin liquid 40% weight per volume barium suspension and progressing through nectar- and spoon-thick liquids to solid stimuli, was used. The mean number of swallows per patient was 17.8 ± 8.8. This study was approved by the ethics committees at the Toronto Rehabilitation Institute, Bloorview Kids Rehab, and University of Toronto. All patients gave informed consent prior to participation.

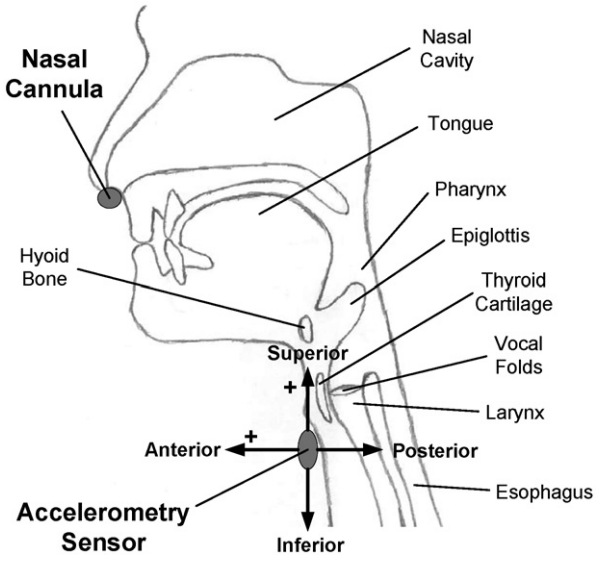

Figure 1. Locations of the dual-axis accelerometer and nasal cannula with respect to relevant anatomical structures. Axial orientation and polarity are also shown for the accelerometer.

Dual-axis accelerometry signals were acquired via a dual-axis accelerometer (ADXL322, Analog Devices) placed on the neck just below the thyroid cartilage, with the axes oriented in the A–P and S–I directions. The sensor was attached to the neck with a double-sided electrode collar (650455, VIASYS Healthcare). Nasal airflow signals were recorded with a nasal cannula (Pro-Flow Cannulas Model 1259, Grass Technologies) placed at the nares, connected to a pressure transducer (PTAFLITE, Grass Technologies). See Fig. 1 for an illustration of sensor location and orientation. Each signal channel was sampled at 10 kHz by a custom LabVIEW application. A pre-amplifier with a bandpass filter (Model P55, Grass Technologies) was utilized for each channel, with the cutoff frequencies set at 0.1 Hz and 3 kHz. Amplification was set at 10 and 10,000 for the two accelerometry channels and nasal airflow, respectively.

The signal acquisition hardware was comprised of two separate components: one for the acquisition of the accelerometry and nasal airflow signals and the other for videofluoroscopy recording. The two components were synchronized by resetting the time-code generator (Time Code Master Model 5010, Evertz Microsystems), which inserted time stamps on the X-ray videos, when signal acquisition started immediately prior to the beginning of the VFSS session. Signal acquisition and video recording were stopped immediately after the end of the session.

2.2. Clinical swallow ratings

The X-ray video of each swallow was analyzed and rated by a speech-language pathologist. First, individual swallows were located in the videos. Swallow onset was defined as the moment when the leading edge of the bolus crossed the inferior margin of