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ORIGINAL ARTICLE

Anthropometric and Demographic Correlates of Dual-Axis Swallowing Accelerometry Signal Characteristics: A Canonical Correlation Analysis

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Abstract Swallowing accelerometry has been proposed as a potential minimally invasive tool for collecting assessment information about swallowing. The first step toward using sounds and signals for dysphagia detection involves characterizing the healthy swallow. The purpose of this article is to explore systematic variations in swallowing accelerometry signals that can be attributed to demographic factors (such as participant gender and age) and anthropometric factors (such as weight and height). Data from 50 healthy participants (25 women and 25 men), ranging in age from 18 to 80 years and with approximately equal distribution across four age groups (18-35, 36-50, 51-65, 66 and older) were analyzed. Anthropometric and demographic variables of interest included participant age, gender, weight, height, body fat percent, neck circumference, and mandibular length. Dual-axis (superior-inferior and anterior-posterior) swallowing accelerometry signals were obtained for five saliva and five water swallows per participant. Several swallowing signal characteristics were derived for each swallowing task, including variance, amplitude distribution skewness, amplitude distribution kurtosis, signal memory, total signal energy, peak energy scale, and peak amplitude. Canonical correlation analysis was performed between the anthropometric/demographic variables and swallowing signal characteristics. No significant linear relationships were identified for saliva swallows or for superior-inferior axis accelerometry signals on water swallows. In the anterior-posterior axis, signal amplitude distribution kurtosis and signal memory were significantly correlated with age ($r = 0.52$, $P = 0.047$). These findings suggest that swallowing accelerometry signals may have task-specific associations with demographic (but not anthropometric) factors. Given the limited sample size, our results should be interpreted with caution and replication studies with larger sample sizes are warranted.

Keywords Swallowing · Dysphagia · Accelerometry · Signal processing · Cervical auscultation · Deglutition · Deglutition disorders

Introduction

The mechanical act of swallowing produces a source of vibration at the neck. The measurement of these vibrations is known as swallowing accelerometry. Accelerometry is closely related to cervical auscultation, the clinical technique of listening to and interpreting acoustic information collected from the surface of the neck during swallowing. Both swallowing accelerometry and cervical auscultation have been proposed as potentially useful and minimally invasive methods for detecting abnormalities in

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swallowing. Early reports of swallowing sounds, heard either through a stethoscope or a microphone, described a characteristic sound pattern involving a sequence of two clicks, followed by a "swoosh" sound [1]. Previous research has explored methodologic aspects of auscultation [2], including the benefits of using different stethoscopes [3] and the best locations on the neck for collecting swallowing sounds, based on the harmonic-to-noise ratio [4, 5]. Others have explored the temporal correspondence between events in the swallowing acoustic signal and events in swallowing physiology [6–12], linking the primary acoustic burst to passage of a bolus through the upper esophageal sphincter [13]. Most recently, attention has been focused on the possible anatomical and physiologic sources of swallowing acoustic signals. Healthy swallowing has been described to typically include three distinct acoustic events corresponding to laryngeal ascent, upper esophageal sphincter opening, and postswallow glottal release [2, 14, 15]. Hyolaryngeal excursion has been posited as the mechanical source of these vibrations [16]. As this literature has evolved, clinical cervical auscultation practice (which involves listening to swallowing sounds with a stethoscope at the neck) [17] has been criticized for its potential to yield false information based on subjective perceptual interpretation and the absence of a clear scientific basis upon which to classify the sounds that are registered in swallowing [17, 18]. It appears that signal-processing techniques may be necessary in order for the field of swallowing research to establish the characteristics of both healthy and disordered swallows and to confirm the validity of any clinical interpretations that might arise from the analysis of swallowing acoustics.

Several studies have characterized the sounds of healthy swallowing to serve as a source of comparison for dysphagic swallowing [12, 19, 20]. In these studies, a device (single-axis accelerometer or electret microphone) was placed on the skin surface on the anterior neck at the level of the cricoid cartilage [2, 4]. The sounds associated with swallowing were recorded as signals and later subjected to spectrographic analysis in order to identify signal intensity, frequency, and duration. Sound spectrography is commonly used in speech science for the analysis of speech sounds [21]. Cichero and Murdoch [19] applied this technique to the analysis of swallowing sounds collected using an electret microphone, and filtered using a 1024-point narrow-bandwidth Hamming window filter with no preemphasis. Using these methods they reported that the frequency range of swallow sounds was 0-2500 Hz, with a predominant region of spectral intensity between 490 and 550 Hz. A second, but quieter, area of spectral intensity was observed in the 2-kHz range [19].

Speech sound spectrography is built on some fundamental assumptions, including source-filter theory [21]. According to this theory, sounds with a rich harmonic structure are generated at the sound source (for speech, vibration of the vocal cords) and are then filtered by the locations and degrees of constrictions in the anatomy of the human vocal tract through which speech sounds travel. It is common to report fundamental frequency in speech sound analysis, but also to report energy that is seen in the first and second formant ranges. Formants are resonant frequencies arising from the filtering characteristics of the vocal tract and are labelled numerically (F1, F2, F3). An open vocal tract configuration in males will typically generate resonant frequencies at around 500, 1500, and 2500 Hz. Changes in tongue position and shape will alter formant frequencies in speech: The F1 formant is most closely associated with tongue height (degree of constriction) such that sounds made with a lower tongue position will generate a higher F1 frequency (above 500 Hz). The F2 formant reflects the anterior-posterior location of tongue raising during vowel production; sounds produced with an anterior tongue to palate constriction have higher F2 values [21].

Filtering is used in speech spectrography to locate consistent frequency components related either to the harmonics of the source (for which narrow-band filters are used) or to the resonating formants (which are easier to see using wide-band filters) [21]. The earlier work by Cichero and Murdoch [19] used a narrow-band filter, reporting regions of spectral intensity in the F1 and upper F2 ranges (500 and 2500 Hz); they did not report fundamental frequency measures. A follow-up study by Youmans and Stierwalt [20] obtained similar results using an accelerometer and a 1024-point narrow-band filter. In contrast to speech sounds, however, swallowing sounds are predominantly short-lived transient sounds and their spectral composition is not as well defined over time. Whether it is appropriate to assume that sounds recorded through the skin of the neck are likely to be subject to the filtering characteristics of the vocal tract remains unclear. While the origin of swallowing sounds remains subject to debate, there should be no debate that swallowing sounds are unlikely to have a spectral composition that is rich in harmonics. The most likely source of swallowing vibrations is the physical motion of the hyolaryngeal structures. It is physically implausible that these sound-generating movements might occur at rates above 50 Hz.

We are conducting a research program to explore the potential of swallowing accelerometry to serve as a noninvasive tool in clinical swallowing assessment to aid in the differentiation of healthy and physiologically abnormal swallows. We use a dual-axis accelerometer to collect swallowing vibrations simultaneously in both the anterior-posterior and superior-inferior axes [22]. As part of this line of research, we are developing and testing signal-processing techniques to automatically divide swallowing accelerometry signals into individual segments corresponding to swallows [23], and we are exploring the need for and utility of filters to remove artifacts arising from potential sources of contaminating noise in the signal such as head movement [23, 24]. For the purposes of the present study, it may be useful for the reader to familiarize him/herself with the definitions of the signal characteristics that have been explored in this analysis compared with those used in previous studies [19, 20]. A brief glossary of definitions is included at the end of the article.

Most authors agree that the first step to using sounds and signals for dysphagia detection involves characterizing the healthy swallow. The purpose of this article is to explore systematic variations in swallowing accelerometry signals that can be attributed to demographic factors (such as participant gender and age) and anthropometric factors (such as weight and height). Cichero and Murdoch [19] reported that the duration of the swallowing acoustic signal increased with age but that the temporal location of the peak frequency, the intensity of the signal, and the frequency at peak intensity remained constant across age, gender, and bolus volume. Youmans and Stierwalt [20] confirmed a correlation between age and signal duration but also reported that intensity of the acoustic signal decreased with age. None of their measures were sensitive to gender [20]. Huckabee et al. [25] reported the effect of subcutaneous fat on the amplitude of surface electromyography signals collected from the submental muscles. Similarly, the mechanical attenuation of the superficial measurement of muscle activity as a result of subcutaneous adipose tissue has been previously reported in mechanomyographic studies [26, 27]. While the present study was not concerned with muscle activity, we recognized the possibility that adipose tissue might impose similar mechanical damping on swallowing accelerometry signals.

This was an exploratory study; the objective was to characterize dual-axis swallowing accelerometry signals and their variation across anthropometric and demographic variables in healthy individuals. Anthropometric variables of interest included weight, height, body composition (body mass index and body fat percent), neck circumference, and mandibular length. Demographic variables of interest included age, gender, and habitual physical activity levels. In formulating our research questions, we decided to collect data in a manner similar to current clinical screening protocols for identifying dysphagia. Specifically, we decided to collect a series of repeated 5-ml water swallows from participants. This procedure has been reported to be sensitive to the presence of dysphagia in stroke patients [28, 29]. Although swallow screening protocols frequently collect up to 10 consecutive 5-ml swallows of water, we decided that a series of five repeated 5-ml water swallows should be adequate to characterize swallowing signals in healthy adults. In addition, we were curious to determine whether saliva swallowing signals differ from those generated from a water bolus. Previous authors have reported variations in swallowing sounds across bolus volumes and consistencies, but to our knowledge no previous descriptions of saliva swallowing signals exist. To discriminate the differences between physiologic and bolus influences in the signal, we asked our participants to perform both saliva swallows and water swallows.

Methods

A total of 408 healthy individuals (age range = 18–80 years) participated in this study. Participants were recruited from the general public in the exhibit area of a science museum. Eligibility was confirmed through a series of questions regarding health history, specifically focusing on risk factors for and history of dysphagia. Individuals whose medical history included a neurologic condition, dysphagia, head or neck cancer, or tracheotomy were excluded. Furthermore, participation required the ability to independently stand and ambulate (to support collection of anthropometric data). All participants provided written consent. The research protocol was approved by the research ethics boards of the collaborating hospital-based research institutes and by the science museum. Each participant completed a two-part data collection protocol. Step 1 involved the collection of anthropometric and demographic data. Step 2 involved the acquisition of swallowing signals using dual-axis accelerometry.

Anthropometric data collection involved recording the participant's height, weight, body fat percent, neck circumference, and mandibular length. During training, the research personnel involved in collecting anthropometric measures each performed three duplicate sets of measurement on a group of ten pilot participants to ensure acceptable intra- and interrater agreement in measurement. Participants were asked to remove their shoes, socks, sweaters, and heavy coats prior to anthropometric measurement. Participants were asked to report any alcohol consumption and whether they exercised during the 24 h prior to the study; the manual for the bioelectrical impedance analysis machine that was used in the study (BIA Meter, BC-550, Tanita) indicated that these factors can affect the validity of the body composition measures that were collected. If a participant reported significant alcohol consumption (i.e., more than 2 drinks) in the previous 24 h or significant physical exercise within the prior 3 h, he/she was excluded from the study.

Height (in cm) was measured using a free-standing stadiometer, with the participant's head positioned in the

Frankfurt plane (i.e., with the plane passing through the inferior margin of the left orbit and upper margin of each ear canal parallel to the floor), feet together, knees straight, and heels, buttocks, and shoulders in contact with the vertical surface. Weight was measured using the bioelectric impedance analysis equipment (BIA Meter, BC-550, Tanita). Prior to proceeding with weight and body fat percentage measurements, the participant's age, gender, and self-reported habitual physical activity level (Level 1: no little or no activity; Level 2: 3 or 4 h of exercise per week; Level 3: > 10 h of exercise per week) were also documented and entered into the BIA meter settings, as per the manufacturer's guidelines for obtaining accurate measurement. The BIA meter was zero-balanced before the participant stepped onto the scale, following the manufacturer's instructions. Body mass index (BMI) was derived as the ratio between weight and height measurements.

After anthropometric and demographic data collection, participants underwent a brief assessment by a registered speech-language pathologist (SLP) to rule out the presence of overt clinical signs that might suggest the presence of swallowing difficulties [30–32]. The SLP evaluated voice quality, tongue range of motion, maximum phonation time, and strength of volitional cough. Participants were asked whether they experienced difficulty such as coughing when drinking water [30]. Water swallows were not specifically observed at this stage of data collection because they would be included in the next stage of the study procedures. Those participants displaying abnormal results on any of these items were excluded from the remainder of the study. Individuals who reported awareness of swallowing difficulties with water were advised to discuss this concern with their family physician.

The second part of the protocol involved the collection of dual-axis swallowing accelerometry data. A schematic diagram of the data collection setup is shown in Fig. 1. The participant was seated in a chair and a dual-axis accelerometer (Analog Devices, ADXL322) was secured on the participant's neck (in midline, anterior to the cricoid cartilage) using double-sided tape. The accelerometer was oriented to record vibrations in the superior-inferior (SI) and anterior-posterior (AP) directions. Swallowing signals were amplified ten times by a GRASS P55 amplifier, band passed between 0.1 Hz and 3 kHz, and sampled at 10 kHz using a USB data acquisition card (National Instruments, NI-USB 9215A) and a custom LabView program. Since the amplifier and accelerometer were both battery-powered, power line noise was not a consideration. Data were saved onto the hard drive of the attached computer for subsequent offline analysis.

Immediately following accelerometer attachment, a task training set of three cued swallows was performed to ensure adequate accelerometer contact and good signal quality, and to familiarize the participant with the data collection procedures. Participants were instructed to remain as still as possible and to refrain from speaking during data collection. Once the training task was completed, each participant was cued to perform five saliva swallows with 30-s rests between each swallow to allow for saliva production. The participant was then asked to complete five water swallows with the chin in a neutral position (perpendicular to the floor) with brief rests between each swallow.

Analysis

For the current analysis, the signals of 50 randomly sampled participants (25 women and 25 men), ranging in age from 18 to 80 years and with approximately equal distribution across four age groups (18–35, 36–50, 51– 65, 66 and older) were extracted from the larger data set of 408 individuals. A data set of 500 swallows was obtained, comprising the five saliva and five water swallows from each participant. Time-linked accelerometry signals were

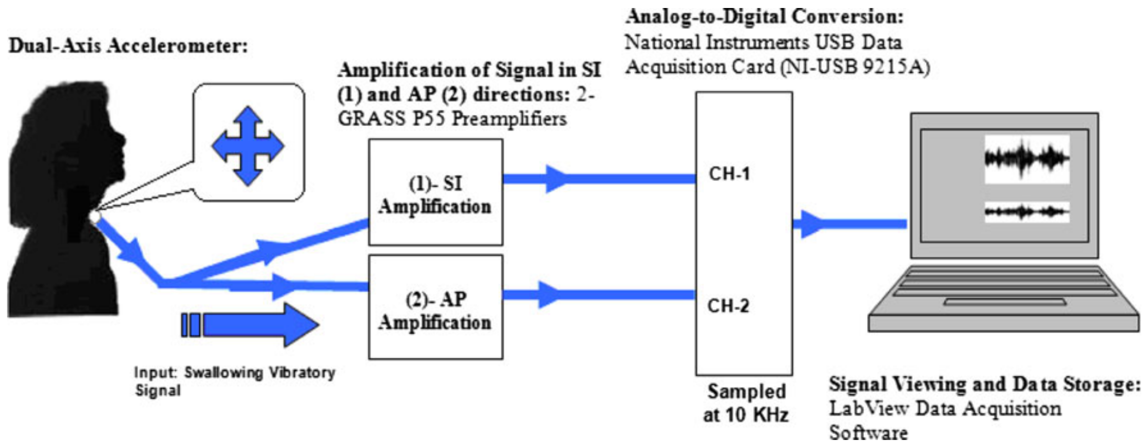

Fig. 1 Schematic diagram of data collection setup

captured in both the superior-inferior (SI) and the anterior-posterior (AP) direction during all swallowing tasks; therefore the data set included 500 SI and 500 AP signals.

The accelerometry signals were first denoised using an 8-level Daubechies wavelet via soft-thresholding [33] and then segmented manually in the following manner: Each swallowing sequence was displayed on a computer screen, and a cursor was used to mark the onset and offset locations for swallows within each sequence. Onset and offset were determined by visual identification of the characteristic increase and decrease in signal magnitude preceding and succeeding a burst of signal activity. This procedure was completed independently in duplicate by two trained raters. The extracted segment for each swallow was the region of intersection between the corresponding swallows marked by each rater. The extracted segments were acoustically verified by audio playback on the computer. The interrater intersections for the SI and AP axes were 73 ± 0.9% and 75 ± 1.7%, respectively, across all tasks. Note that interrater intersection refers to the average temporal overlap between the corresponding swallows segmented by the two raters. For example, 73% interrater intersection means that if one rater picked out a swallow of 1 s in duration in the SI axis, then on average 730 ms of the same swallow was also identified by the other rater in the SI axis. This measure is different from conventional interrater agreement, which in this case would be 100% since every swallow picked out by one rater was also identified by the other rater, albeit with potentially different temporal extents. Figure 2 illustrates a typical swallow accelerometry signal containing five swallowing events, with onset and offset boundaries for each swallow marked by dashed vertical lines.

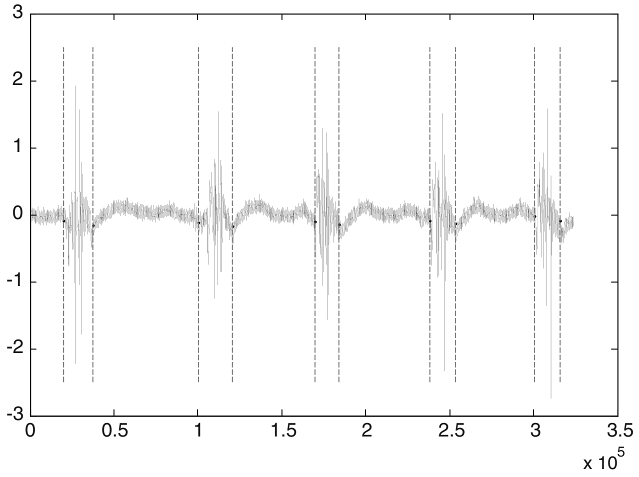

Fig. 2 Sample of a swallow accelerometry signal, with dashed vertical lines showing the boundaries of five swallowing events detected during signal segmentation

Following segmentation, a variety of signal characteristics were calculated: variance, skewness, and kurtosis of the signal's amplitude distribution, signal memory (when the autocorrelation of the signal decays to $1/e$ of its maximum), total energy of the swallowing signal, scale (the level of the discrete wavelet transform of the signal bearing the highest fraction of the signal energy), peak amplitude, and duration. These variables have been used in previous studies of dual-axis accelerometry signals by Lee et al. [34] and represent fundamental summary statistics and spectral features of the signal. For the present study, signal characteristics were computed separately for each of the 500 swallows and then averaged for each participant, for each swallow task (saliva and water), and for each axis (AP and SI). Given that we had 50 participants, this procedure yielded 50 element vectors for each signal feature, for each task, for each of the two axes.

To explore the relationship between anthropometric/demographic variables and dual-axis swallowing accelerometry signal characteristics, we performed a canonical correlation analysis. Canonical correlation analysis is a multivariate method of measuring the linear relationship between two multidimensional variable sets. The analysis uncovers canonical variate pairs (linear combinations of the original variables) that are maximally correlated [35–37].

For the present study, the first multidimensional variable set consisted of the anthropometric and demographic variables. These included height, weight, age, gender, body fat percent, neck circumference, mandibular length, BMI, and self-reported habitual activity level. The discrete variable of gender was coded as an indicator variable ($0 =$ female, $1 =$ male). Collinearity of variables was checked using the correlation coefficient. Our check for collinearity revealed several strong correlations ($r \geq 0.6$) between paired anthropometric variables: weight and BMI ($r = 0.88$), neck circumference and mandibular length ($r = 0.85$), body fat percentage and BMI ($r = 0.72$), and weight and neck circumference ($r = 0.69$). Therefore, the anthropometric and demographic variable set was reduced, leaving only height, weight, age, gender, and self-reported habitual activity level. Clearly, of these remaining measures, self-reported habitual activity level should be considered with caution due to the possibility of inaccuracy in interview-style reporting of this type of data.

The second multidimensional variable set comprised axis-specific swallowing accelerometry signal characteristics, averaged within participant across the five swallows performed in each task. As with the anthropometric/demographic variables, collinearity between signal characteristics was checked using the correlation coefficient. This revealed a strong inverse relationship ($r = -1$) between signal memory and duration. The signal characteristics variable set was therefore reduced, leaving variance, skewness, kurtosis, signal memory, total signal energy, peak energy scale, and peak amplitude.

Two further steps occurred before the canonical correlation analysis. First, coefficients of variation (CV) were inspected for all variables. The CV represents the ratio of the standard deviation to the mean and is a useful statistic for comparing the degree of variation across variables [38, 39]. Typically, CV values less than 1 are considered to reflect low variance, while values over 1 are considered to reflect high variance [40]. In this study we decided on an *a priori* basis to exclude from the analysis any variables with CV > 1. This decision was made to mitigate the possibility that genuine correlations might be masked by high variance in certain variables. Table 1 presents CV data for the anthropometric/demographic variable set. None of these variables had high variance. Similarly, Table 2 presents axis-specific CV data for the swallow accelerometry signal characteristic variables on the saliva and water swallows, respectively. As shown by the shaded cells in Table 2, the variables of skewness and signal amplitude had excessively high coefficients of variation in the SI direction on both tasks. Similarly, the variables of signal variance, skewness, total energy, and amplitude had excessively high coefficients of variation in the AP direction on both tasks. Accordingly, these high variance variables were excluded from the task- and axis-specific canonical correlation sets.

Second, all outliers within the data set were removed. Outliers were defined *a priori* as values falling outside 2.5 standard deviations of the mean of a given variable. With these steps completed, the canonical correlation proceeded. Four separate within-task, within-axis analyses were performed. A criterion of $P < 0.05$ was used for determining statistical significance.

The power of the canonical correlation test for zero correlation was estimated based on the formulation of Sugiyama and Ushizawa [41], who reported power estimates for canonical problems comparable to those considered here in terms of the number of variables, the strength of the correlations, and the sample size.

Table 1 Coefficients of variation for anthropometric and demographic variables

Variable	Coefficient of variation (σ/μ)	Decision
Weight	0.06	Include
Height	0.23	Include
Age	0.35	Include
Activity level	0.28	Include

Variables with coefficients of variation greater than 1 were excluded from subsequent analysis

Results

For saliva swallows there were no significant correlations between anthropometric/demographic variables and swallowing accelerometry signal characteristics, in either the superior-inferior axis ($r = 0.65$, $P = 0.39$) or the anterior-posterior ($r = 0.54$, $P = 0.43$) axis. This was also true for superior-inferior axis signal characteristics on water swallows ($r = 0.64$, $P = 0.059$). For anterior-posterior axis signal characteristics on water swallows, a statistically significant correlation was identified between participant age and the variables of signal kurtosis and memory ($r = 0.52$, $P = 0.047$). Figure 3 illustrates the canonical weights for each significant variable in this relationship. Specifically, participant age was negatively correlated with signal memory and positively correlated with signal kurtosis. The power of the final test was estimated as lying between 70 and 80% according to the tables from Sugiyama and Ushizawa [41].

Discussion

Swallowing accelerometry has been proposed as a potential minimally invasive tool for discriminating healthy from disordered swallowing in clinical assessment. Before the potential of this tool can be validated and established, it is essential to understand the characteristics of swallowing accelerometry signals, to determine their inherent variability, and to determine the extent to which systematic variation in these signals can be attributed to known participant factors such as demographic and anthropometric variables.

In this discussion we formulate some possible explanations for the correlations uncovered in our analyses. First, it is important to comment on the absence of correlations between anthropometric variables (height and weight) and dual-axis swallowing accelerometry signal characteristics. This finding suggests that normative reference values for dual-axis swallowing accelerometry signal characteristics might be proposed, without consideration for subgroups within the healthy adult population. Similarly, our analysis failed to find correlations between gender or participant-reported habitual activity level and dual-axis swallowing accelerometry signal characteristics, again suggesting that normative reference values could be proposed without consideration of these factors.

Our analysis did reveal task- and axis-specific correlations between participant age and dual-axis swallowing accelerometry signal characteristics. On the one hand, these results show a lack of variation in these signals when the experimental task is saliva swallowing. On the other hand, our results suggest that anterior-posterior axis

Table 2 Coefficients of variation for swallowing accelerometry signal characteristics by task and axis

Task	Axis	Variable	Coefficient of variation (σ/μ)	Decision
Saliva swallows	Superior-inferior	Variance	0.53	Include
		Skewness	2.32	Exclude
		Kurtosis	0.62	Include
		Memory	0.36	Include
		Energy	0.7	Include
		Scale	0.2	Include
		Amplitude	1.23	Exclude
	Anterior-posterior	Variance	1.35	Exclude
		Skewness	3.98	Exclude
		Kurtosis	0.69	Include
		Memory	0.35	Include
		Energy	1.33	Exclude
		Scale	0.12	Include
		Amplitude	2.72	Exclude
Water swallows	Superior-inferior	Variance	0.68	Include
		Skewness	1.16	Exclude
		Kurtosis	0.63	Include
		Memory	0.35	Include
		Energy	0.62	Include
		Scale	0.22	Include
		Amplitude	1.26	Exclude
	Anterior-Posterior	Variance	1.12	Exclude
		Skewness	56.54	Exclude
		Kurtosis	0.75	Include
		Memory	0.4	Include
		Energy	1.04	Exclude
		Scale	0.16	Include
		Amplitude	11.98	Exclude

Variables with coefficients of variation greater than 1 were excluded from subsequent analysis

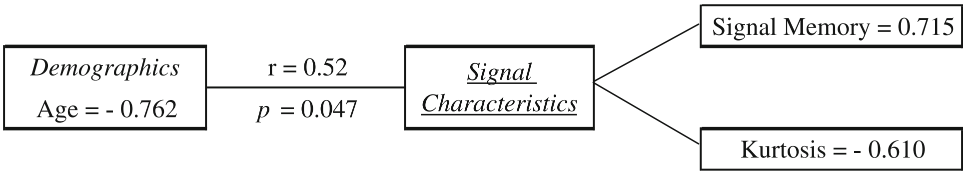

Fig. 3 Canonical weights for the significant correlation observed between participant age and anterior-posterior axis swallowing accelerometry signal characteristics on water swallows

vibrations generated during water swallows can be expected to vary as a function of participant age.

We determined that anterior-posterior axis accelerometry signal memory was negatively correlated with participant age. Recall that signal memory was determined to be inversely correlated with signal duration in the data reduction stage of this research. Thus, this implies that the durations of anterior-posterior axis swallowing vibrations increase with age. This finding is consistent with previous reports that the duration of swallowing acoustic sounds increases with age [19, 20], although we found that this phenomenon was present only in the anterior-posterior vibration axis. Age-related increases in swallowing vibration durations would be consistent with general observations of motor slowing in aging. Furthermore, the duration of swallowing apnea (airway closure during swallowing) is known to increase with age [42]. Prolonged apnea may contribute to longer overall swallowing signal duration, particularly if mechanical events associated with airway protection constitute the source of swallowing vibrations [43].

The isolation observed in this study of the age-related accelerometry signal variation to the anterior-posterior axis is particularly interesting in light of the suggestion that the mechanics associated with hyolaryngeal excursion are the putative source of swallowing vibrations [43]. To date, there is a paucity of literature describing normative ranges of axis-specific hyolaryngeal movement in swallowing, and a relative age-related impairment in anterior-posterior movement has not been reported. Kim and McCullough [44] observed significant reductions in both the vertical and the horizontal range of hyoid movement in healthy participants aged 70 years or older during 5- and 10-ml swallows of thin liquid barium compared to participants aged 20–50 years.

Our analysis also identified a positive correlation between anterior-posterior axis signal kurtosis and age on water swallows. Signal kurtosis refers to the peakedness of the amplitude distribution of the swallowing signal. These results therefore show that the distribution of anterior-posterior axis swallowing vibrations becomes concentrated in lower-amplitude ranges in older participants. Age-related declines in muscle tone might account for a preponderance of weakened A-P signal amplitudes, leading to inflated kurtosis. As with the signal memory data (above), this finding is particularly interesting given the suggestion that hyolaryngeal movement provides the mechanical source of swallowing vibrations.

It is important to comment on the overall low occurrence of statistically significant patterns of variations in our data according to anthropometric and demographic variables. One reason for this lack of overall variation may well be the fact that this study focused on tasks that might be assumed to vary minimally (i.e., saliva swallows and water swallows). Unlike previous studies of swallowing acoustics or vibrations, we also employed a rigorous data reduction procedure prior to our analysis. This procedure found that several characteristics of swallowing accelerometry signals have inherently high variance. In particular, it is important to note that accelerometry signal amplitude has high variance. The high variability inherent in these signal characteristics makes them unsuitable to use in the differentiation of healthy from disordered swallowing accelerometry signals. Whether such high variance is also characteristic of the amplitudes of hyolaryngeal excursion, as measured from videofluoroscopic recordings [44–48], remains to be determined.

Finally, it is interesting to note that the influence of age in this study was noted only with the water-swallowing task and not with saliva swallows. To our knowledge, this is the first report in the literature of swallowing accelerometry measures with saliva swallows. However, previous authors have reported variations in cervical auscultation measures across boluses of different consistency [20]. Similarly, the literature on hyoid movement suggests that movement amplitudes may differ according to the stimuli tested [46, 48]. It is interesting to speculate on the observation that a stimulus (i.e., water) was necessary to reveal age-related differences in the durational characteristics of anterior-posterior axis accelerometry signals. Whether different stimuli of increased viscosity and/or density would elicit swallows with enhanced age-related accelerometry differences remains a question for future research. Furthermore, this finding raises the possibility that vibratory signals collected from the neck during swallowing are somehow influenced by properties of the bolus itself. The degree to which this is true and the mechanisms behind this putative influence need to be studied further. As discussed in the Introduction, the physiologic origins of swallowing sounds remain a subject of debate, as does the extent to which swallowing sounds might be filtered and modified by the characteristics of the vocal tract (such as geometry and volume) and any liquids or substances that are present in the pharynx.

Given the moderate power of the correlation test, a limitation of the present study is the sample size. While Monte Carlo simulations have indicated that a sample size of 50 is sufficient for canonical correlation analysis when strong correlations exist [49], future studies would be strengthened by considering larger samples.

Conclusion

This study aimed to disclose any systematic relationships between accelerometry signal characteristics in healthy adult swallows and anthropometric/demographic variables. This is an essential step in the exploration of swallowing accelerometry as a potential valid tool for differentiating healthy from disordered swallowing in clinical assessment. In this study, a lack of significant linear correlation between signal characteristics and anthropometric/demographic variables was observed in saliva-swallowing tasks. However, relationships were observed for water-swallowing tasks, although these were isolated to the durational characteristics of vibrations detected along the anterior-posterior axis. These findings imply that patient age should be taken into account in the detection of swallowing abnormalities using dual-axis accelerometry to evaluate water swallows.

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Health and Long-term Care in Ontario. The views expressed do not necessarily reflect those of the ministry.

Glossary

Daubechies Wavelet	A family of orthogonal wavelets often used to generate a time-frequency representation of physiologic and biomechanical signals.
Frequency at Peak Intensity	(used by Cichero and Murdoch [19]): The peak frequency at the point of the peak intensity (FPI), measured in Hz, was defined as the highest frequency at the point of highest intensity and was obtained directly from the sound spectrogram.
Frequency Range	(used by Cichero and Murdoch [19]): The highest frequency of an acoustic signal, in Hz, obtained directly from a sound spectrogram.
Kurtosis	A measure of the "peakedness" of the probability distribution of a variable (in the case of this article, of the accelerometry signal's amplitude distribution).
Peak Frequency	The frequency of the "loudest sound," in Hz.
Peak Intensity	(used by Cichero and Murdoch [19]): The point of highest displacement of an acoustic signal on an energy contour (5-ms frame length, no smoothing), recorded in decibels (dB).
Scale	Generally, the "frequency" dimension of a wavelet transform. In this article, scale is the level of the discrete wavelet transform of the signal bearing the highest fraction of the signal energy.
Signal Memory	The lag at which the autocorrelation of the signal decays to $1/e$ of its maximum.
Skewness	A measure of the asymmetry of the probability distribution of a variable.
Variance	A measure of statistical dispersion, averaging the squared distance of a variable's possible values from the mean.
Wavelet Transform	A wavelet is a mathematical function used to divide a signal into different scale and time components. A wavelet transform generates a multiresolution time-frequency representation of a signal. Wavelet transforms have advantages over traditional Fourier transforms for representing functions that have discontinuities and sharp peaks, and for accurately deconstructing and reconstructing finite, nonperiodic, and/or nonstationary signals.

References

1. Vice F, Bosma J, Cervical auscultation of feeding in adults. Video available from the University of Maryland School of Medicine (undated).
2. Cichero JA, Murdoch BE. Detection of swallowing sounds: methodology revisited. Dysphagia. 2002;17:40–9. doi:10.1007/s00455-001-0100-x.
3. Hamlet S, Penney DG, Formolo J. Stethoscope acoustics and cervical auscultation of swallowing. Dysphagia. 1994;9:63–8. doi:10.1007/BF00262761.
4. Takahashi K, Groher ME, Michi K. Methodology for detecting swallowing sounds. Dysphagia. 1994;9:54–62.
5. Takahashi K, Groher ME, Michi K. Symmetry and reproducibility of swallowing sounds. Dysphagia. 1994;9:168–73. doi:10.1007/BF00341261.
6. Joshi AM, Reddy NP, Rane M, Canilang EP, Casterline J, Candadai RS. Biomechanical measurement of the swallowing reflex. J Biomech. 1989;22:1031. doi:10.1016/0021-9290(89)90304-7.
7. Reddy NP, Katakam A, Gupta V, Unnikrishnan R, Narayanan J, Canilang EP. Measurements of acceleration during videofluorographic evaluation of dysphagic patients. Med Eng Phys. 2000;22:405–12. doi:10.1016/S1350-4533(00)00047-3.
8. Reddy NP, Thomas R, Canilang EP, Casterline J. Toward classification of dysphagic patients using biomechanical measurements. J Rehabil Res Dev. 1994;31:335–44.
9. Reddy N, Canilang E, Casterline J, Rane M, Joshi A, Thomas R, et al. Noninvasive acceleration measurements to characterize the pharyngeal phase of swallowing. J Biomed Eng. 1991;13:379–83. doi:10.1016/0141-5425(91)90018-3.
10. Selley WG, Ellis RE, Flack FC, Bayliss CR, Pearce VR. The synchronization of respiration and swallow sounds with videofluoroscopy during swallowing. Dysphagia. 1994;9:162–7. doi:10.1007/BF00341260.
11. Leslie P, Drinnan MJ, Zammit-Maempel I, Coyle JL, Ford GA, Wilson JA. Cervical auscultation synchronized with images from endoscopy swallow evaluations. Dysphagia. 2007;22:290–8. doi:10.1007/s00455-007-9084-5.
12. Boiron M, Rouleau P, Metman EH. Exploration of pharyngeal swallowing by audio signal recording. Dysphagia. 1997;12:86–92. doi:10.1007/PL00009524.
13. Perlman AL, Ettema SL, Barkmeier J. Respiratory and acoustic signals associated with bolus passage during swallowing. Dysphagia. 2000;15:89–94.
14. Cichero JA, Murdoch BE. The physiologic cause of swallowing sounds: answers from heart sounds and vocal tract acoustics. Dysphagia. 1998;13:39–52. doi:10.1007/PL00009548.
15. Cichero JA, Murdoch BE. What happens after the swallow? Introducing the glottal release sound. J Med Speech-Lang Pathol. 2003;11:34–41.
16. Moriniere S, Beutter P, Boiron M. Sound component duration of healthy human pharyngoesophageal swallowing: a gender comparison study. Dysphagia. 2006;21:175–82. doi:10.1007/s00455-006-9023-x.
17. Borr C, Hielscher-Fastabend M, Lucking A. Reliability and validity of cervical auscultation. Dysphagia. 2007;22:225–34. doi:10.1007/s00455-007-9078-3.

18. Leslie P, Drinnan MJ, Finn P, Ford GA, Wilson JA. Reliability and validity of cervical auscultation: a controlled comparison using videofluoroscopy. Dysphagia. 2004;19:231–40.
19. Cichero JA, Murdoch BE. Acoustic signature of the normal swallow: characterization by age, gender, and bolus volume. Ann Otol Rhinol Laryngol. 2002;111:623–32.
20. Youmans SR, Stierwalt JA. An acoustic profile of normal swallowing. Dysphagia. 2005;20:195–209. doi:10.1007/s00455-005-0013-1.
21. Kent RD. Phonetics acoustic. In: Kent RD, editor. The Speech Sciences. San Diego: Singular Publishing; 1997. p. 329–67.
22. Lee J, Steele CM, Chau T. Time and time-frequency characterization of dual-axis swallowing accelerometry signals. Physiol Meas. 2008;29:1105–20. doi:10.1088/0967-3334/29/9/008.
23. Sejdić E, Steele CM, Chau T. Segmentation of dual-axis swallowing accelerometry signals in healthy subjects with analysis of anthropometric effects on duration of swallowing activities. IEEE Trans Biomed Eng. 2009;56(4):1090–7.
24. Sejdic E, Komisar V, Steele CM, Chau T. An investigation of baseline characteristics of dual-axis swallowing accelerometry characteristics. IEEE Trans Biomed Eng. 2009 (submitted).
25. Huckabee M, Garcia M, Barofsky I. SEMG measurement of the head and neck: applications to dysphagia rehabilitation. Dysphagia. 1996;11:165–8. doi:10.1007/BF00417909. [abstract].
26. Evetovich T, Housh T, Johnson G, Smith D, Ebersole K, Perry S. Gender comparisons of the mechanomyographic responses to maximal concentric and eccentric isokinetic muscle actions. Med Sci Sports Exerc. 1998;30:1697–702. doi:10.1097/00005768-199812000-00007.
27. Nonaka H, Mita K, Akataki K, Watakabe M, Itoh Y. Sex differences in mechanomyographic responses to voluntary isometric contractions. Med Sci Sports Exerc. 2006;38:1311–6. doi:10.1249/01.mss.0000227317.31470.16.
28. Kidd D, Lawson J, Nesbitt R, MacMahon J. Aspiration in acute stroke: a clinical study with videofluoroscopy. Q J Med. 1993;86:825–9.
29. Martino R, Pron G, Diamant NE. Screening for oropharyngeal dysphagia in stroke: insufficient evidence for guidelines. Dysphagia. 2000;15:19–30.
30. Mari F, Matei M, Ceravolo MG, Pisani A, Montesi A, Provinciali L. Predictive value of clinical indices in detecting aspiration in patients with neurological disorders. J Neurol Neurosurg Psychiatry. 1997;63:456–60. doi:10.1136/jnnp.63.4.456.
31. Logemann JA, Veis S, Colangelo L. A screening procedure for oropharyngeal dysphagia. Dysphagia. 1999;14:44–51. doi:10.1007/PL00009583.
32. Daniels SK, Ballo LA, Mahoney MC, Foundas AL. Clinical predictors of dysphagia and aspiration risk: outcome measures in acute stroke patients. Arch Phys Med Rehabil. 2000;81:1030–3. doi:10.1053/apmr.2000.6301.
33. Donoho DL. De-noising by soft-thresholding. IEEE Trans Inf Theory. 1995;41:613–27. doi:10.1109/18.382009.
34. Lee J, Blain S, Casas M, Kenny D, Berall G, Chau T. A radial basis classifier for the automatic detection of aspiration in children with dysphagia. J Neuroeng Rehabil. 2006;3:14–31. doi:10.1186/1743-0003-3-14.
35. Abdelmonem AA, Clark V, May S. Computer aided multi-variate analysis. New York: CRC Press; 2004.
36. Hardoon DR, Szedmak S, Shawe-Taylor J. Canonical correlation analysis: an overview with application to learning methods. Southampton, UK: Image, Speech and Intelligent Systems Research Group, School of Electronics and Computer Science, University of Southampton, 2004.
37. Kelly L, Manly BFJ. Multivariate statistical methods: a primer. 3rd ed. New York: CRC Press; 2004.
38. Stevens JP. Applied multivariate statistics for the social sciences. 4th ed. Mahwah, NJ: Lawrence Erlbaum Associates; 2002.
39. Feinstein AR. Principles of medical statistics. Boca Raton, FL: Chapman & Hall; 2002.
40. Smeitink E, Dekker R. A simple approximation to the renewal function. IEEE Trans Reliab. 1990;39:71–5. doi:10.1109/24.52614.
41. Sugiyama T, Ushizawa K. Power of largest root on canonical correlation. Commun Stat. 1992;21:947–60.
42. Hiss SG, Treole K, Stuart A. Effects of age, gender, bolus volume, and trial on swallowing apnea duration and swallow/respiratory phase relationships of normal adults. Dysphagia. 2001;16:128–35. doi:10.1007/s004550011001.
43. Moriniere S, Boiron M, Alison D, Makris P, Beutter P. Origin of the sound components during pharyngeal swallowing in normal subjects. Dysphagia. 2008;23:267–73. doi:10.1007/s00455-007-9134-z.
44. Kim Y, McCullough GH. Maximal hyoid displacement in normal swallowing. Dysphagia. 2008;23:274–9. doi:10.1007/s00455-007-9135-y.
45. Chi-Fishman G, Sonies BC. Effects of systematic bolus viscosity and volume changes on hyoid movement kinematics. Dysphagia. 2002;17:278–87. doi:10.1007/s00455-002-0070-7.
46. Ishida R, Palmer JB, Hiiemae KM. Hyoid motion during swallowing: factors affecting forward and upward displacement. Dysphagia. 2002;17:262–72. doi:10.1007/s00455-002-0064-5.
47. Kendall KA, Leonard RJ. Hyoid movement during swallowing in older patients with dysphagia. Arch Otolaryngol Head Neck Surg. 2001;127:1224–9.
48. Perlman AL, Vandaele DJ, Otterbacher MS. Quantitative assessment of hyoid bone displacement from video images during swallowing. J Speech Hear Res. 1995;38:579–85.
49. Mendoza JL, Markos VH, Gonter R. A new perspective on sequential testing procedures in canonical analysis: a Monte Carlo evaluation. Multivariate Behav Res. 1978;13:371–82. doi:10.1207/s15327906mbr1303_8.

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