AGE, SEX, AND HEAD POSITION EFFECTS ON SWALLOWING ACCELEROMETRY AND SOUNDS

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Accelerometry (the measurement of vibrations) and auscultation (the measurement of sounds) are both noninvasive techniques that have been explored for detecting abnormalities in swallowing. The differences between these techniques and the information they capture about swallowing have not previously been explored in a direct comparison. In this study, we investigated the differences between dual-axis swallowing accelerometry and swallowing sounds by recording data from adult participants and calculating a number of time and frequency domain features. During the experiment, 55 participants (ages 18-65) were asked to complete five saliva swallows with a neutral head position and then five saliva swallows in a 'chin-tuck' position. The resulting data was processed by previously designed techniques utilizing wavelet denoising, spline filtering, and fuzzy means segmentation. The pre-processed signals were then used to calculate nine time, frequency, and time-frequency domain features for each independent signal. In addition to finding a number of features that varied with the participant's age, sex, and head position, our statistical analysis determined that the majority of our chosen features were significantly different for different transducers. We conclude that swallowing accelerometry and swallowing sounds provide different information about deglutition despite utilizing similar transduction methods.

Keywords: Swallowing accelerometry signals, swallowing sounds, saliva swallows, signal characteristics.

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1.0 INTRODUCTION

1.1 MOTIVATION

1.1.1 Defining Dysphagia

Dysphagia is a term used to describe a multitude of abnormal swallowing disorders [5]. Typically it is divided into three categories: Ororpharyngeal dysphagia for causes that originate in or near the patient's pharynx, Esophageal dysphagia for causes that originate in the esophagus, and Functional dysphagia for those where no cause can be located [6]. All forms of dysphagia have common symptoms which include difficulty controlling food within the mouth, difficulty initiating a swallow, significant coughing after a swallow, or painful swallowing, among others. These events are a sign that the muscles and structures in the patient's throat are not operating properly as the patient swallows [5]. Since the epiglottis and other structures required to protect the airway are among them, this can result in food being allowed to enter the trachea and possibly triggering an infection [6]. Even if this is not the case, dysphagia causes eating to become problematic if not outright unpleasant, and patients can become dehydrated or suffer from malnutrition as they attempt to avoid an unpleasant activity [7], [8].

1.1.2 Incidence and Prevalence

It is estimated that ten million Americans are diagnosed with dysphagia every year [9]. Dysphagia can occur in people of any age, but the incidence increases with age [9], [10]. Studies estimate that the prevalence of dysphagia is nearly 10% in people over the age of fifty, but that estimate only includes reported cases [9]. In addition to those who do not seek medical care for their condition, many patients suffer from 'silent aspirations' or otherwise are not properly diagnosed [11]. Therefore, the true prevalence of dysphagia may be over 20% in the elderly population [5], [9].

These estimates increase significantly in those who are hospitalized or otherwise admitted to a medical care facility. It is estimated that over 25% of hospital patients demonstrate signs of dysphagia while that statistic can be as high as 75% in acute trauma centers, nusing homes, or other advanced care facilities [9]. The rate of 'silent aspirations' in the hospitalized population is similarly high, with as many as 80% of dysphagic patients in acute care centers demonstrating signs of silent aspirations, and so exact statistics are difficult to estimate [12].

While it is far less common, dysphagia can still occur in children, particularly in infants. A small amount of regurgitation or "spitting up" is not uncommon, but this occurs often enough to be classified as gastroesophageal reflux disease in approximately 8% of infants [10]. Since they cannot provide the same level of feedback as an adult it is far more difficult to assess dysphagia in this population [10]. Fortunately, the majority of these infant cases of dysphagia fix themselves through the course of normal development and aging, but they can still have lasting effects on the patient's growth [9], [10].

1.1.3 Potential Benefits

The cost and availability of tests to diagnose dysphagia is one area that has potential for improvement. Most physicians utilize expensive x-ray and endoscopy equipment which is not easily afforded by smaller medical facilities [13], [14]. Even without that expense, all currently accepted diagnostic methods require at least one specialist to directly administer the examination and interpret the results. If such personel are not available on site then the patient has no choice but to travel to a facility that does have one on staff. Depending on the source of the patient's dysphagia this could be incredibly difficult to accomplish without outside assistance. All of these things, purchasing and maintaining delicate equipment, hiring and training diagnostic specialists, arranging travel to distant medical facilites, significantly reduce the availability of diagnostic screening while increasing the cost to administer it.

Developing a diagnostic method that uses simpler equipment which non-specialists can operate would enable more, smaller facilities to offer dysphagia screenings at a significantly reduced cost.

The costs associated with administering a test for dysphagia also impacts the health of dysphagic patients. As it stands, only those who are showing clear outward signs of swallowing difficulties are likely to be recommended to a specialist for screening. This means that the estimated 30% of dysphagic patients who are not aware of their own condition will not be tested or treated until it develops into a larger medical issue such as pneumonia [11]. With more widely available and cheaper diagnostic methods those who exhibit silent aspirations can obtain the medical care they need before it develops a more dangerous and expensive medical issue. Furthermore, reducing the cost of administering the test would ensure that the financial burden would not impact one's ability to seek necessary medical care. Medical costs for the elderly can reach well over $100,000 with little variation for their percieved healthiness [15]. As they are typically on fixed incomes and are the most likely to develop dysphagia, any potential reduction in health care expenses for the elderly would be a great benefit.

The reliability of dysphagia screening is another potential area of improvement. The most common and most widely approved methods of diagnosis rely on the analysis of at least one trained specialist [13], [14]. While this method is clearly adequate, it is not perfect. Swallowing is a complex biological process with many variations even between individual swallows of a normal, healthy person. When you add in the human element to administering the test and subsequently judging the results there is an unavoidable risk of error. If it were possible to automate this diagnostic process then the sensitivity and specificity of dysphagia screening could improve and ensure that medical care is given to those who need it.

1.1.4 Contributions of this Research Towards the Issues

This study attempts to investigate a possible method of diagnosing dysphagia which could potentially be developed into a cheap, automated testing system. When compared to existing methods of diagnosis, even high quality microphone and accelerometer equipment is cheap and easy to use. However, there has not been sufficient work done to characterize how these signals behave in a clinical setting. This study intends to explore various time and frequency domain features of these signals recorded from normal, healthy swallowing subjects. This will enable us to determine how these two transduction methods differ and if they are worthy of further investigation. It will also enable future studies to repeat the experimental methods on dysphagic subjects and compare the results to our baseline recordings to determine their viability as diagnostic tools for swallowing disorders. Knowledge from this experiment will provide a foundation for the development of a cheap, automated diagnostic test for dysphagia.

1.2 VIBRATION TRANSDUCTION

1.2.1 Accelerometry

One model of accelerometer often used in scientific applications is the MEMS accelerometer. Using microfabrication techniques, a capacitor is etched into a circuit board where one plate is fixed while the other is suspended above it [16]. This second plate is free to move along the axis perpendicular to the plate when subjected to forces in that direction [16]. The magnitude of the applied force affects how far the mobile plate is displaced and in what direction, which thereby changes the capacitance of the circuit and the subsequent output voltage of the overall device [16]. Including multiple such capacitors oriented orthogonal to one another will produce a single device that can detect vibrations along multiple axes [16]. A diagram of this system is shown in figure 1.

Typically, accelerometers are used to detect or quantify the motion of a larger object [16]. However, with the proper bandwidth, they can record higher frequency signals such as vibrations [16]. In doing so, an accelerometer can accurately record sounds and have been proven to do so effectively in a number of swallowing-related studies among others [17], [18], [19].

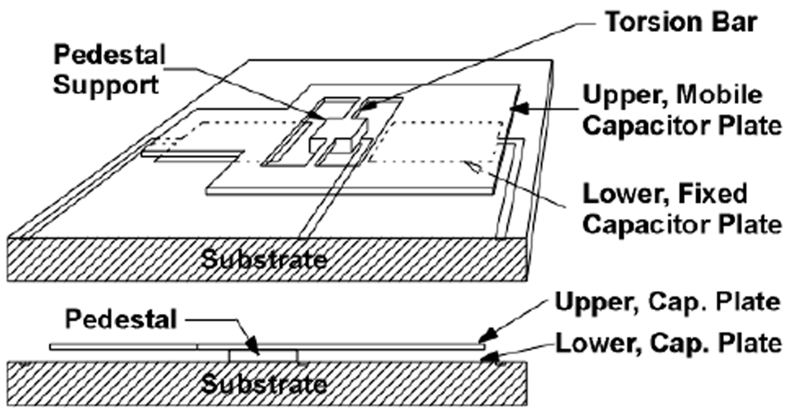

Figure 1: Diagram of the key element of a MEMS accelerometer [1]

1.2.2 Microphones

A commonly found style of microphone used for scientific applications is the electret condeser microphone. Unlike the standard condenser microphone, the electret condenser uses a permanently polarized film diaphragm in place of an externally charged capacitor diaphragm [20]. When sound waves reach the film and cause it to move, the electic field within the device changes and a signal is produced [20]. These microphones can have a wide array of frequency responses which may include all or only part of the range of human hearing and so are useful for a wide array of applications including swallowing studies [21], [22], [23].

In many situations, it is important to account for the polar pattern of a microphone. Depending on the orientation of the polarized film and the existence of other structures, the film may have a smaller or greater response to sounds of the same intensity originating from different locations [24]. This could enhance the system's noise rejection, but it might also affect its ability to record the intended signal and may not be ideal for certain applications [24]. One method used to counter this issue is to develop a contact microphone. This device would not pick up ambient sounds and vibrations from the air since the recording diaphragm is enclosed in a solid protective casing [20]. Instead, only sounds which originate from an object directly in contact with the case are converted to sound waves within the device and are allowed to reach the diaphragm [20]. This modification to the standard electret microphone design makes it easier to record signals from one specific source.

1.3 RESEARCH OBJECTIVES

This research has two key objectives. First, it seeks to demonstrate whether or not dual-axis swallowing accelerometry signals and swallowing sounds are significantly different in healthy subjects. Past research has looked at each transducer individually, but little work has been done to compare the two, albeit similar, transduction methods. In addition to the basic size differences these two transducers can have different temperature responses, sensistivities, and polar patterns as well as having completely different responses to motion (e.g., [25], [26]). Secondly, we will investigate a number of time and frequency domain features of each swallowing signal to determine their values in normal, healthy adults as well as how they change. We will specifically estimate their dependencies on the subject's age, sex, and head position while swallowing. We will accomplish this by first collecting sound and accelerometry data from a number of healthy adult subjects while they make dry swallows. We will then apply signal processing algorithms that have been proven adequate for such studies in order to characterize various attributes of the signals. Finally, statistical analysis techniques will be used to investigate which of these attributes vary with respect to each of our variables.

Past studies have demonstrated that an accelerometer is capable of detecting a subject's cardiac dynamics, which is known to change with age [27], [28], whereas the acoustic properties of the neck would likely change as a person's skin loses its elasticity in later years [29]. Meanwhile, there are some notable differences in the anatomy of the neck and throat between the sexes, particularly in the size of the laryngeal prominence, that could affect either of these recordings and should be properly accounted for [30], [31]. Finally, it is known that many physiological structures in the neck move when a swallow is occuring [32]. It is logical then, to assume that altering the head position, which will change the relative locations of all of these structures, will affect their dynamics and the signals they produce [33]. The widespread acceptace of the 'chin-tuck' maneuver gives merit to this claim [34], [35].

1.4 OVERVIEW

Chapter 2 covers the relevant background topics for this research. It details the physiological process of swallowing as well as a number of ways this process can be impeeded or disrupted, resulting in dysphagia. It also provides a brief overview of the current methods used to diagnose dysphagia.

Chapter 3 covers the methodology of the experiment. It details not only the experimental setup, but the signal processing algorithms, extracted features, and statistical tests utilized as well.

Chapter 4 lists the results of the experiment including both the average values of each extracted feature and the output of the statistical analysis.

Chapter 5 attempts to explain the results presented in chapter 4 based on past research and to draw conclusions based on the data. It ends with possible avenues for future research.

2.0 BACKGROUND

2.1 STAGES OF DEGLUTITION

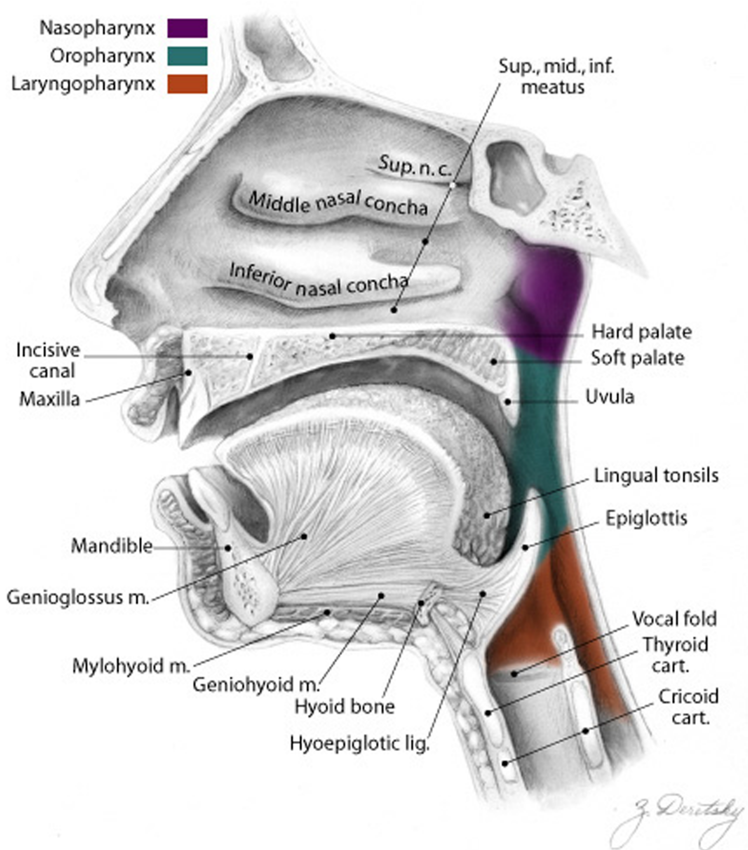

Figure 2: Lateral view of the human head and neck showing pharynx divisions [2]

A lateral cross-section of the human head and neck can be seen in figure 2. It clearly shows the different sections of the throat that will be refered to later as well as several other notable structures. Meanwhile, figure 3 displays the major muscles and arteries that influence swallowing activity.

Physiologically, swallowing is divided into three separate phases as can be seen in figure 4. The first stage, the oral phase, consists entirely of voluntary activity [32]. It begins when the mouth is opened to allow material to enter the oral cavity [32]. After the material is masticated sufficiently and a bolus is formed, the tounge is then pressed against the hard palate and the bolus is propelled posteriorly (figure 4 parts A and B) [32].

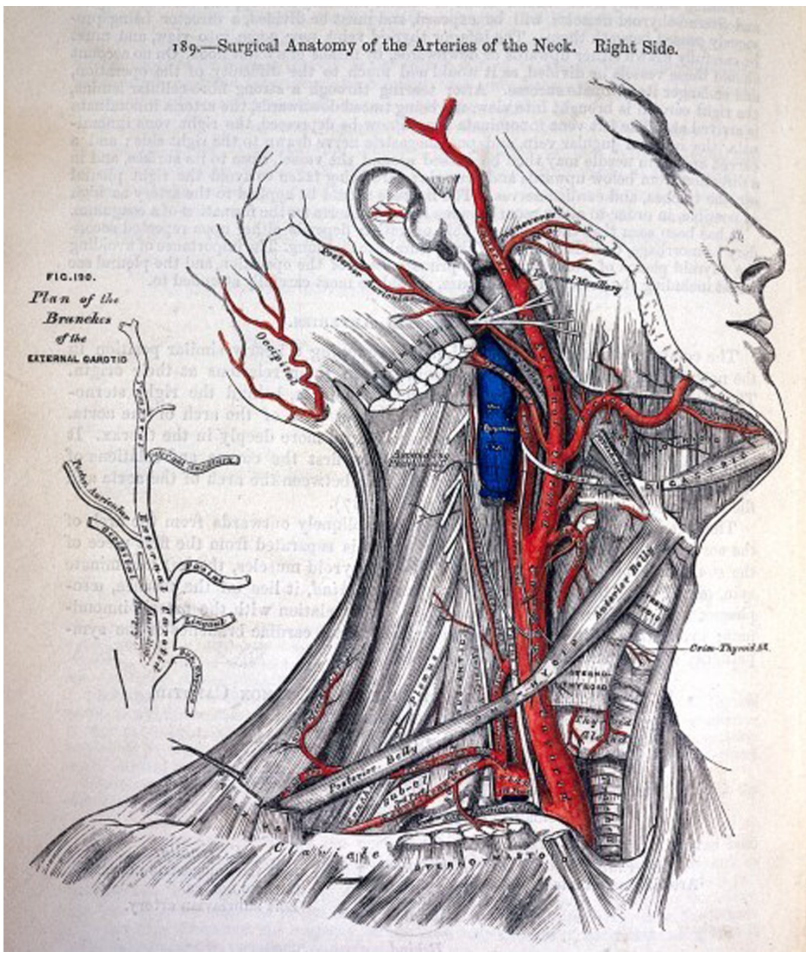

Figure 3: Gross muscle anatomy of the human neck [1].

The pharyngeal phase, whose activity is involuntary but may be initiated conciously, is the second stage of deglutition [32]. It begins once the bolus has passed the palatoglossal arch and entered the oropharynx [36]. This phase involves temporarily sealing all unwanted bolus pathways including the nasopharynx by the soft palate, the oral cavity by the tounge, and the larynx by the epiglottis (figure 4 part C) [36]. The adduction of the vocal folds further helps to keep the bolus out of the larynx [37]. Because of these valves, all actions such as breathing, coughing, and mastication are inhibited during the pharyngeal phase [38]. The oropharynx and laryngopharynx, larynx, and hyoid structures are all then pulled in the superior and anterior directions so as to accept the bolus and to further seal the larynx and nasopharynx [36]. Peristalsis of the oropharynx and layngopharynx muscles then moves the bolus down towards the upper esophageal sphincter (figure 4 part D) [36].

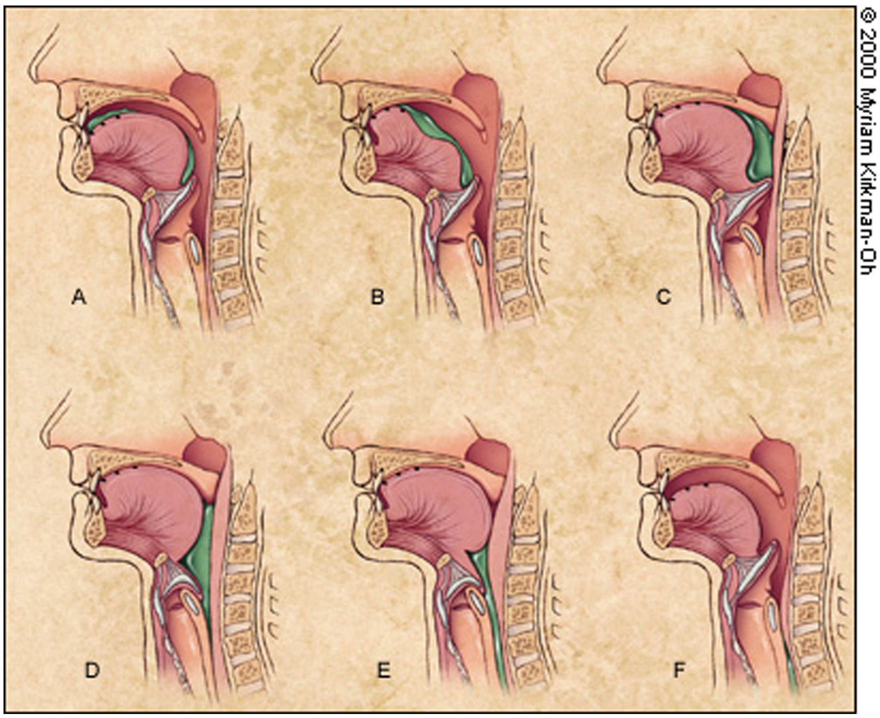

Figure 4: Stages of the healthy swallowing process [3]. A is the volunary oral stage, B demonstrates the preparations before the pharyngeal stage, C, D, and E represent different points in the pharyngeal stage, and F is the esophageal stage.

The third stage is the esophageal phase and is completely involuntary [32]. As the bolus is traveling through the pharynx, the upper esophageal sphincter relaxes to allow the bolus to enter the esophagus (figure 4 part E) [32]. Peristalsis of the the muscles surrounding the pharynx and esophagus push the bolus downward until it passes through the lower esophageal sphincter and into the stomach (figure 4 part F) [38]. The pharynx, larynx, and hyoid all relax and return to their initial positions after the bolus has passed into the esophagus [38]. The tounge, vocal cords, epiglottis, and soft palate likewise return to their resting positions and non-swallowing activities can resume [38].

2.2 PATHOLOGY

2.2.1 Nervous Origins

Figure 5 displays the major motor nerves in the neck and their corresponding musculature. On the other hand, figure 7 displays a number of muscles

The most common cause of dysphagia is some form of neurological damage or impairment, with approximately 500,000 cases reported every year [9]. Specifically, abnormalities in the cranial nerves, which control both the autonomic and voluntary portions of swallowing, can interfere with or completely prevent the proper muscle activation sequence [7]. Stroke patients have a particularly high incidence of dysphagia after the stroke event, most likely due to the occulsion-induced cell death [7]. Similarly, severe head or neck trauma can be sufficient to damage or dislodge these delicate nerve cells. Regardless of the exact cause, the end result is that the muscles which control swallowing are no longer receiving input from the brain, and are functionally useless. Without proper muscle activation it is no surprise that a patient would have difficulty forcing a bolus of food through the esophagus, would not be able to properly protect their larynx as they swallowed, or both [35].

However, completely deactivating these muscles is not the only neurological source of dysphagia. Conditions such as Huntington's Disease, Parkinson's Disease, and multiple sclerosis are all characterized by the impaired motor and mental capabilities of the patient. Often times, this impairment is extended to the muscles that control swallowing. The cranial nerves are still functional, but the muscles they control are not activated correctly or in the correct sequence [9]. This can lead to the larynx being unprotected at important times

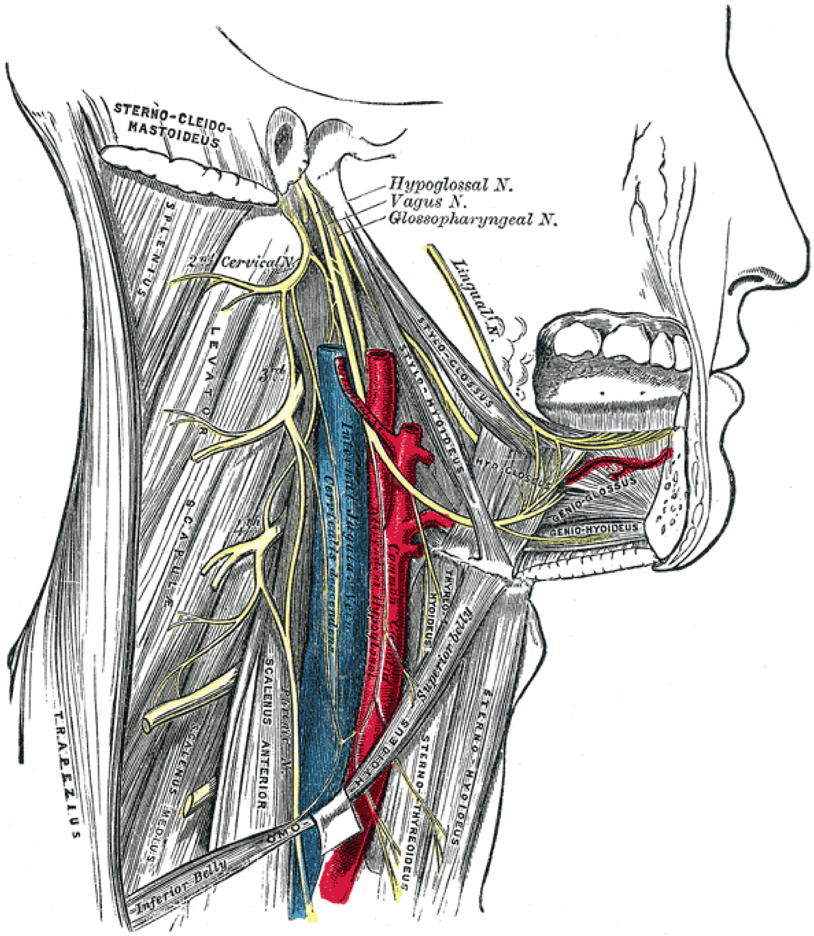

Figure 5: Major motor nerves in the neck [30].

in the swallowing process and subsequent aspiration [39]. Alternatively, it could result in uncoordinated peristalsis of the pharynx or esophagus and prevent the bolus from travelling where it is intended, causing discomfort or pain in the patient [39].

Figure 5 displays the major motor nerves in the neck and their corresponding musculature. Damage to or incorrect activation of any of these structures can have significant repercussions on the subject's ability to swallow safely.

2.2.2 Esophageal Origins

While various nervous complications are more common, there are also a number of anatomical causes of dysphagia. Conditions such as gastroesophageal reflux disease and eosinophilic esophagitis tend to cause inflamation of the esophagus. Though the causes can vary from an allergic reaction to a genetic predisposition, they both result in a narrow esophageal opening and cause food to become "stuck", sometimes painfully, before continuing on to the stomach [6]. Achalasia is similar to this situation, but the narrow esophagus is due to poor peristalsis and incomplete muscle relaxation rather than simple inflamation of the tissues[6]. Of course, not all of these conditions directly affect the esophageal stage of swallowing. Should the pressure in the layngopharynx increase too much for some reason, such as a slow opening of the upper esophageal sphincter, part of the pharyngeal wall will expand outward forming a Zenker's diverticulum[6]. This results in food remaining stuck in the pharynx during swallowing and, in addition to being uncomfortable, can put the patient at risk of aspiration or other negative outcomes.

2.2.3 Other Origins

Naturally, a patient's ability to swallow correctly is affected by the biological structures present in and around the throat. Therefore it is expected that cancer could potentially be a cause of dysphagia, depending on the exact location of the tumor [3]. A growth could apply pressure to the pharynx or esophagus, thereby narrowing the blous pathway or otherwise forming an obstruction. This would obviously make it more difficult to pass the blous towards the stomach or could modify the dynamics of its movement and allow the bolus to travel down an unintended pathway. Extracting the tumor could potentially make this situation even worse. Much of the surrounding tissue includes muscles that control swallowing movements and removing them can reduce the protection of the larynx or decrease the force of peristalsis [3]. These complications are not unique to cancer, however. Tracheostomies, swollen lymph nodes, vocal fold cysts, chondrolaryngoplasties, or any number of similar conditions or surgical interventions near the gastrointestional tract could result in the same obstructions or muscle damage mentioned previously [3].

2.3 ASSESSMENT OF PATHOLOGICAL CONDITIONS

2.3.1 Videofluoroscopy

Videofluoroscopy, sometimes refered to as a modified barium swallow, has been the chief method for diagnosing swallowing disorders for many years [5], [40]. The patient, while either sitting or standing, swallows small amounts of food or liquid that has been coated with a small amount of barium sulfate [39], [40]. This compund is used because in addition to being a reasonable x-ray contrast agent it has a low water solubility and is generally not absorbed by the gastrointestional tract. A fluoroscopic camera is set up to capture pictures in the sagital plane and aligned so as to display the oropharynx, pharynx, and upper esophagus. In this position it is possible to see the action of all major structures involved in swallowing [40]. While the camera is active a radiologist and a logopedist or other language correction specialist observe the movement of key anatomical structures as well as the timing and duration of each swallowing stage [40]. This process is repeated while video is collected in the coronal plane to check the symmetry of bolus movement and muscle activity [40]. The specialists then check the results for any signs of aspiration or incorrect muscle activity and determine whether or not the activity constitutes a medical condition. Despite the cost and logistics associated with this method, it has been shown to be a very reliable assessment of dysphagia in most people [5]. Figure 6 displays example images from this test for both a normal swallow and a swallow that resulted in aspiration.

2.3.2 Gastroesophageal Endoscopy and Biopsy

Unlike videofluoroscopy, which indirectly assesses the activity of physiological structures based on the movement of a bolus, gastroesophageal endoscopy directly observes that activity [41]. The patient is asked to lie on their side and a topical anasthetic is applied to the upper sections of the pharynx [41]. An endoscope is then inserted either through the nasopharynx or oral cavity and into the oropharynx [41]. As the tool is guided further down, as far as the duodenum if needed, the examiner observes the surrounding tissue for any abnormal structures or discoloration [41]. In some situations the patient may be asked to make dry

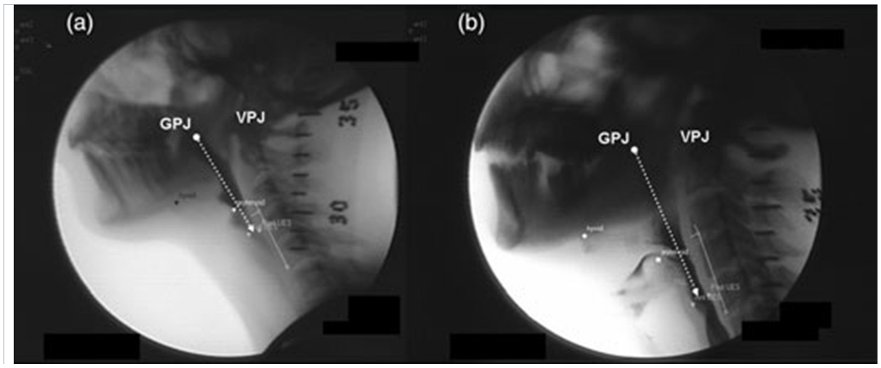

Figure 6: Videofluoroscopic image of a) a normal swallow and b) a swallow that caused aspiration [4].

swallows or to comsume small amounts of liquid so that the examiner can directly observe the dynamics of various key structures in the pharynx when not at rest [41]. Furthermore, during the examination the examiner may choose to take a biopsy sample for later histological analysis. While the endoscopic evaluation can determine any physcial abnormalities the biopsy can determine immunological or genetic causes of the disorder [41]. Even though this technique is as effective when observing all but the smallest structural details, it is typically only used to confirm the results of a videofluoroscopic examination [14]. Due to the device limitations only a small part of the patient's physiology can be observed during an individual swallow which makes the examination process far more time consuming than videofluoroscopy [14].

2.3.3 Cervical Auscultation

One technique for diagnosing swallowing disorders that has received some recognition is cervical auscultation. Unlike videofluoroscopy or endoscopy, cervical auscultation can be performed quickly and easily at the patient's bedside [42]. A sound recording device, typically a stethescope, is placed over the thoratic cartilage and the examiner listens as the patient makes a swallow [13]. A normal patient will produce a distinct series of sounds which are either out of order or missing in a dysphagic patient, and the examiner bases their diagnosis on this information [13]. While this technique is simple to perform, its effectiveness, reproducibility, and reliability have all been questioned and so has not gained widespread acceptance in the field [42]. Lately, there have been efforts to automate this process and improve its viability as a diagnositic method with varying degrees of signal processing [17], [18], [19], [21], [22], [23].

2.3.4 Electrophysiology

Yet another method that exists for diagnosis swallowing disorders utilizes EMG recordings [43]. Swallowing activity is controlled by well over a dozen different muscles and each one produces an electric signal [30]. Figure 7 shows a number of these unique and independently operated muscles that contract in a relatively small portion of the neck. By placing conducting electrodes onto the surface of the skin the activity of those muscles can be monitored and the subsequent EMG waveforms or muscle recruitment patterns can be analyzed [43]. Even though this is an interesting avenue of investigation, its use is entirely experimental and still requires a great deal of research before any practical applications are seen [43].

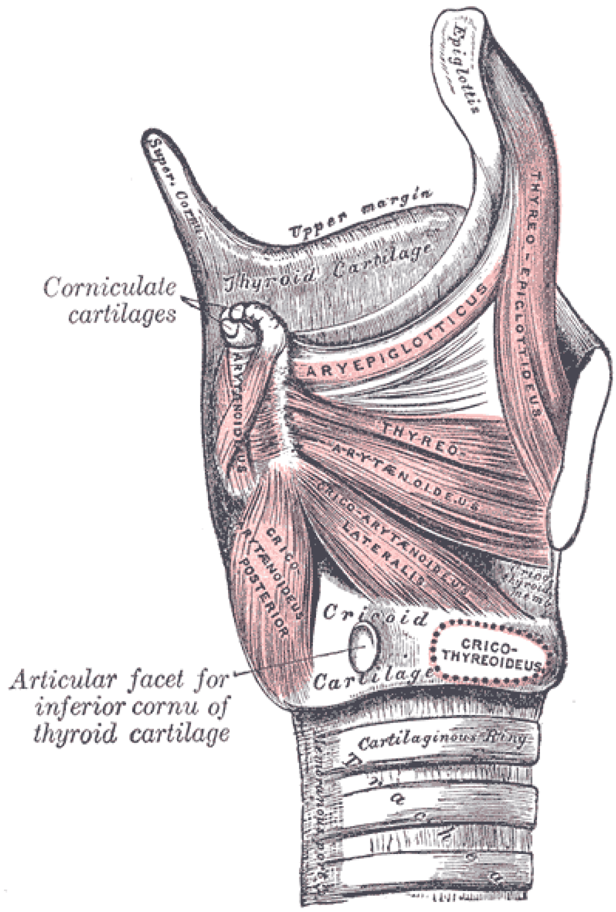

Figure 7: Drawing showing the number of muscles operating on a small portion of the throat [30].

3.0 METHODOLOGY

3.1 DATA COLLECTION

Our recording equipment consisted of a dual-axis accelerometer and a contact microphone attached to the participant's neck with double-sided tape. The accelerometer (ADXL 322, Analog Devices, Norwood, Massachusetts) was mounted in a custom plastic case, and affixed over the cricoid cartilage in order to provide the highest signal quality [44]. We aligned the x-axis of the accelerometer in the anterior-posterior direction while the y-axis of the accelerometer was aligned in the superior-inferior direction. It was powered by a power supply (model 1504, BK Precision, Yorba Linda, California) with a 3V output, and the resulting signals were bandpass filtered from 0.1 to 3000 Hz with ten times amplification (model P55, Grass Technologies, Warwick, Rhode Island). Both voltage signals were fed into a National Instruments 6210 DAQ and recorded at 40 kHz by the LabView program Signal Express (National Instruments, Austin, Texas). This setup is sufficient to accurately record the full range of swallowing vibrations and has been proven to be effective at detecting swallowing activity in previous studies [17], [45]. The microphone (model 411L, AKG, Vienna, Austria) was placed below the accelerometer and slightly towards the right lateral side of the trachea so as to avoid most contact between the two devices without greatly impacting signal quality. Overlap with the sternocleidomastoid muscle was minimized to avoid unnecessary signal attenuation. It was powered by a power supply (model B29L, AKG, Vienna, Austria) set to 'line' impedance with a volume of '9' and the resulting voltage signal was sent to the previously mentioned DAQ. Again, the signal was sampled by Signal Express at 40 kHz.

The protocol for the study was approved by the Institutional Review Board at the University of Pittsburgh. 56 participants were recruited from the neighborhoods surrounding the University of Pittsburgh campus. All participants confirmed that they had no history of swallowing abnormalities and were divided into four age ranges for later statistical analysis: 18 to 29, 30 to 41, 42 to 53, and 54 to 65. One participant's data was eliminated from our calculations due to mistakes made during recording. Table 1 shows the composition of each age category at the conclusion of the experiment. All testing was performed in the iMED laboratory facilities at the University of Pittsburgh.

Table 1: Composition of participant population.

Age Range	Males	Females	Age
18-29	11	6	22.6 ± 2.8
30-41	8	7	33.2 ± 2.8
42-53	3	5	46.0 ± 3.0
54-65	6	9	59.2 ± 3.6
Total	28	27	38.9 ± 14.9

With their head in the neutral position, each participant was asked to make five saliva swallows with a few seconds between each swallow to allow for saliva accumulation. This process was repeated once, but with the head in the chin-tuck position when the swallow occurred. Each unique task was recorded as a separate text file by the Signal Express software and imported into MATLAB (Mathworks, Natick, Massachusetts).

3.2 DATA PRE-PROCESSING

The dual-axis accelerometer signal was first down sampled to 10 kHz in order to utilize previously developed algorithms for pre-processing dual-axis swallowing accelerometry signals (e.g., [46], [47], [48]). At an earlier date, the device's baseline output was recorded and modified covariance auto-regressive modeling was used to characterize the device noise [27], [49]. The order of the model was determined by minimizing the Bayesian Information Criterion [27]. These autoregressive coefficients were then used to create a finite impulse response filter

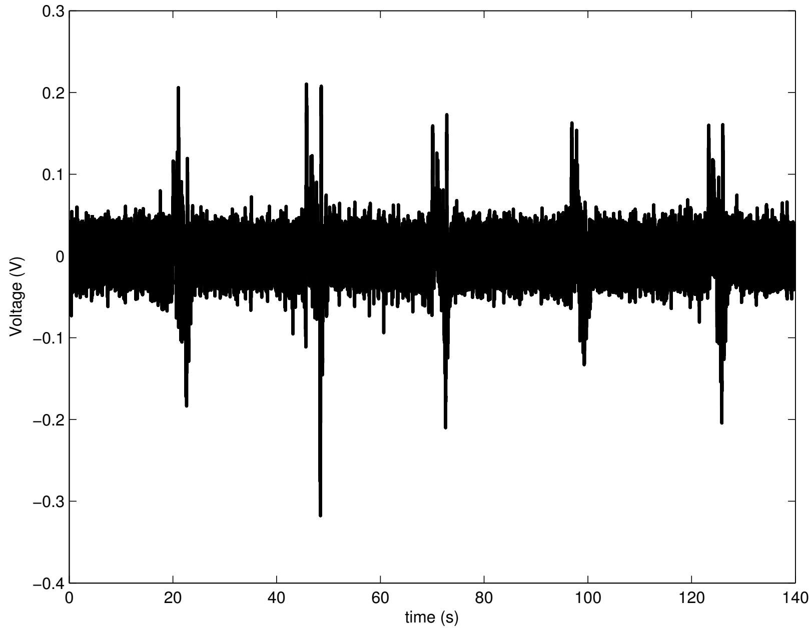

Figure 8: Raw output from accelerometer recording system.

and remove the recording device noise from our signal [27]. Afterwards, motion artifacts and other low frequency noise was removed from the signal through the use of least-square splines. Specifically, we used fourth-order splines with a number of knots equal to $\frac{N f_l}{f_s}$, where N is the number of data points in the sample, fs is the original 10 kHz sampling frequency of our data, and f_l is equal to either 3.77 or 1.67 Hz for the superior-inferior or anterior-posterior direction, respectively. The values for f_l were calculated and optimized in previous studies [48]. After subtracting this low frequency motion from the signal we denoised the remaining data by using tenth-order Meyer wavelets with soft thresholding [46]. The optimal value of the threshold was determined through previous research to be $\sigma\sqrt{2\log N}$, where N is the number of samples in the data set and σ, the estimated standard deviation of the noise, is defined as the median of the down-sampled wavelet coefficients divided by 0.6745 [46]. Previous research by Wang and Willett demonstrated a useful method for segmenting data sets into two distinct categories based on local variances [50]. For this study, we applied a modified version of their method and used a proven two-class fuzzy c-means segmentation

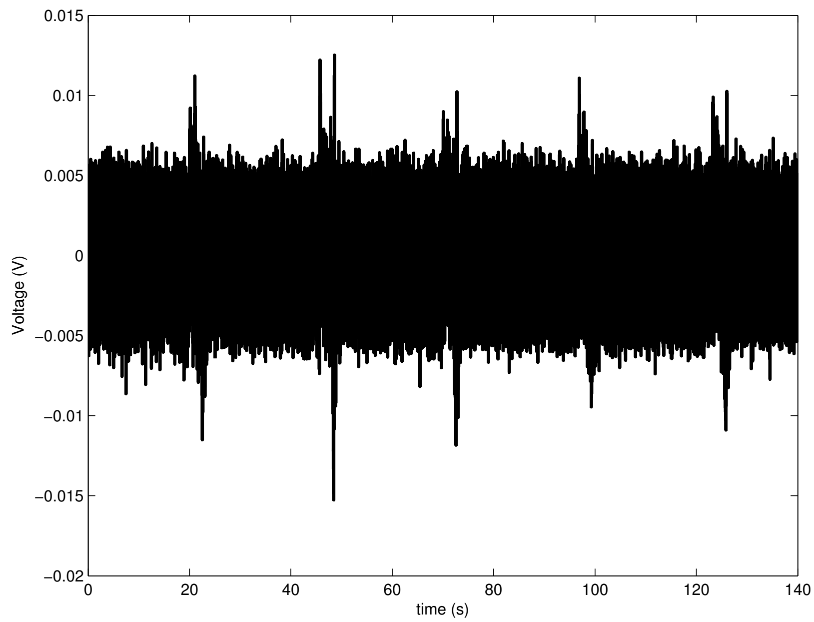

Figure 9: Accelerometer signal after device noise is removed.

technique to determine which parts of a given data stream contained swallowing activity [47]. Lastly, the anterior-posterior accelerometer data was imported into WavePad Sound Editor (NCH Software, Greenwood Village, Colorado) for manual acoustic analysis and elimination of false positives.

Figures 8 through 11 demonstrate this process one on set of data. Figure 8 is the signal recorded by Signal Express from the output of our accelerometer's amplifier with no digital processing applied. Figure 9 shows this same signal after the FIR filter has been applied to remove the device noise from the signal. Note how the signs of colored noise around the 35 and 60 second marks have been eliminated in favor of constant white noise across the signal. Similarly, figure 10 shows the signal after removing the low frequency head movements. Our wavelet denoising algorithm finishes the processing by removing the majority of white noise in the signal and is shown in figure 11. Compared to figure 8, figure 11 shows much clearer divisions between individual swallows with only a minimum amount of noise.

The device noise filtering algorithm was recalculated with respect to the microphone system and an FIR filter was applied to the swallowing sound signal to eliminate device noise

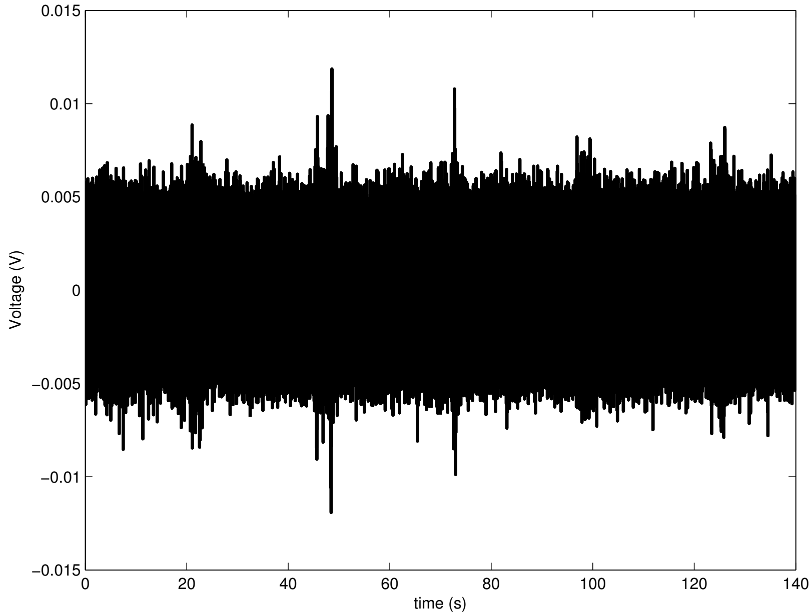

Figure 10: Accelerometer signal after device noise and head movements are removed.

from that signal just like with the accelerometer. We also applied the same 10 level wavelet denoising process to further refine the data. No splines or other low-frequency removal techniques were applied to the swallowing sounds because we had not investigated if such frequencies contained important sound information. We did not develop new segmentation algorithms to extract the five individual swallows from the microphone signal, but instead simply used the time points given by the accelerometer segmentation process.

3.3 FEATURE EXTRACTION

3.3.1 Time Domain

Our next step involved extracting a number of signal features from dual-axis swallowing accelerometry signals and swallowing sounds. In the time domain, the skewness and kurtosis

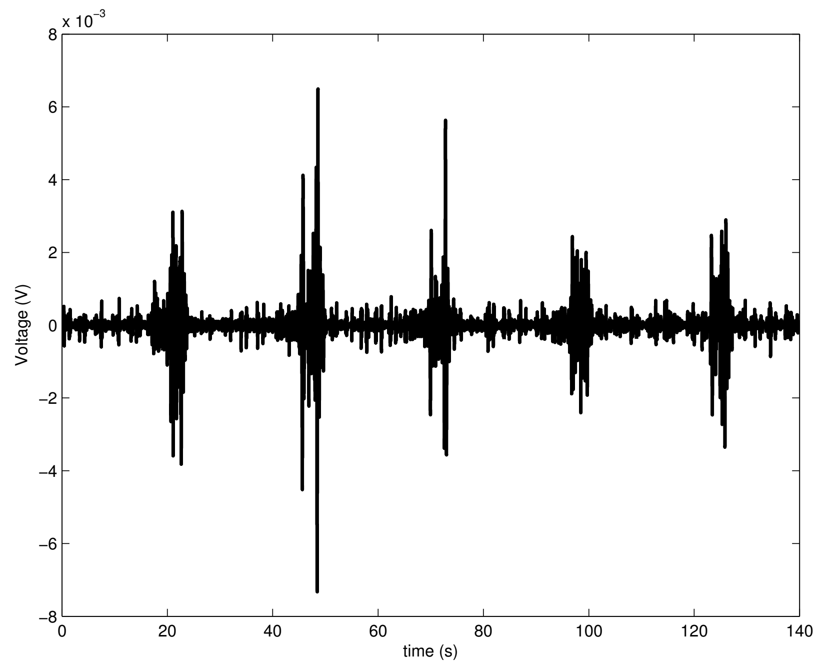

Figure 11: Device noise after device noise and head movements are removed and wavelet denoising is applied.

were calculated by using the standard formulas [19], [51]:

$$y_1 = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^3}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2\right)^{3/2}} \tag{3.1}$$

$$y_2 = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^4}{\left(\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2\right)^{2}} \tag{3.2}$$

where μ is the mean of the signal, y_1 is the skewness, y_2 is the kurtosis, and n is the length of the signal x. Finding the swallow duration only required converting the MATLAB indices given in the segmentation step into proper time units.

3.3.2 Information-Theoretic Features

To calculate the information-theoretic features we followed the procedures outlined in previous publications (e.g., [17], [19]). The signals were normilized to zero mean and unit variance, then divided into ten equally spaced levels, ranging from zero to nine, that contained all recorded signal values. We then calculated the entropy rate feature of the signals. It is found by subtracting the minimum value of the normalized entropy rate of the signal from 1 to produce a value that ranges from zero, for a completely random signal, to one, for a completely regular signal [17]. The normalized entropy rate is calculated as

$$NER(L) = \frac{SE(L) - SE(L-1) + SE(1) * perc(L)}{SE(1)} \tag{3.3}$$

where $perc$ is the percent of unique entires in the given sequence L [17]. SE is the Shannon entropy of the sequence and is calculated as

$$SE(L) = -\sum_{j=0}^{10^L-1} \rho(j) \ln(\rho(j)) \tag{3.4}$$

where $\rho(j)$ is the probability mass function of the given sequence. Lastly the original signal was quantized again, but this time into 100 discrete levels. This allowed us to calculate the Lempel-Ziv complexity as

$$C = \frac{k \log_{100} n}{n} \tag{3.5}$$

where k is the number of unique sequences in the decomposed signal and n is the pattern length [52].

3.3.3 Frequency Domain

Next, in the frequency domain, we determined the bandwidth of the signals along with the center and peak frequencies. The center frequency was simply calculated by taking the Fourier transform of the signal and finding the weighted average of all the positive frequency components. Similarly, the peak frequency was found to be the Fourier frequency component with the greatest magnitude. We defined the bandwidth of the signal as the standard deviation of its Fourier transform [17].

3.3.4 Time-Frequency Domain

We also calculated a number of signal features in the time-frequency domain by utilizing a ten-level discrete Meyer wavelet decomposition. The energy in a given decomposition level was defined as

$$E_x = ||x||^2 \tag{3.6}$$

where x represents a vector of the approximation coefficients or one of the vectors representing the detail coefficients. $|| * ||$ denotes the Euclidean norm [17]. The total energy of the signal is simply the sum of the energy at each decomposition level. From there, we could calculate the wavelet entropy as the Shannon entropy of the wavelet transform. Applying equation 3.4 we produce the following expression:

$$WE = -\frac{Er_{a10}}{100}\log_2\frac{Er_{a10}}{100} - \sum_{k=1}^{10}\frac{Er_{d_k}}{100}\log_2\frac{Er_{d_k}}{100} \tag{3.7}$$

where Er is the relative contribution of a given decomposition level to the total energy in the signal and is given as [17]

$$Er_x = \frac{E_x}{E_{total}} * 100\% \tag{3.8}$$

3.4 STATISTICAL ANALYSIS

Our statistical analysis involved transfering the processed features from Matlab to the SPSS (IBM, Armonk, New York) statistical analysis software. There we ran 25 mixed ANOVA's, one for each extracted feature for all signals plus one for the duration, with the participant's head position as the within-subjects factor and the participant's age and gender as between-subjects factors. Even though the test is robust against violations of assumptions due to our sample size all data was reciprocol transformed to improve the data normality and homogeneity of variance. A p-value of less than 0.05 was required for significance after applying the Holm-Bonferroni method to correct for family-wise false positive errors. Afterwards, we ran 32 Wilcoxon signed-rank tests (8 attributes compared across 2 signal pairs and 2 head positions) to determine which attributes of the swallowing sounds were significantly different from the swallowing accelerometry signals. Here, data was divided only by the participant's head position and a p-value of less than 0.001 was required for significance after applying the Bonferoni correction.

4.0 RESULTS

4.1 AGE, SEX, AND HEAD POSITION

Tables 2-5 and Figures 12-14 summarize the results of our analysis. Presented data was divided by head position only for convenience and readability. In the anterior-posterior direction, we found a number of attributes that varied significantly with respect to the subject's swallowing position. The anterior-posterior skewness ($p = 0.025$), kurtosis ($p = 0.014$), center frequency ($p = 0.004$), and peak frequency ($p = 0.001$) all varied significantly between the neutral and chin-tuck swallowing positions. The significance of the kurtosis

Table 2: Time domain features in the neutral head position

	A-P	S-I	Sounds
Skewness	-0.221 ± 1.694	0.083 ± 2.141	0.268 ± 3.147
Kurtosis	16.82 ± 61.47	20.40 ± 51.71	38.98 ± 317.3
Entropy Rate	0.989 ± 0.012	0.990 ± 0.008	0.987 ± 0.018
L-Z Complexity	0.060 ± 0.030	0.071 ± 0.026	0.080 ± 0.063
Duration (s)	2.505 ± 1.428		

and center frequency also carried some dependence on age ($p = 0.006$ and $p = 0.013$). On the other hand, only the superior-inferior kurtosis ($p = 0.027$) and Lempel-Ziv complexity ($p = 0.029$) varied significantly with the swallowing position. In this case, the Lempel-Ziv complexity significance also showed dependence on the participant's age ($p = 0.016$), but the kurtosis significance depended on the subject's gender ($p = 0.003$). The swallowing sounds' kurtosis ($p = 0.035$), and wavelet entropy ($p = 0.036$) also showed statistically significant

Table 3: Time domain features in the chin-tuck position

	A-P	S-I	Sounds
Skewness	-0.504 ± 2.098	-0.523 ± 5.111	0.262 ± 4.330
Kurtosis	41.66 ± 175.9	89.92 ± 337.5	146.7 ± 682.5
Entropy Rate	0.990 ± 0.007	0.991 ± 0.006	0.988 ± 0.013
L-Z Complexity	0.060 ± 0.025	0.067 ± 0.027	0.072 ± 0.050
Duration (s)	2.441 ± 1.207		

dependence on the swallowing position. The later attribute's significance showed dependence on age ($p = 0.048$) as well as the combined interaction of age and gender ($p = 0.023$).

Only the entropy rate ($p = 0.004$) showed any significant variation due to the participant's age in the superior-inferior direction, which demonstrated some dependence on the subject's gender ($p = 0.009$). However, in the anterior-posterior direction, participant age significantly affected the center frequency ($p = 0.001$), Lempel-Ziv complexity ($p = 0.032$), entropy rate ($p = 0.044$), and peak frequency ($p = 0.025$). The significance on the last three attributes showed some dependence on gender ($p = 0.015$, $p = 0.003$, $p = 0.024$). The peak frequency ($p = 0.004$) was the only swallowing sound features to show age dependence.

Table 4: A summary of frequency domain features in the neutral head position

	A-P	S-I	Sounds
Peak Frequency (Hz)	3.175 ± 11.10	8.841 ± 45.84	38.90 ± 282.3
Center Frequency (Hz)	25.23 ± 48.50	28.61 ± 71.48	198.6 ± 477.4
Bandwidth (Hz)	54.60 ± 95.83	37.93 ± 77.19	433.9 ± 665.6
Wavelet Entropy	1.404 ± 0.595	1.680 ± 0.576	1.295 ± 0.682

The Lempel-Ziv complexity ($p = 0.002$), center frequency ($p = 0.004$), and peak frequency ($p = 0.023$) in the superior-inferior direction all demonstrated a dependence on the subject's gender whereas only the Lempel-Ziv complexity ($p = 0.002$) did so in the anterior-

Table 5: A summary of frequency domain features in the chin-tuck position

	A-P	S-I	Sounds
Peak Frequency (Hz)	2.672 ± 2.775	6.278 ± 7.615	31.42 ± 304.6
Center Frequency (Hz)	45.54 ± 134.1	77.94 ± 187.3	438.9 ± 1236
Bandwidth (Hz)	89.18 ± 180.5	109.7 ± 192.6	656.9 ± 1052
Wavelet Entropy	1.570 ± 0.633	1.771 ± 0.688	1.337 ± 0.664

posterior direction. The swallowing sound also showed gender dependence in its bandwidth ($p = 0.001$) and center frequency ($p = 0.006$). The swallowing duration showed significant changes due to the combined interaction of age and gender only ($p = 0.005$), where older males had longer durations than younger females. All other attributes and interactions that were not listed here were non-significant.

Figures 12-14 show the average energy distribution of the wavelet coefficients of all three signals where d_1 contains the highest detail frequencies, d_{10} contains the lowest, and a_{10} contains all unsorted approximation frequencies. They all show that the vast majority of swallowing energy is contained in the lowest frequency components, though a small amount of that energy shifts to the higher frequencies when the participant is in the chin-tuck position. We clearly see that over seventy percent of the swallowing sound energy remains below 39 Hz (a_{10}, Figure 14), while over eighty percent of both accelerometer signals remain below the same level ($a_{10} + d_{10} + d_9$, Figures 12 and 13).

4.2 SOUND AND ACCELEROMETRY CONTRASTS

Our contrast tests found a number of significant differences between the swallowing sounds and swallowing accelerometry signals. When compared to the anterior-posterior signal, we found that only the kurtosis ($p = 0.018$), entropy rate ($p = 0.001$), and wavelet entropy ($p = 0.006$) of the swallowing sounds were not significant in the neutral position while only

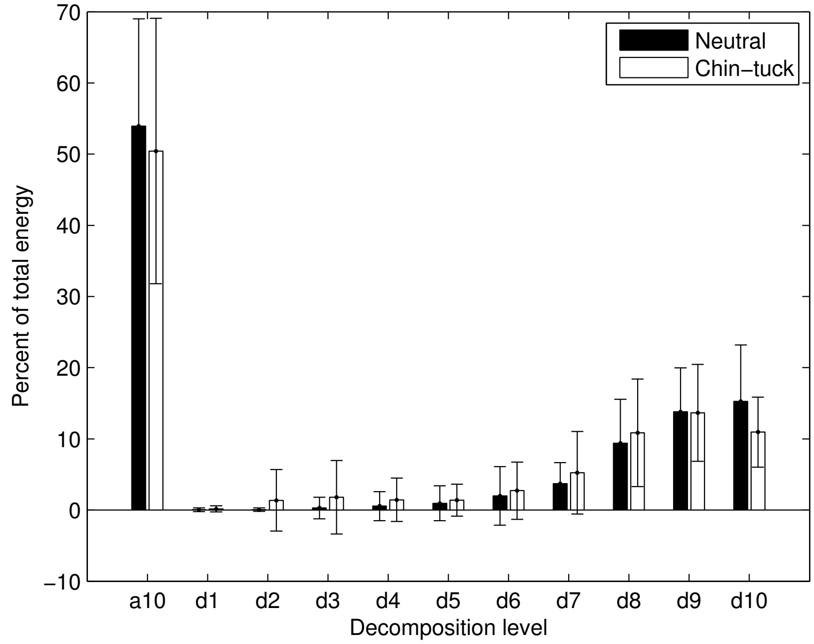

Figure 12: Wavelet energy composition of S-I swallowing accelerometry signals

the skewness ($p = 0.009$) and kurtosis ($p = 0.162$) were not sigificantly different in the chin tuck position. All other anterior-posterior signals did vary significantly from the swallowing sound counterparts ($p = 0.000$ for all). On the other hand, the superior-inferior skewness and L-Z complexity did not vary significantly in either the neutral ($p = 0.255$ and $p = 0.069$) or chin-tuck ($p = 0.437$ and $p = 0.868$) position. Again, all other superior-inferior attributes were significantly different from the microphone features ($p = 0.000$ for all).

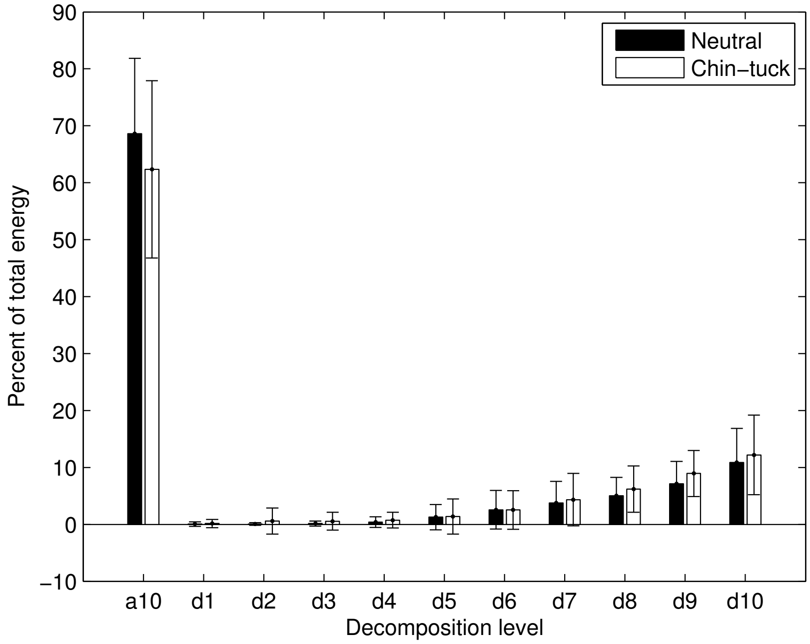

Figure 13: Wavelet energy composition of A-P swallowing accelerometry signals

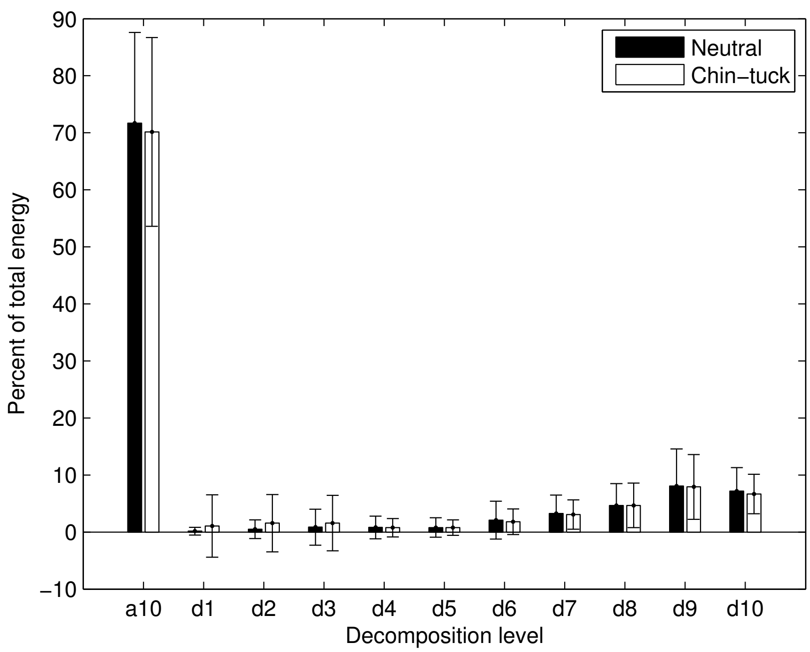

Figure 14: Wavelet energy composition of swallowing sounds

5.0 DISCUSSION

5.1 DEMOGRAPHIC AND POSTURE EFFECTS ON SWALLOWING SOUNDS AND ACCELEROMETRY SIGNALS

In this study, we found that both the peak and center frequencies of the A-P accelerometer signal as well as the peak frequency of the swallowing varied with age, i.e., these values decrease as the participant's age increases. In a previous study, we found that our recording setup contains noise due to vasomotion and cardiac dynamics [27]. One part of this trend is likely a product of the changes in cardiac dynamics with age [28]. The other could be due to the loss of skin elasticity with age, where the low-pass nature of the tissue is enhanced and more high frequency vibrations are removed from the signal [29]. Since this age dependence was not seen in the S-I accelerometer signal, the cardiac dynamics, which would chiefly apply forces in the A-P direction due to major arteries and veins running in the superior-inferior direction, are the more likely cause of this age dependence [30].

With these age differences accounted for, our statistical tests still showed a significant interaction between the A-P center and peak frequencies and the subject's swallowing position. The kurtosis of all three signals also varied with swallowing position and was generally larger for chin-tuck recordings. Similarly the skewness of the A-P recording tended to have a larger negative magnitude for chin-tuck swallows when compared to the neutral position. Unfortunately we cannot determine with certainty what physiological changes correspond to these recordings [8]. We do know that entering the chin tuck position moves the tongue towards the posterior wall of the pharynx, increases the vallecular space, and narrows the diameter of the airway entrance by moving the epiglottis posteriorly [33]. Since the hyolaryngeal excursion is one of the largest components of the accelerometry signal, it is possible that these physiological changes are a sign that this structure operates differently during chin-tuck swallows [53]. We also know that the pressures applied by the upper esophageal sphincter and the pharynx are not significantly different in chin-tuck swallows [54]. We conclude that the difference in these attributes during chin tuck swallowing are most likely due either to modified temporal muscle activity or modified saliva fluid dynamics in the throat due to the mentioned physiological changes.

On a related note, we also found significant interactions between the center and peak frequencies of the A-P accelerometer signal as well as the swallowing sound's center frequency and gender. Specifically, all of these signals tend to be higher in males than in females. Furthermore, the bandwidth of the swallowing sounds was generally greater in males than in females. We suspect that these differences are due to the gender based variations of the laryngeal prominence, since our recording devices were placed just below this structure [30]. This structure tends to protrude further in males, yet undergoes the same motion during a swallow as females [31], [55]. This could produce higher frequency vibrations in male subjects as tissues are displaced faster to accommodate the larger moving structure.

Our finding that the swallow duration does not significantly vary with regards to sex or demonstrate any notable trends with regard to age runs counter to past research on this subject [56]. Our results are similar to a previous study that used the same automated segmentation algorithms, and so we can exclude recording errors as the source of the discrepancy [47]. Meanwhile, other studies which reported sex differences on swallowing duration utilized visual inspection of the videofluoroscopic images or sound spectrum ([57] and [56] respectively), and reported much shorter durations. We assume, then, that our loss of sex dependence on swallowing duration is a result of processing and segmentation differences between this and past studies. The lack of age dependence in our swallowing duration data is most likely due to our small sample size and imperfect population sampling. Our previous study, which did report significant effects of age, utilized a sample size that was orders of magnitude larger than this study and so had more statistical power to detect what is presumably minor influences [47].

5.2 COMPARING SWALLOWING SOUNDS AND SWALLOWING ACCELEROMETRY SIGNALS

5.2.1 Time Domain

Our time domain contrasts found a few significant differences between swallowing vibrations and sounds. We noticed that the in the neutral position the anterior-posterior accelerometer signal skewness has a significantly lower value. In fact, while swallowing sounds can have either positive or negative skewness, the A-P accelerometer signal had typically negative skewness. This means that in the neutral position swallows produce vibrations in the anterior-posterior direction that slowly increase in intensity before decreasing much quicker, whereas swallowing sounds do not follow such a consistent pattern [51]. The superior-inferior skewness in the chin-tuck position followed the same statistically significant pattern.

In addition to the skewness, we also found that the anterior-posterior accelerometer signal had a significantly lower Lempel-Ziv complexity in both the neutral and chin-tuck positions when compared to the swallowing sounds. While the complexity of both signals is already quite low, this indicates that our discretized A-P accelerometer data can generally be compressed further without losing information about the signal [58]. Neither of these attributes can tell us much about the physiology of swallowing, but they could no doubt be important considerations when designing future studies.

The last significant time domain comparison we found was the entropy rate, which was lower in both accelerometer signals than in swallowing sounds in the neutral position. Only the anterior-posterior accelerometer signal was significantly lower in the chin-tuck position. However, all three signals were close to 1 in all situations with only a single mean having a value below 0.99, indicating that all of our discretized signals were highly predictable. While the exact level of regularity varies with each signal, our study shows that both dry swallowing sounds and accelerometry follow a predictable pattern when the data is discretized to ten levels.

5.2.2 Frequency Domain

Our frequency feature contrasts are particularly interesting. First, they show that the swallowing sounds contain significantly higher frequency components when compared to either accelerometer direction in either head position. This demonstrates the existence of higher-frequency features which only one transduction method detected. Second, our results demonstrate peak and center frequencies that are much lower than those reported in many other studies [23], [44], [45]. Even though we cannot exclude the possibility that our recording technique is the source of the discrepancy, it is more likely due to our use of different experimental setups. Several of these past studies utilized recording devices which could generally not detect sounds below 50 Hz and so would not be able to detect as much low frequency information as our microphone which could detect sounds as low as 10 Hz [23], [59], [60]. This difference could be amplified by the manual auditory or spectrogram based segmentation of other studies [23], [45]. In addition to possible human error, these studies do not take into account the non-linear nature of human hearing, which generally does not extend below 20 Hz, and may have excluded valuable data from their analysis which we were able to reliably examine [61]. Finally, one also cannot ignore the different hardware and transduction methods used by the recording devices in these studies, which would invariably affect the data recording and analysis [23], [59].

5.2.3 Time-Frequency Domain

The wavelet energy plots (Figures 12-14) are distributed as one would expect, in a rough exponentially decaying pattern as frequency increases. Clearly, they show that the overwhelming majority of the signal's energy is contained in the lowest frequency components for either head position, particularly for the anterior-posterior direction of the accelerometer signal. This is logical, considering the timescale that swallowing operates on and the temporal dynamics of swallowing [62]. They also further support our findings that swallowing sounds contain more higher frequency components than vibrations by showing that the accelerometer signals hold approximately 10% more of their energy at or below 40 Hz. However, these plots also reveal that, when compared to the neutral position, swallows made in the chin-tuck position contain more energy at the higher frequencies. This suggests that either the chin-tuck position changes the acoustic properties of the throat towards more high-pass behavior, or that the modified physiology produces more, higher frequency, detail components in the recorded signal.

6.0 FINAL REMARKS

6.1 CONCLUSIONS

In this study we recorded data from healthy adult subjects making dry swallows with both a dual-axis accelerometer and a contact microphone. The nine different time and frequency domain features demonstrated varying degrees of significance with respect to the subject's head position, age, gender, or combination thereof. When comparing the swallowing sound features to the accelerometer signals, we found that most of the features were significantly different. We conclude that despite their similarities, these two methods of transducing swallowing vibrations provide distinct information about the underlying physiological processes.

6.2 FUTURE WORK

There are a number of different ways to follow up the results presented in this paper. As stated previously, we sought to provide exactly that opportunity.

Repeating this same experiment with infants or children as the subjects would be one option. Dysphagia can still occur in the pediatric population and diagnosis can be difficult, as they cannot always express their symptoms adequately. Since our results cannot necessarily be applied to these subjects, gathering the same data would allow for further research into developing a child-oriented diagnostic method alongside the adult focused system.

As mentioned earlier, we would like to repeat our data collection and analysis on subjects that have been positively diagnosed with dysphagia. Naturally, to develop a diagnostic method, we must investigate how the recording method functions with the target population as well as how the processing algorithms perform with the new data. We would then compare those results with what we discovered in this experiment and investigate if there are any consistent differences between the healthy and pathological populations.

Finally, it would be useful to pair our sound and vibration recording method with a videofluoroscopic or other recording method that can observe the subject's anatomy during a swallow. One of the main shortcomings of this experiment was that we could determine what differences existed in the signals as we varied age, sex, and head position, but we could not reliably determine what physiological or anatomical changes occured alongside those variables. Such information could greatly enhance our ability to determine the strengths and weaknesses of our recording methodology and provide further insight into the dynamics of swallowing.

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