THE ASSOCIATION OF HIGH RESOLUTION CERVICAL AUSCULTATION SIGNAL FEATURES WITH HYOID BONE DISPLACEMENT DURING SWALLOWING

by

Qifan He

B.S in Electrical Engineering, INSA-Lyon, 2017

Submitted to the Graduate Faculty of

the Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science

University of Pittsburgh

2018

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Qifan He

It was defended on

November 14, 2018

and approved by

Ervin Sejdić, Ph.D., Associate Professor

Department of Electrical and Computer Engineering

Department of Bioengineering, Department of Biomedical Informatics

Zhi-Hong Mao, Ph.D., Professor

Department of Electrical and Computer Engineering

Department of Bioengineering

Murat Akcakaya, Ph.D., Assistant Professor

Department of Electrical and Computer Engineering.

Thesis Advisor: Ervin Sejdić, Ph.D., Associate Professor

Department of Electrical and Computer Engineering

Department of Bioengineering, Department of Biomedical Informatics

THE ASSOCIATION OF HIGH RESOLUTION CERVICAL AUSCULTATION SIGNAL FEATURES WITH HYOID BONE DISPLACEMENT DURING SWALLOWING

Qifan He, M.S.

University of Pittsburgh, 2018

Recent publications have suggested that high-resolution cervical auscultation(HRCA) recordings producing combined accelerometric and acoustic signals may provide an alternative, non-invasive option for swallowing assessment. However, the relationship between hyoid bone displacement, a key component to the safe swallowing, and HRCA recordings is not thoroughly understood. Therefore, we investigated the relationship between hyoid bone displacement and HRCA signal features. We hypothesized that HRCA signal features would be associated with aspects of hyoid bone displacement. We measured hyoid bone displacement in horizontal and vertical directions, along with the hypotenuse of displacement, from videofluoroscopy images of 129 single swallows collected from 46 patients, and concurrently recorded vibratory/acoustic signals produced during these swallows. Our results showed that the vertical displacement of both the anterior and posterior landmarks of the hyoid bone were strongly associated with the Lempel-Ziv complexity of superior-inferior and anterior-posterior swallowing vibrations from HRCA signals. Horizontal and hypotenuse displacements of the posterior aspect of the hyoid bone were strongly associated with the standard deviation of swallowing sounds from HRCA signals. Medial-Lateral swallowing vibrations and patient characteristics such as age, sex and history of stroke were not significantly associated with aspects of hyoid bone displacement. The results imply that some vibratory and acoustic features extracted from HRCA recordings can provide information about the magnitude and direction of hyoid bone displacement. These results provide additional support for using HRCA as a non-invasive tool to assess physiological aspects of swallowing such as hyoid bone displacement. Future research should explore associations between HRCA signals and other swallow kinematic events such as laryngeal vestibular closure, upper esophageal sphincter opening and initiation of the pharyngeal swallow to improve the use of HRCA for assessment of swallowing and biofeedback during dysphagia therapy.

Keywords: High resolution cervical auscultation, swallowing accelerometry, swallowing sounds, dysphagia, signal processing, hyoid displacement

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

First, I would like to sincerely thank my advisor, Dr. Ervin Sejdić, for his guidance, understanding and patience during my master studies. Second, I would like to thank our collaborators, Subashan Perera and James L. Coyle, for their help and expertise in this study. Third, I am deeply indebted to my colleagues, Yassin Khalifa and Zhenwei Zhang, who provided me with assistance, inspiration, courage and support. Fourth, I wish to thank my family for their support, for believing in me, for encouraging me when I failed. Lastly, I want to express my great appreciations to all my teachers in my academic life and to my committee members for their time and interest.

1.0 INTRODUCTION

1.1 SWALLOWING AND DYSPHAGIA

The human body requires a certain daily amount of food and liquid which provide energy and nutrition. Deglutition (i.e. swallowing) is a vital biomechanical process for human beings and animals to remain alive and healthy. This is a complex neuromuscular process that requires the cooperation and coordination of more than 20 pairs of muscles, resulting in the safe passage of liquids and solids from the mouth to the stomach without entering the airway [1]. Concretely, after entering the mouth, the food is masticated and transformed into a bolus through the movement of teeth and saliva. Then the bolus is propelled into the pharynx, where it will be detected by the biological sensor, which sends a signal to the brain in order to urge it to swallow, making the vocal folds close. The epiglottis then covers the larynx in order to make the bolus pass into the esophagus, then into the digestive system. The closure of the epiglottis prevents the bolus from moving into the larynx which would lead to the lung [2, 3, 4]. Figure 1.1 shows the mechanism of healthy swallowing.

Due to its complexity, the swallowing process, which involves muscles, synchronized movements and neural control, is sometimes wrongly executed. Dysphagia is the word that refers to any swallowing disorder. It typically occurs in patients who suffer from a variety of neurological conditions, head and neck cancer and their treatment [5, 6]. The signs of dysphagia includes difficulty in swallowing food and liquid, and choking or coughing before, during or after swallowing. Health complications raised by dysphagia include pneumonia, malnutrition, dehydration and even death in some cases [7, 8]. In general, it makes patients feel uncomfortable while swallowing, and therefore largely decreases the quality of life [8, 7].

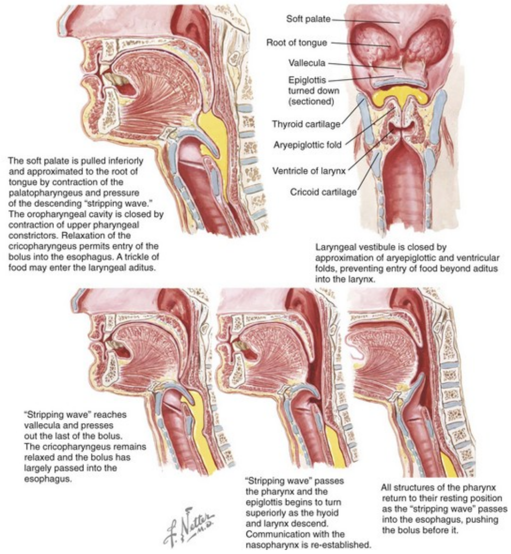

Figure 1.1: Swallow mechanism [9]

1.2 DIFFERENT METHODS OF DIAGNOSIS

Depending on the available resources and the patient's symptomatology, different forms of diagnoses of dysphagia can be carried out, such as non-instrumental, clinical examinations and sophisticated imaging studies using endoscopic or x-ray (videofluoroscopy or VF) instrumentation.

Among them, the videofluoroscopic swallowing studies (VFSS) and the fiberoptic endoscopic evaluation of swallowing (FEES) are currently regarded as the gold standard for identification of oropharyngeal kinematic impairments, airway protection deficits and disordered transfer of swallowed material to the digestive system [3, 10]. These two methods are typically readily available in acute care hospitals, rehabilitation centers and outpatient clinics. Compared with them, clinical evaluation is not effective as it is limited by its reliance on real-time observation, that is the examiner has no idea of any activity occurring once the mouth is closed, which is the case during the majority time of the swallowing activity [11].

Videofluoroscopic swallowing study (VFSS) provides a sequence of real-time radiographic images that capture the structure and biomechanical functions of the upper aerodigestive tract, and the flow of swallowed materials through oral and pharyngeal cavities [12, 13]. VF is used for identification of oropharyngeal kinematic impairments, airway protection deficits, and disordered transfer of swallowed material to the digestive system and enables clinicians to determine appropriate interventions to remediate these errors [3, 10]. The results of VFSS are believed to be the most reliable compared to other techniques [14]. Unfortunately, VF is invasive, relatively expensive and is not available at all facilities or to patients who are unable to participate in imaging studies [11, 15, 16, 17]. Besides, VFSS data needs to be analyzed by a clinical expert [18], thus the process can be time-consuming and expensive. Moreover, exposure to x-ray, even though minimal, can be dangerous in some case [16, 17]. Last but not least, VF allows for only brief durations of observation of patient swallowing function in order to limit radiation exposure, with an average duration of 2.9 minutes depending on factors such as swallowing impairment severity, medical diagnosis, and clinician experience [16]. This requires clinicians to infer function over time during eating and drinking.

FEES uses a flexible endoscope which can be inserted into the patient's nose. Positioned at the level of the soft palate, the endoscope provides a downward view of the pharynx, which allows the examiner to observe the elevation and retraction of the soft palate during swallowing. The endoscope can also provide observation of the pharynx immediately before and after the pharyngeal swallow if placed behind the uvula. Even though FEES cannot capture the oral phase of the swallow, the pharyngeal phase can be analyzed very well. The portability and repeatability of this technique are its main advantages [19]. On the other hand, from the moment when the pharyngeal phase is triggered until the pharynx relaxes after the swallow, the pharynx is closed, making the view of pharynx unavailable during this period [20]. Other disadvantages of FEES are complications such as discomfort, gagging, vomiting, vaso-vagal syncope and laryngospasm [21], and that it must be performed by a trained specialist.

Given the drawbacks and limited accessibility of VFSS and FEES, clinicians would benefit from a noninvasive, alternative method for assessing, monitoring, and treating aspects of swallowing impairments. Pulse oximetry is one of the non-invasive methods that have been proposed during the last few years. It uses a probe attached to the finger, toe or earlobe for measuring arterial oxygen saturation level (SpO2), or the percentage of hemoglobin that is saturated with oxygen, before, during, and after swallowing [22]. It is suspected that in the case of failure of the airway protector, the level of SpO2 decreases. However, pulse oximetry can provide only information about airway invasion instead of a comprehensive analysis of dysphagia. The primary limitation of pulse oximetry is the inevitable time delay between the occurrence and detection of airway invasion.

Conventional cervical auscultation using stethoscopes and human judgment to observe and assess swallowing function has long been a popular solution to noninvasive testing. However, it has repeatedly been found to lack adequate objectivity and inter-observer reliability, due to the limitations of the human auditory system and the fact that stethoscopes are designed and tuned for specific purposes such as observing heart and lung sounds [14].

High-resolution cervical auscultation (HRCA), based on the recording of swallowing vibrations and sounds using accelerometers and microphone, has been considered as a promising non-invasive and automated alternative to VF for dysphagia [18, 23]. Studies showed that accelerometry signals from healthy and abnormal swallows have certain waveform characteristic [24] and also the amplitude of the signal depends on the extent of laryngeal elevation [25], which is an important component of airway protection. A number of studies investigated accelerometer signal for diagnosing dysphagia [26, 27]. Although only anterior-posterior (AP) accelerometer direction was considered at the beginning, later studies about tri-axis accelerometer signal showed that superior-inferior (SI) and medial-lateral (ML) directions contain some information which is absent in AP direction [27, 28]. Advantages of HRCA include mobility, cost-effectiveness, non-invasiveness, and suitability for day-to-day monitoring. On the other hand, evaluating and making decision with HRCA alone is subjective and often with low accuracy, hence the development of algorithms for automatic analysis, can make diagnostic conclusions more objective and significantly decreases the number of erroneous diagnoses. Nevertheless, HRCA has yet to be fully investigated and confirmed as a suitable surrogate for imaging.

1.3 MOTIVATION FOR THIS RESEARCH

1.3.1 Prevalence of oropharyngeal dysphagia

Dysphagia is a common illness among the elderly. 16 million older Europeans and 10 million older Japanese adults suffer from oropharyngeal dysphagia [5, 29]. Overall, oropharyngeal dysphagia affects 30%-40% of people who are older than 65 years [30]. Dysphagia is also commonly presented in people between the age of 70 and 79 (17%) and people above the age of 80 (33%), who live independently in their own house [31]. Additionally, 47.4% of older people who have been hospitalized with an acute illness have this condition, along with 50% of older people who live in nursing homes [19, 32]. Finally, 60% and 80% of older people who suffer from Parkinsons and Alzheimers, respectively, are affected by oropharyngeal dysphagia [5].

Moreover, patients with neurological conditions frequently experience swallowing disorders. Dysphagia is often diagnosed among patients who suffer from traumatic brain injuries, with up to 70% for severe acute traumatic brain injuries and up to 50% for severe chronic traumatic brain injuries. Dysphagia is commonly found in patients who have a stroke, precisely 64-78% during the acute phase and 40-81% during the chronic phase [5, 6].

Finally, it is quite common that patients who have been through chemotherapy or surgery in the larynx area to have oropharyngeal dysphagia. Due to altered anatomy, mass effects or cancer, patients who have experienced radio chemotherapy are 44% more likely to have dysphagia after their treatment [5, 33].

1.3.2 Current assessment issues

Dysphagia is a severe health issue which in the worst case can lead to death if left untreated. The common assessment of dysphagia is to use X-ray, which is invasive and dangerous to patient's health. Additionally, the high price of equipment, long waiting lists, and needs for specialists keep the patients from being treated in time and properly.

1.3.3 Alternative assessment methods

Like mentioned above, the value of HRCA has been investigated as a potential surrogate for VF when VF is either unavailable, infeasible or not desired by the patient due to its mobility, low cost, suitability for day to day monitoring and non-invasiveness. It screens patients suspected for dysphagia to identify those for whom oral intake may be dangerous, and expedite their referral for gold standard diagnostic testing with VF, while identifying those who do not need diagnostic testing and who should not be unnecessarily deprived of oral intake. Moreover, HRCA has the potential to infer the movement of a specific structure during swallowing, which in return can make the assessment of dysphagia more accurate.

Hyoid bone displacement, which plays a crucial role in swallowing, reflects the integrity of the mechanism responsible for timely and complete airway closure and the opening of the upper esophageal sphincter (UES) which, in turn, enables clearance of material to the digestive system. Prior research indicates that hyoid bone displacement is highly correlated with airway protection and UES opening [4]. The superior-anterior movement of the hyoid bone reflects the actions of musculature that contract somewhat sequentially in order to facilitate airway (laryngeal vestibular) closure and UES opening, thus directing swallowed materials away from the airway and into the esophagus. Clinicians typically assess and monitor these aspects of swallowing by measuring hyoid bone displacement from VF images.

HRCA signal features are associated with laryngeal vestibule closure and re-opening, UES opening, and the position of the hyoid bone [34]. Research suggests that changes in several HRCA signals features reflect both vertical and horizontal displacement of the hyoid bone during swallowing [35]. For example, weak accelerometry signals recorded from a dual-axial accelerometer are related to reduced hyoid bone excursion compared to stronger signals reflecting more complete hyoid displacement [35].

HRCA offers much more than the ability to grossly monitor hyoid displacement. HRCA signal features of the time, frequency, and time-frequency domains provide rich information regarding the subtleties of structure displacement that lie beyond the limited visual inspection capabilities offered by VF, and warrant continued investigation to elucidate the diagnostic potential of HRCA in swallowing assessments. Therefore, we compared tri-axial accelerometry HRCA signal features in the time, frequency, and time-frequency domains in the anterior-posterior (AP), superior-inferior (SI), and medial-lateral (ML) directions with concurrently recorded vertical, horizontal and hypotenuse hyoid bone displacements from VF images. We hypothesized that HRCA signal features would be strongly associated with hyoid bone displacement.

1.4 RECORDING DEVICE

1.4.1 Accelerometry

A widely used accelerometer in scientific applications is the MEMS accelerometer [36]. This tri-axial accelerometer consists of three capacitors positioned orthogonal to one other. Each capacitor is etched into a circuit with micro-fabrication techniques and has the same performance. A capacitor is made of two plates. In this study, one plate is fixed to the neck of the patient while the other plate is suspended above the fixed one [36], as shown in Figure 1.2. The magnitude of the force exerted on the suspended plate modifies the distance between the two plates and so modulates the capacitance of the capacitor [36].

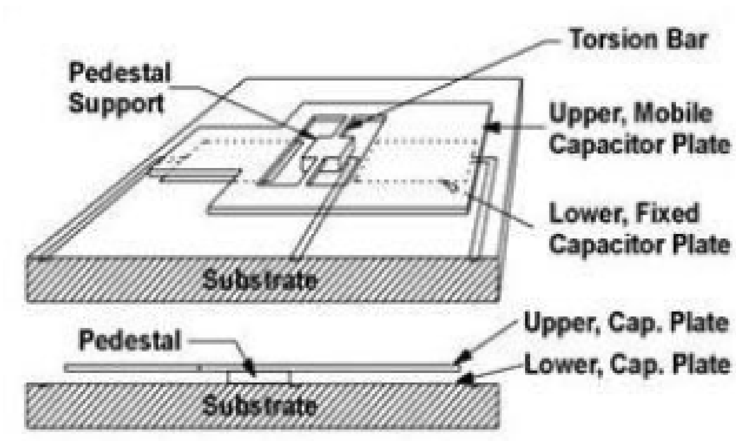

Figure 1.2: Accelerometry [36]

1.4.2 Microphone

The microphone used in this study typically is an electret condenser microphone [37]. This microphone is made of a polarized film that moves when it is contacted by the sound waves as shown in Figure 1.3. This movement modifies the electric field of the device, thus producing the signal. The electret condenser microphone has a large array of frequencies, which allows the microphone to record sounds that can or cannot be heard by humans. Thereby, the microphone, with its large range of frequencies and applications, can record swallowing sounds [37, 38]. Due to the microphones polarized film, the orientation is very important. Different orientations of the microphone may have effects on the recording. Two sounds that have the same intensity but a different polarization will have a different electrical output due to the orientation of the polarized microphone [38]. This way noise rejection can be increased, and therefore can affect the predetermined signal recording.

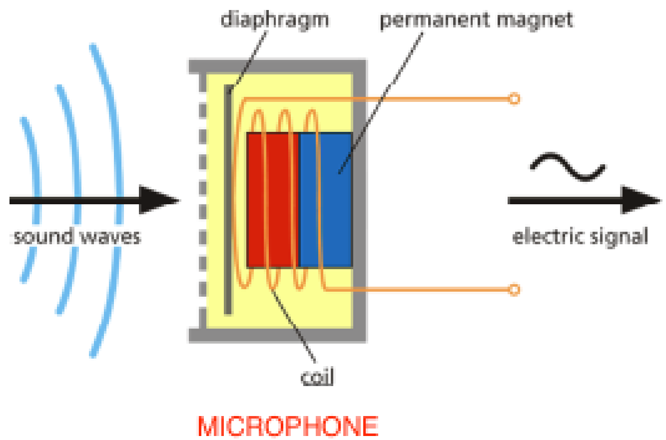

Figure 1.3: Microphone [37]

1.4.3 Thesis structure

Chapter two provides the related background information about the swallowing mechanism, hyoid bone, dysphagia and treatments for dysphagia. Precisely, the detailed normal swallowing stages are described, followed by a brief introduction of the role of hyoid bone in these three stages. Then the causes and the symptoms of dysphagia are mentioned along with its treatments. In chapter three, we will describe the methods we used in this research, including data collection, the methods to pre-process the collected signals, extracted features in time, information-theoretic, frequency, time-frequency domains along with the statistical test. Chapter four presents the results while chapter five discusses these findings and their impact. Finally, chapter six concludes the overall discussion of the significance of the findings, the limitation of this research and the potential future studies.

2.0 BACKGROUND

2.1 SWALLOWING MECHANISM

Swallowing is the first step to transport food and liquid from mouth to stomach and it is a vital bio-mechanical process for nourishing and hydrating the human body. It requires the participation and coordination of more than 20 muscles. Figure 2.1 shows the different structures of the mouth and throat involved in the swallowing process. After entering the mouth, the food is masticated and transformed into a bolus through the movement of teeth and saliva. Then the bolus is propelled into the pharynx, where it will be detected by the biological sensor, which sends a signal to the brain in order to urge it to swallow, making the vocal folds close. The swallowing process has three different stages: the oral preparatory stage, the oropharyngeal stage and the esophageal stage [22].

2.1.1 Oral preparatory stage

In this stage, the food is chewed, mixed with saliva and formed into a bolus for swallowing (as shown in Figure 2.2) [40]. The movement of the tongue can help gather food left between cheeks and between teeth. Then, the bolus will be propelled into oropharynx with the help of different muscles in the oral cavity [41]. The oral preparatory phase can be further broken down into two stages. The first one consists of transporting the ingested food and liquid from the incisal area to the molar region of the oral cavity while the second consists of the mechanical breakdown of food. The second is not always needed. It only exists when solid food is presented and needs to be broken down and be mixed with the saliva to form a cohesive bolus. In the case of fluids, the second stage is absent.

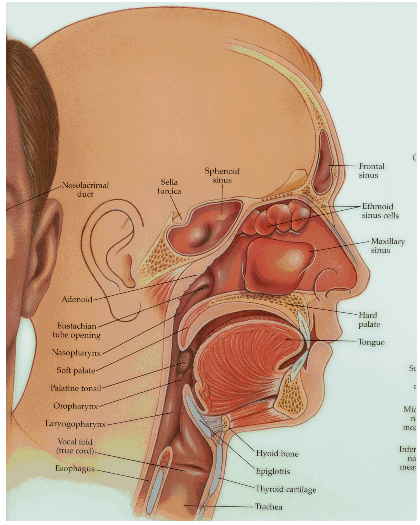

Figure 2.1: Cross-section of the human head and neck [39]

2.1.2 Pharyngeal stage

Figure 2.3 shows the mechanism of the pharyngeal phase, which consists of involuntary and reflex mechanisms triggered by special biological sensors. In order to successfully enter the stomach and be digested at the end of the swallowing process, the bolus needs to pass through the laryngeal. Such process requires different muscles to contract and relax consecutively and coordinately. Concretely, the following actions are involved so as to complete this phase:

1. Mouth closes, nasopharynx is blocked as soft plate elevates itself to prevent bolus form coming back up toward the nose.

2. Larynx will then be closed as well thanks to the suprahyoid muscles in order to prevent the entry and the overflow of the bolus into the airway.

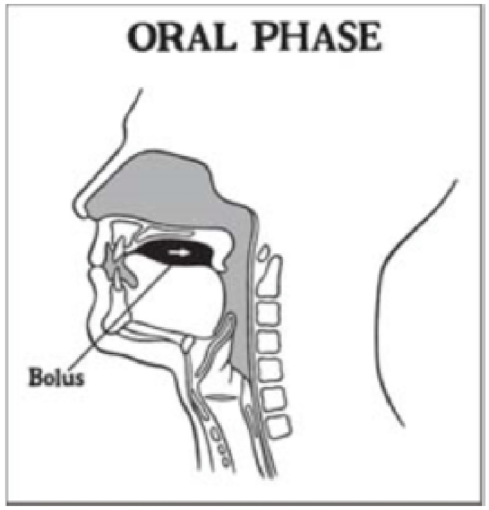

Figure 2.2: Oral stage [42]

3. In order to completely stop the bolus from entering the airway, the epiglottis will move to cover the larynx that leads to lungs.

4. The upper esophageal sphincter will first start relaxing to open the esophagus so that food can enter due to the pressure gradient created by peristalsis.

5. Finally, the tongue base forms a ramp shape so that the bolus is directed into the pharynx.

This part of the swallowing, which is necessary to trigger the pharyngeal phase, is voluntary, while the rest of the phase proceeds automatically [24].

2.1.3 Esophageal stage

This stage is completely voluntary and it can take between 8 and 20 seconds to complete. Figure 2.4 depicts the esophageal phase, which begins when food leaves the pharynx and

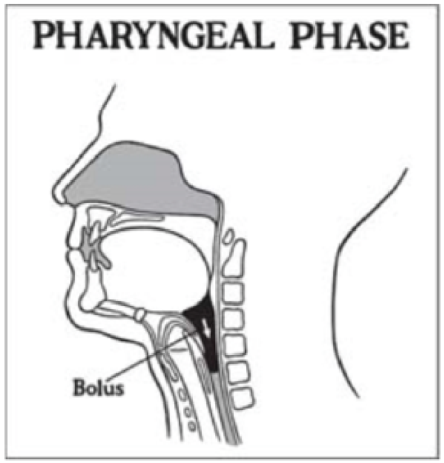

Figure 2.3: Pharyngeal stage [42]

enters the esophagus, and ends when it arrives to the stomach. The tube-like structure in figure 2.4 is the esophagus. It has two important sphincters, the upper and lower esophageal sphincters [43]. They serve the purpose of preventing food and saliva from being regurgitated toward the mouth by acting as physical barrier [44].

2.2 HYOID BONE

2.2.1 Hyoid bone structure

Derived from the Greek word hyoeides, meaning 'shaped like the letter upsilon (u)', the hyoid bone is a horseshoes-shaped bone situated in the anterior midline of the neck between the chin and the thyroid cartilage, as shown in Figure 2.5. When at rest, it lies at the level of the base of the mandible in the front and the third cervical vertebra behind. The hyoid bone is anchored by the muscles from the anterior, posterior and inferior directions. It also provides attachment to the muscles of the floor of the mouth and the tongue above, the larynx below and the epiglottis and pharynx behind [45].

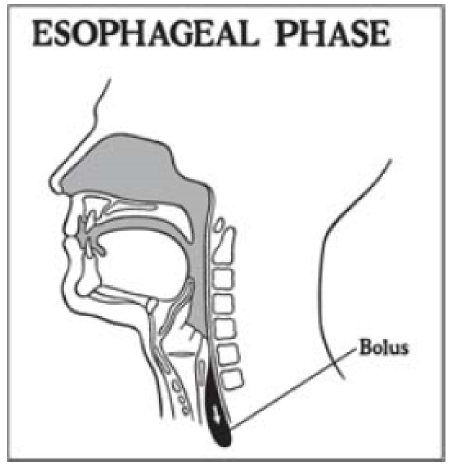

Figure 2.4: Esophageal stage [42]

The hyoid bone is important for a variety of physiological functions, such as breathing, swallowing and speech. Studies have shown that an inferiorly positioned hyoid bone is strongly related to several disorders [46].

2.2.2 The role of the hyoid bone in the swallowing process

During the swallowing process, the hyoid bone has two important functions: One, the displacement of hyoid bone enables the epiglottis to cover the airway so that aspiration can be avoided (Figure 2.7). The second function of hyoid bone is to help open the esophagus to allow the bolus to enter the digestive area [48]. To accomplish these two main functions, the hyoid bone moves upward and forward during the swallowing process. The Figure 2.6 shows the trajectory of the hyoid bone movement.

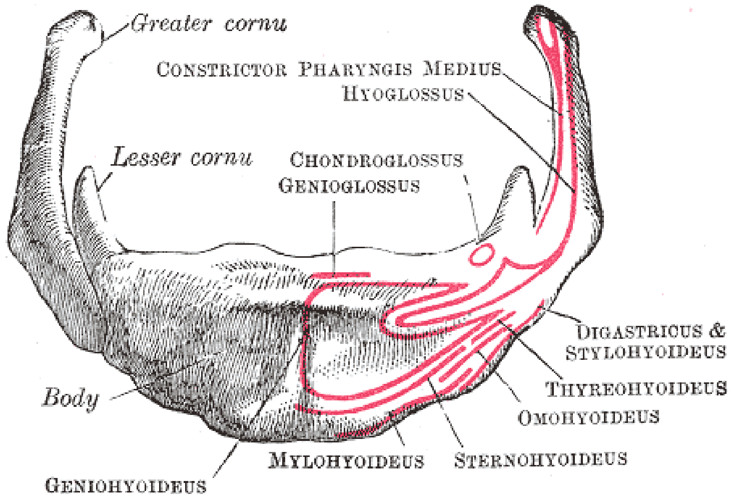

Figure 2.5: Structure of hyoid bone [47]

For the majority of patients who suffer from dysphagia, the movement of the hyoid bone followed by a well-defined two-step pattern during swallowing is influenced by its resting positions. The first movement of the hyoid bone occurred well before the passage of the bolus through the faucial isthmus. During this movement, the hyoid bone was elevated between 4 and 18 mm. The second movement of hyoid bone occurred in the sector between 0 and 75 degrees. A one-step movement of the hyoid bone is suspected to due to the weakness in the styloglossus and/or stylohyoideus muscles [49].

2.3 DYSPHAGIA

Dysphagia, derived from the Greek words 'dys' meaning disorders or ill and 'phagos' meaning eat or swallow, is a term that is used to describe the multitude of swallowing difficulties and impairments [22]. Typically it can be classified into three categories: oropharyngeal dysphagia which occurs at or near patient's pharynx; esophageal dysphagia for causes that

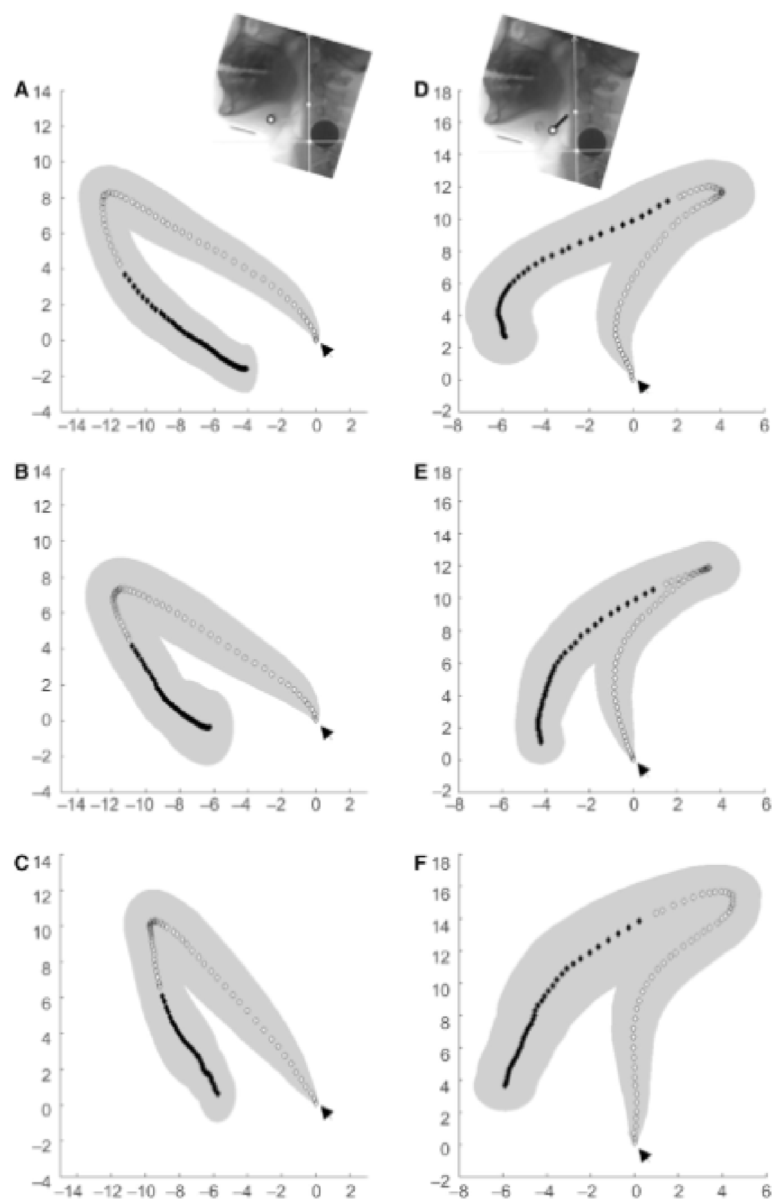

Figure 2.6: Trajectory of hyoid bone movement during swallowing [50]

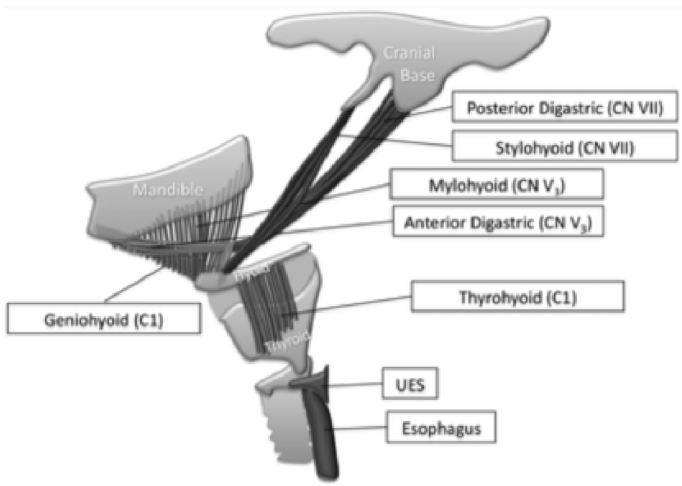

Figure 2.7: Hyplaryngeal structure showing the suprhyoid muscles with their attachment [51]

originate in the esophagus; and functional dysphagia for those where the cause cannot be precisely located [52]. People affected by oropharyngeal dysphagia can have difficulties in forming and safely moving the bolus, which is formed from mashed food and saliva, from the mouth to the stomach. Esophageal dysphagia is mostly caused by structural abnormalities or motor dysfunctions [3].

2.3.1 What causes dysphagia

There are mainly three situations where swallowing difficulties occur. First, while the bolus enters in the pharynx, the larynx remains open, that is the epiglottis fails to cover the airway, which allows bolus to enter in the airway. Second, liquid and food can enter into the airway if the larynx doesn't close completely or if it closes in a delayed fashion, that is if it is not synchronous with the arrival of the bolus. Lastly, the overflow of the bolus in larynx may occur if the volume of the material exceeds the volume of the laryngeal cavity.

The causes for dysphagia can be classified into three categories: neurological conditions, structural and mechanical disorders, and conditions of the neck or head [6, 10, 29].

2.3.1.1 Neurological diseases Neurological diseases which involve muscles less controllable by the brain during swallowing process can cause dysphagia. Moreover, some sensors may not detect the bolus at all or detect it with an important delay during a swallow. Therefore, the epiglottis cannot be closed in time, which would result in the entry of bolus into the airway [6].

2.3.1.2 Head or neck diseases Patients who have cancer or a mass in the neck usually suffer from dysphagia as well. The mass would occupy the space and apply pressure on the pathway of the bolus, narrow the esophagus and the larynx, making swallowing more difficult [53, 54]. Removing the mass using surgical methods could make the dysphagia even more severe as the operation requires to cut some links between the tumor and muscles. This would further weaken the muscles involved in the swallowing process [6, 53].

2.3.1.3 Mechanical causes Mechanical causes like obstruction or structural impairment, which cause inflammation of tissues, can cause dysphagia [6]. According to previous study, fifty to eighty percent of patients who have systemic sclerosis suffer from esophageal dysphagia [6].

2.3.2 Symptoms

Dysphagia can present itself in several easily observed ways, including coughing after a swallowing, pain during swallowing, or simply difficulty with initiating a swallow [22]. Most of the time, these symptoms indicate that the muscles and anatomical structures involved in swallowing are not functioning correctly [22]. Therefore the structures that serve to prevent food from entering the airway are of particular interest. However, airway protection is related to many factors including hyolaryngeal displacement and posterior movement of the tongue base, both of which serve to direct the epiglottis into the right position necessary to protect the airway, as well as the elevation and anterior-directed tilting of the arytenoids [55]. If any part of the above process fails to operate correctly during a swallow, then food can be allowed to enter the trachea, and airway penetration takes place, which can potentially result in a pulmonary infection and more serious health outcomes [52]. Even if this particular scenario doesn't occur, people who suffer from dysphagia often feel uncomfortable during the swallow, which affects their quality of life and can cause malnutrition as the patient attempts to avoid unpleasant activity [7, 8]. In the following paragraphs, we present some of the most common reactions to dysphagia.

Aspiration and penetration are two of the most common symptoms of swallowing dysfunction. Aspiration occurs when mashed food, liquid or secretions enter into the larynx or other lower respiratory organs, lung for example. Supraglottic penetration occurs when the bolus enters into the airway, whereas supraglottic aspiration occurs when the bolus penetrates the airway deeper than the level of the vocal folds [3, 10]. To evaluate the degree of penetration, a scale named penetration aspiration score (PA score) has been given to each swallow, which range from 1, representing no penetration of swallowed material into the airway, to 8, indicating aspiration of swallowed material through the larynx and into the trachea without reflexive effort by the patient to eject aspirated material [56, 57]. A PA score of 3 for example, represents a swallow in which the bolus enters into the airway, yet remains above the vocal folds.

Choking is a mechanical response to aspiration as liquid entered into the airway must be expelled from it [10]. Some biological sensors that detect liquids or food in the airway make the patient choke. The choking reflex tries to reject the bolus from the airway by expelling air from the lungs.

Pneumonia is one of the most severe diseases caused by dysphagia as it is the main cause of death in this case. It is caused by infection of the lungs after aspirations and inhalation of the bolus (food, liquid, or secretions). Pneumonia then makes swallowing and breathing even more difficult. Patients experience fast breathing, shortness of breath, and heartburn. They also often feel weak and tired, and can experience nausea, fever, and vomiting [58]. Pneumonia is the third leading cause of death in Japan and the first leading cause for older Japanese [59].

Table 2.1: Summary of symptoms related to two types of dysphagia: the oropharyngeal dysphagia (related to the mouth and the throat) and esophageal dysphagia (related to the esophagi).

esophageal dysphagia	feeling of pain while swallowing pocketing of food inside the cheeks spilling of the bolus outside of the mouth slurring of words when speaking avoiding eating weight loss pneumonia
oropharyngeal dysphagia	difficulty in forming a compact bolus slurring of words when speaking feeling that food is stuck in the throat nasal regurgitation pneumonia

2.3.3 Treatment for dysphagia

Different treatments can be implemented to help prevent the further deterioration of dysphagia or help feed a patient, ranging from the severe one like surgery to the less extreme ones such as rehabilitation, physiotherapy and the specialized daily diets. Specialized treatments can be carried out given patient's severity and the cause (neurological or structural) of dysphagia [60, 61].

2.3.3.1 Postural technique One of the most common treatments is physical therapy, which involves exercises for the swallowing muscles, and it is called the postural technique [62]. This treatment intends to increase the patient's muscles' strength so as to help closing or opening specific parts of the swallowing system. The goal of this technique is to decrease the pharyngeal residue and the risk of aspiration. The most common postures include lying down or on the one side, which helps increase the flow of the bolus through the pharynx and help reduce the residues in the oropharyngeal system. Turning and tilting the head also help as they increase the size of the upper esophageal sphincter and the amount of the bolus swallowed [23, 61]. This technique is useful for patients whose cause of dysphagia are brain, nerves or muscle impairments.

2.3.3.2 Diet modification According to the recent studies, certain food and liquid can help make swallowing easier for patients with specific symptoms. For example, patients who have a lot of gastroesophageal reflux need to avoid feeding on chocolate, coffee, fatty food, and acidic food. Therefore, diet modification has been proposed, aiming at increasing bolus viscosity which leads to easier swallow and lower risk of aspiration pneumonia [63].

2.3.3.3 Swallowing maneuvers Patients with dysphagia have been asked to practice different swallowing maneuvers that aim at easing the swallowing process by helping different opening to allow food to pass more smoothly and different closing to avoid airway penetration.

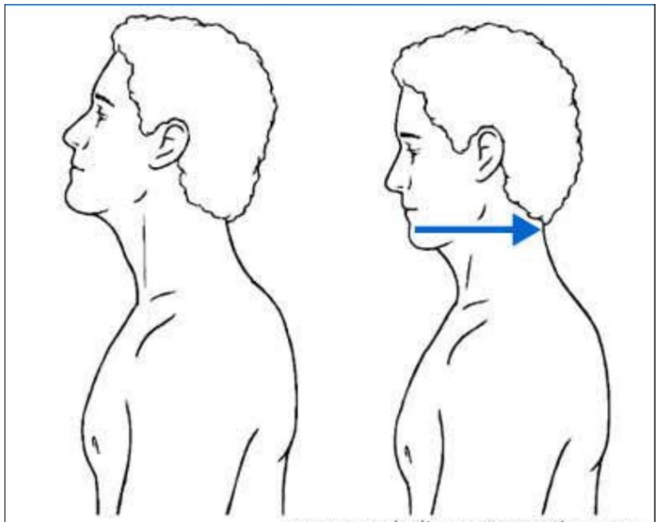

Figure 2.8: Chin-tuck maneuver [42]

The most widely used maneuver is the chin-tuck maneuver, as shown in Figure 2.8. This maneuver consists of putting the chin closer to the chest and swallowing form that position. When doing so, the patient's larynx will be narrowed in order to counterbalance the delay of the epiglottis. Figure 2.9 depicts the influence of this maneuver on the different structures and muscles. It has been found that the chin tuck maneuver can significantly decrease the occurrence of aspiration [64].

The Mendelssohn maneuver is another common maneuver, during which a patient places his hand on his throat at the highest point where his larynx can reach during swallowing. The next step includes squeezing the muscles in the back of the tongue intensely and to keep the voice box at this highest point as long as possible before relaxing the muscles. This maneuver intends to increase the tongue control and decrease the amount of residue in the pharynx and the throat.

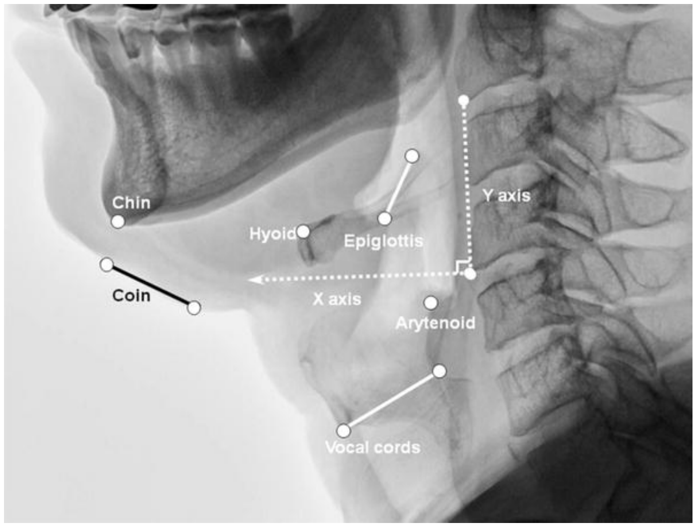

Figure 2.9: Influence of using chin-tuck maneuver [65]

The Valsalva maneuver aims at increasing laryngeal opening during swallowing and reducing the risk of aspiration. The patient is asked to hold his breath during this maneuver and keep his lips opened.

2.4 PREVIOUS CONTRIBUTION ABOUT CERVICAL AUSCULTATION

Cervical Auscultation (CA) describes several techniques using different acoustic information. Among them, high-resolution cervical auscultation (HRCA) based on recordings of swallowing vibrations and sounds has proven the ability to provide a lot of useful information. For example, it has been shown that the chin-tuck maneuver affects only the swallowing vibration but not the sounds [66]. The signal in the ML direction reveals information that signals in the AP and SI cannot provide. By comparing the extracted features from the vibrations in different directions, which gives information such as the dissimilarities, the degree of predictability, and the disordered behavior, we can better understand and assess the swallowing process.

In this study, we have considered the association of features extracted from the cervical auscultation swallowing signals and the sound with the hyoid bone displacement in horizontal, vertical direction and hypotenuse movement. By exploring their relationship, we sought the possibility to infer the hyoid bone movement with the HRCA features. This study is meant to be one of the preliminary steps that can help build a useful tool used in dysphagia assessment.

3.0 METHODOLOGY

3.1 DATA ACQUISITION

This study examined 129 single swallows collected from 46 adult patients with suspected dysphagia (27 males and 19 females, mean age: 64.66 ± 14.99) referred for VF at the University of Pittsburgh Medical Center. Among all the patients, 17 suffer from the stroke while the rest have no stroke history. Swallows analyzed for this study were limited to those in which the entire body of the hyoid bone was visible on all VF frames. Since we are investigating relationships between HRCA signal features and displacement of the hyoid bone and not causal relationships between disease states causing dysphagia and HRCA signals, we did not limit inclusion based on diagnosis. Patients swallowed refrigerated Varibar thin liquid (Bracco Diagnostics, Inc.) ($<$ 5cPs viscosity) or Varibar nectar thick liquid (300 cPs viscosity) from a spoon (3-5mL) or a self-administered comfortable volume by the cup with their heads in a neutral position. Each swallow has also been given a PA score (penetration-aspiration score), which range from 1, representing no penetration of swallowed material into the airway, to 8, indicating aspiration of swallowed material through the larynx and into the trachea without reflexive effort by the patient to eject aspirated material [56, 57]. Most swallows rated 1 or 2 (78.12%) suggesting safe swallows, while few rated from 3 to 8 (21.88%).

Video images were recorded at a rate of 60 frames per second with a resolution of 720×1080. HRCA recording equipment consisted of a tri-axial accelerometer (ADXL 327, Analog Device, Norwood, Massachusetts) affixed to the anterior neck over the palpable arch of the cricoid cartilage and a contact microphone (model C 411L, AKG, Vienna, Austria)

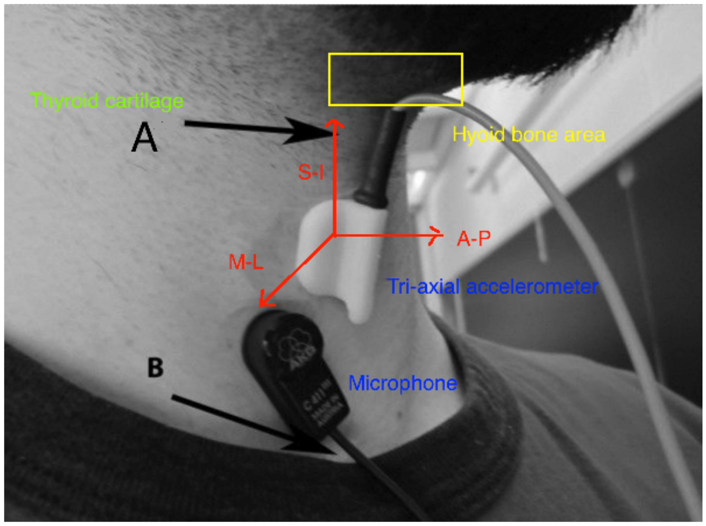

Figure 3.1: Device placement and its different axis. 'A' indicates the thyoid cartilage and 'B' the suprasternal notch. 'A', 'B' are used as reference to place the sensors [56].

affixed just lateral to the accelerometer so as not to interfere with VF observation of the airway column. Both were attached to the participants neck with double-sided tape [67]. Two (SI and ML) of three accelerometer axes were found in the frontal plane of the body with the SI axis parallel to the cervical spine, ML axis perpendicular to SI axis. The AP axis was perpendicular to the coronal plane. Figure 3.1 shows the position of the sensors and the three axes. The signals from the tri-axial accelerometer and microphone were recorded with National instruments 6210 DAQ at a sampling rate of 40 kHz by the LabView Signal Express (National Instrument, Austin, Texas) [18]. The accelerometer was powered by 3-V external power supply (Model 1504, BK Precision, Yorba Linda, CA, USA) and the microphone was powered by the model B291 (Model B291, AKG, Vienna, Austria). The resulting signals were bandpass filtered from 0.1 to 300 Hz with an amplification of ten (model p55, Grass Technologies, Warwick, Rhode Island).

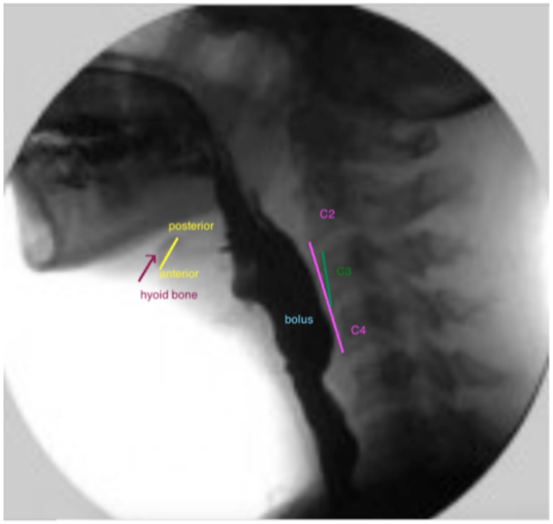

Figure 3.2: Location of anterior and posterior part, C3 compared to C2-C4

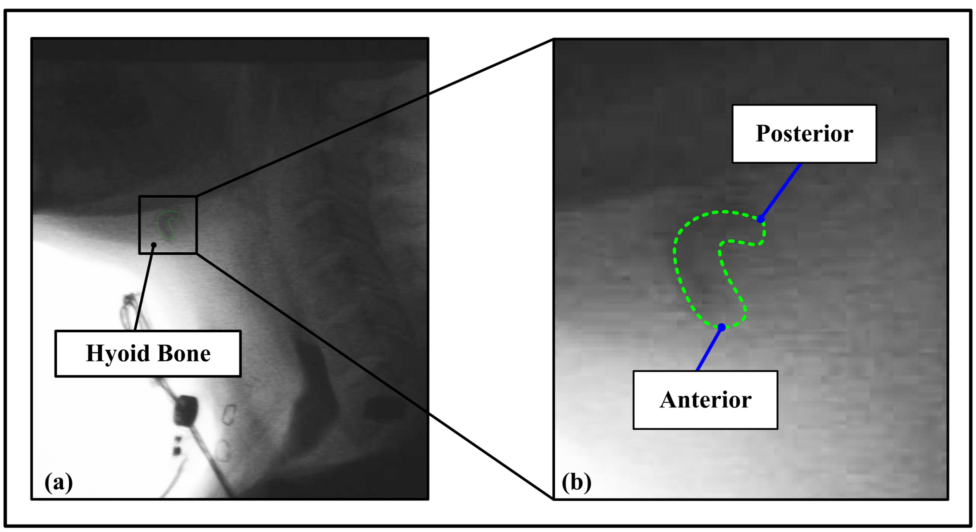

Figure 3.3: Hyoid bone and tracking points. Green dotted line marks the outline of hyoid bone to improve visibility (a) X-ray image of hyoid bone, (b) Posterior and anterior points for tracking.

Table 3.1: Patient distribution and characteristics of the considered swallows

characteristic	**sample**
number of swallows	129
number of patients	46
female	19
male	27
number of stoke patients	17
age range	27 – 94
volume of the bolus	spoon or cup
PA score	1-8
single / multiple swallow	single

Table 3.2: Distribution of swallows

number of swallows		
command 68	not command 61	total 129
white origin 110	other origin 19	total 129
PA12 109	PA38 20	total 129

3.1.1 Image analysis

A speech-language pathologist (SLP) trained in our lab to measure swallowing kinematic displacements determined the beginning and end of each swallow via frame-by-frame temporal analysis of VF recordings.

The most anterior and posterior aspects of the hyoid bone were plotted on each frame and used as vertexes. The body of the hyoid has the shape of a tilted boomerang with two endpoints and a central curved mid portion. In the lateral VF view, one endpoint (superior-anterior) lies anterior to the other (inferior-posterior) endpoint. In previous studies, the anterior landmark of the hyoid was marked as the midpoint on the anterior surface of the hyoid body which we considered subjective and insensitive to the rotation of the hyoid bone. The height of the anterior aspect of the third cervical vertebral body (C3) was used as an anatomic scalar to account for differences in participant height and to equate hyoid displacement to a ”vertebral unit” that is visible during VF data collection and measurements. The C2-C4 linear measure is currently in widespread use and we are currently validating the use of C3 as a surrogate for C2-C4. Figure 3.2 shows the anterior and posterior part of the hyoid bone as well as the length of C3 and C2-C4 while Figure 3.3 shows the tracking points on the hyoid bone structure.

3.2 SIGNAL PRE-PROCESSING

First, the beginning and the ending of each swallowing were determined by an experienced speech language pathologist via frame-by-frame temporal analysis of videofluoroscopic recordings. The signals obtained combine useful information along with noises from multiples sources including mechanical and electrical thermal noise from the accelerometer for example, and undesired information such as head movement signal. In order to have an efficient and clean feature extraction, a preprocessing procedure was carried out. First of all, 4 axial-specific finite impulse response (FIR) filters were created via the auto-regressive (AR) model [68] to filter out the white noise of the detection device. Then we used the least-square spline approximation algorithm [28, 69] to attenuate the low frequency component associated with head movement. Specifically, we fitted a low-frequency ($\leq$ 2 Hz) trend to the time-domain signal and then subtracted the low-frequency trend from the time-domain recording. To further reduce the impact of both white and colored noise on the given signal, a ten-level wavelet transform using the Meyer Wavelet with soft thresholding was used to denoise the filtered signal [70]. Figure 3.4 shows the workflow of data pre-processing while Figures 3.5, 3.6, 3.7 and 3.8 show the raw signals before pre-processing, filtered signals, the denoised signals and several signals after pre-processing respectively.

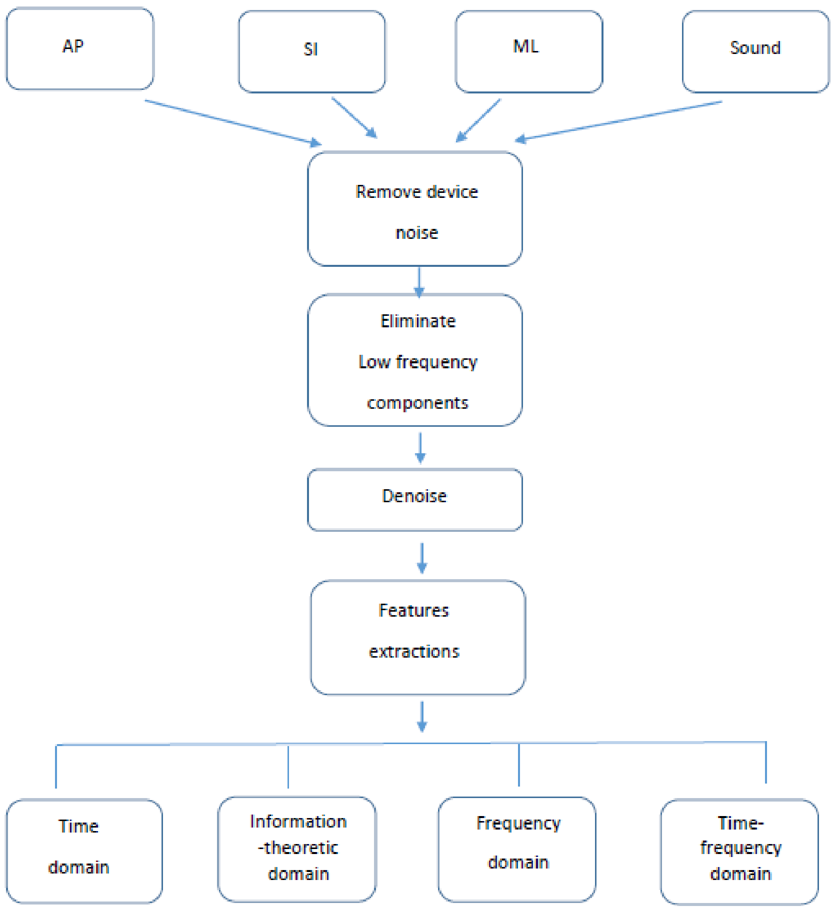

Figure 3.4: Workflow of signal preprocessing

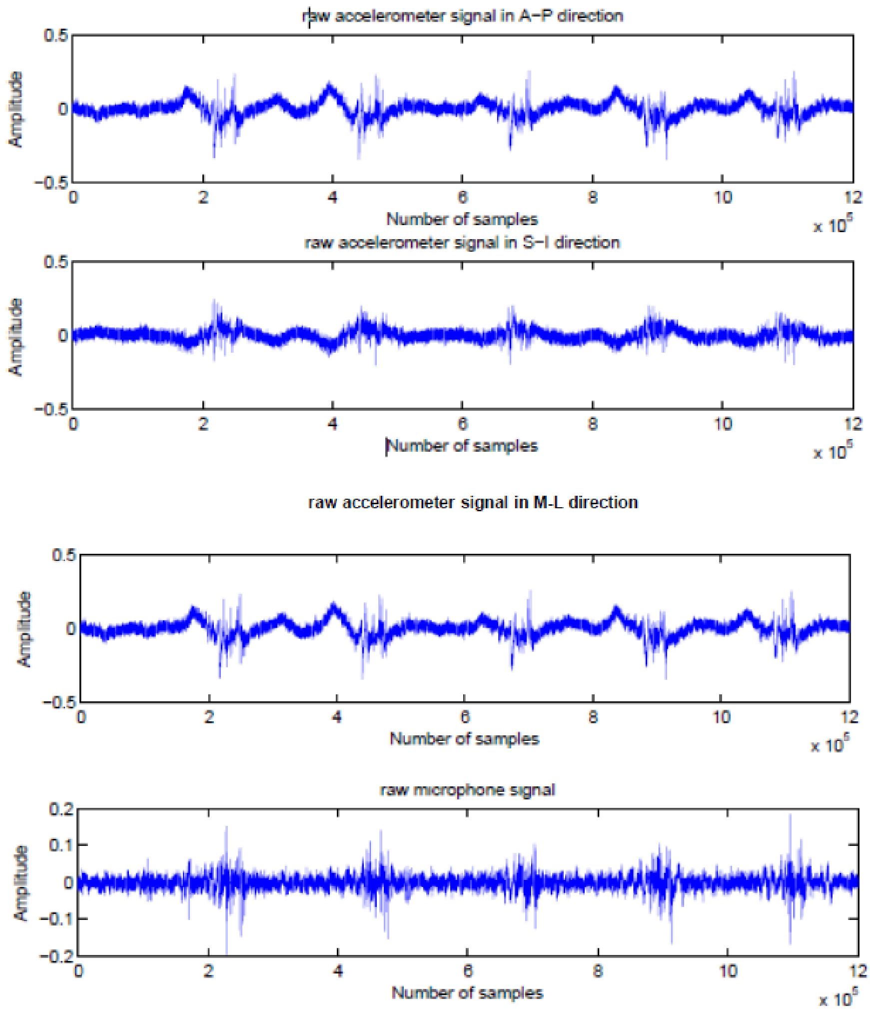

Figure 3.5: Raw swallowing accelerometry signal and swallowing sound

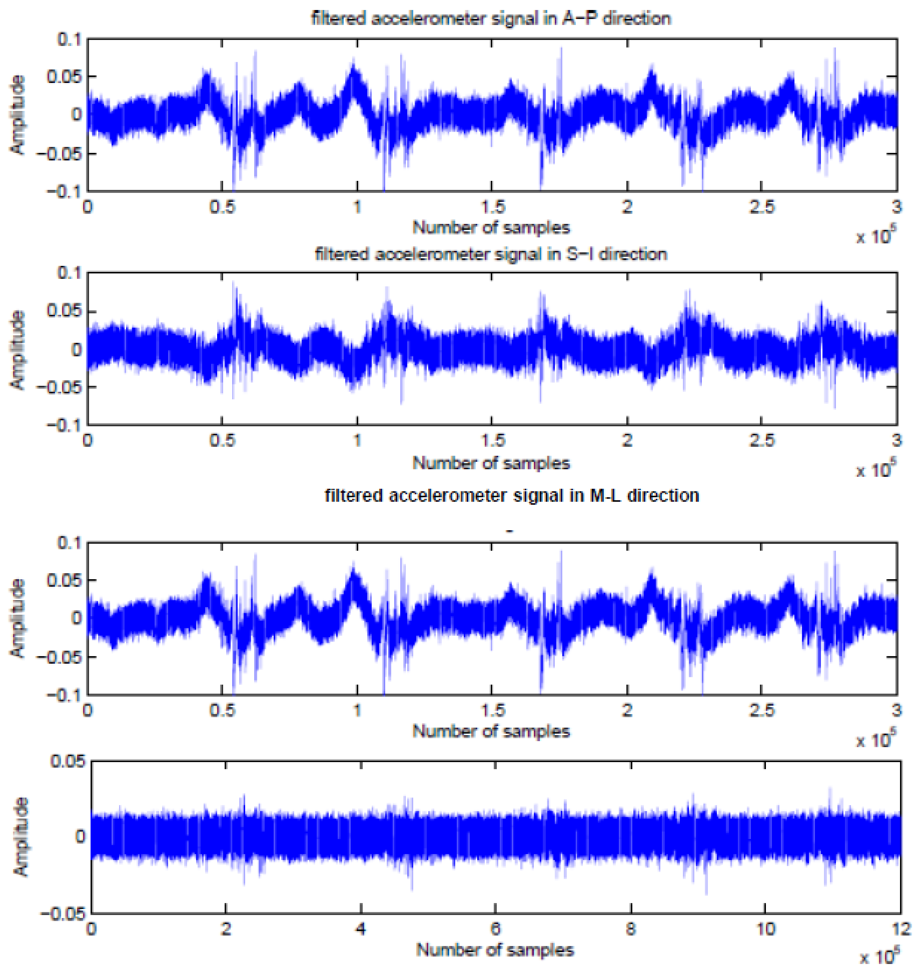

Figure 3.6: Filtered swallowing accelerometry signal and swallowing sound

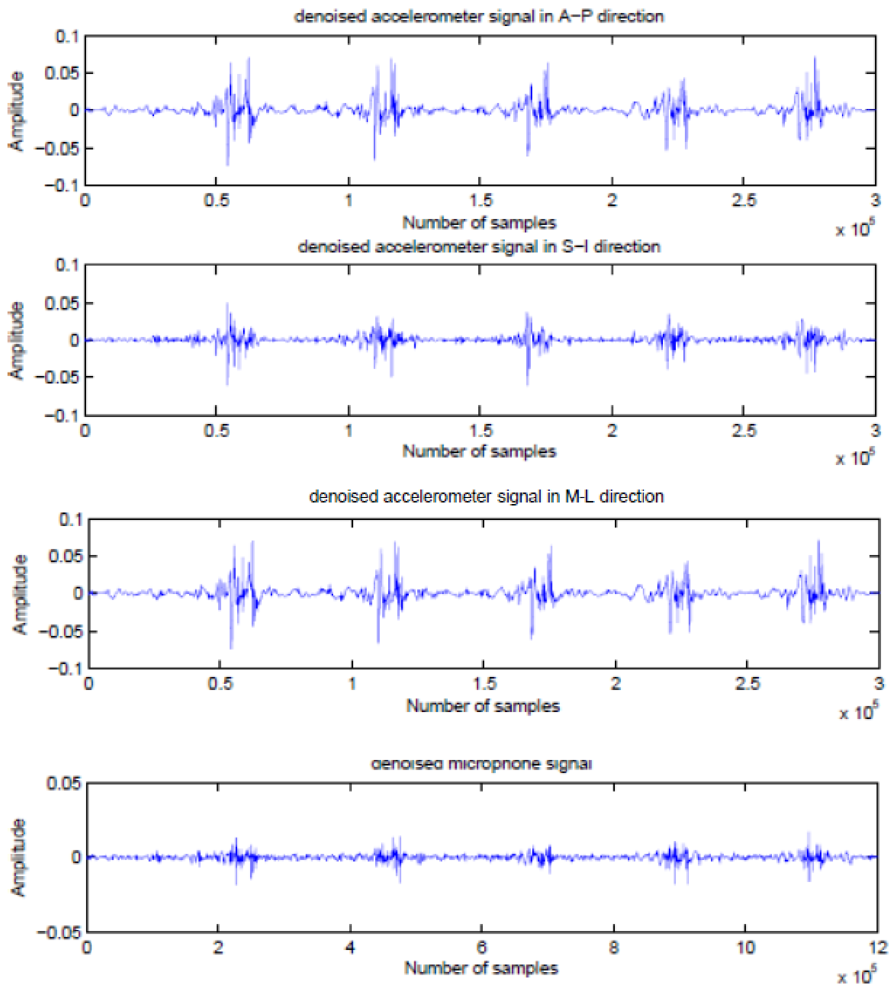

Figure 3.7: Denoised swallowing accelerometry signal and swallowing sound

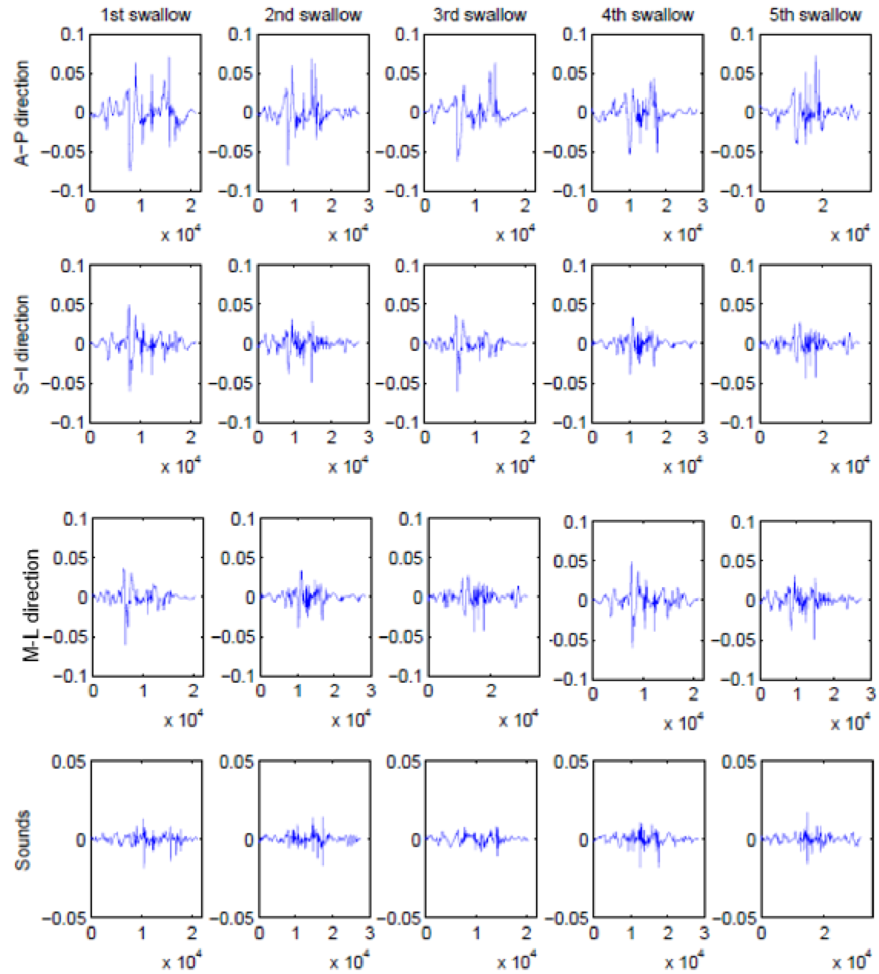

Figure 3.8: Pre-processing swallowing accelerometry signal and swallowing sound

3.3 FEATURE EXTRACTION

Nine features were extracted from the tri-axis swallowing accelerometry and swallowing sound signals to provide key statistical information about the relationship between cervical auscultation signals and the vertical and horizontal hyolaryngeal displacement during swallowing. Features include standard deviation, skewness, kurtosis for time domain analysis, Lempel-Zv complexity (LZC), entropy rate for information-theoretical analysis, peak frequency, spectral centroid, bandwidth for frequency domain analysis and wavelet entropy for time-frequency domain analysis. Besides, these features have been widely used and proved to be efficient in previous related studies [27, 71]. The computational details for these features are described in the following subsections. It should be noted that all of the following features were calculated independently for all four signals (AP vibrations, SI vibrations, ML vibrations and sound)

3.3.1 Time domain features

Time domain features provide us some general information about the shape of the signals. Considering a signal $X = \{x_1, x_2, ...x_n\}$, the following features are calculated:

- **Standard deviation** reflects the fluctuations of signal around its mean value and it is calculated using the following formula:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu_x)^2} \tag{3.1}$$

where the μ_x denotes the mean of the signal.

- **Skewness** describes the asymmetry of an amplitude distribution. Negative and positive skewness indicates the left/right side of the signal distribution has a longer and fatter tail than the other side. This feature can be computed as follows:

$$\xi_x = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)^3}{\left\{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)^2\right\}^{\frac{3}{2}}} \tag{3.2}$$

- **Kurtosis** qualifies how peaked or flat a distribution is. A high kurtosis value tends to have a distribution with a sharp, narrow peak, declines rather rapidly, and has a heavy tail, while a low kurtosis value signifies a distribution with a flattened peak and has thin tails [72]. This feature is computed as:

$$\gamma_x = \frac{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)^4}{\left\{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu_x)^2\right\}^{2}} \tag{3.3}$$

3.3.2 Information-theoretic features

Information-Theoretic domain features show the existence and absence of repeating patterns in a signal.

- **Lempel-Ziv complexity(LZC)** evaluates the predictability of finite sequences. It measures complexity through an estimated number of distinct patterns obtained by parsing a symbolic sequence [73]. Therefore, a biomedical signal must firstly be converted into a binary sequence. For this research, the signal is converted to 100 symbols using 99 equally spaced thresholds, then decomposed into k unique blocks. The LZC is defined as:

$$LZC = \frac{k \log_{100} n}{n} \tag{3.4}$$

where n is the pattern length.

- **Entropy rate** qualifies the extent of regularity in a signal distribution. Zero entropy rate means the repetition of the same pattern while one shows its aperiodic dynamics. It can be calculated through the following steps. First, the signal should be normalized to zero mean and unit variance, then quantized to 10 equally spaced levels. After quantization, these 10 levels are ranged from minimum to maximum and labeled from 0 to 9. One sequence of the signal can be represented by the sum of consecutive quantized levels, which can be written as follows, with m_i the quantized levels and U consecutive points:

$$s_i = m_{i+U-1}.10^{U-1} + ... + m_i.10^0 \tag{3.5}$$

For a given sequence of length L, the normalized entropy rate is calculated as:

$$NER(L) = \frac{SE(L) - SE(L-1) + SE(1) * perc(L)}{SE(1)} \tag{3.6}$$

where perc is the percentage of unique entries in the given sequence L and SE is the Shannon entropy of the sequence, which can be calculated as:

$$SE(L) = \sum_{j=0}^{10^L - 1} P_L(j) ln(P_L(j)) \tag{3.7}$$

where P_L is the probability mass function of the given sequence.

Finally, entropy rate ρ is represented as:

$$\rho = 1 - min(NER(L)) \tag{3.8}$$

3.3.3 Frequency features

Frequency domain features including peak frequency, spectral centroid, and bandwidth are studied in this research.

- **Peak frequency** corresponds to the maximum power and is computed as follows:

$$f_p = arg_{f \in [0, f_{max}]} max |F_x(f)|^2 \tag{3.9}$$

- **Spectral centroid** is evaluated as:

$$\hat{f} = \frac{\int_0^{f_{max}} f |F_x(f)|^2 df}{\int_0^{f_{max}} |F_x(f)|^2 df} \tag{3.10}$$

- **Bandwidth** is defined as follows:

$$BW = \sqrt{\frac{\int_0^{f_{max}} (f - \hat{f})^2 |F_x(f)|^2 df}{\int_0^{f_{max}} |F_x(f)|^2 df}} \tag{3.11}$$

3.3.4 Time-frequency features

Time-Frequency domain features provide simultaneously descriptions of the signal in time and frequency domain.

- **Wavelet entropy** qualifies the disorderly behavior in the time-frequency domain. a tenth-order Meyer Wavelet is used in this study as it is continuous, has a known scaling function [74], and more closely resembles swallowing signals in the time domain compared to Gaussian or other common wavelet shapes [70]. The energy at the kth level is defined as

$$E_{d_k} = \| d_k \|^2 \tag{3.12}$$

where d_k is a vector containing wavelet approximation coefficients at kth level of decomposition and $\| . \|$ means the Euclidean norm. The total energy of the signal is the sum of the energy at each level. The wavelet entropy can be calculated as :

$$WE = -\frac{Er_{a_{10}}}{100} \log_2 \frac{Er_{a_{10}}}{100} - \sum_{k=1}^{10} \frac{Er_{d_k}}{100} \log_2 \frac{Er_{d_k}}{100} \tag{3.13}$$

where Er is the relative contribution of a given decomposition level to the total energy and is defined as:

$$Er_x = \frac{E_x}{E_{total}} * 100\% \tag{3.14}$$

A summary of all measures and their meanings can be found in Table 3.3.

Table 3.3: A summary of HRCA features extracted for this study

Feature and abbreviation	**Definition**
Standard deviation of signal amplitude (σ_{ML}, σ_{AP}, σ_V)	Describes the fluctuation of the signal around mean; higher values indicate a greater variation around mean value.
Skewness of signal amplitude (ξ_{ML}, ξ_{AP}, ξ_V)	Describes the asymmetry of amplitude distribution; negative skewness indicates that distribution of signal amplitudes lies predominantly on the right of the mean amplitude, positive skewness indicates the values are predominantly on the left of the mean amplitude.
Kurtosis of signal amplitude (γ_{ML}, γ_{AP}, γ_V)	Describes the how the signal is peaked or flat around its mean value
Lempel-Ziv complexity (LZC_{ML}, LZC_{AP}, LZC_V)	Measures the complexity-predictability of the signal; higher values indicate a less predictable, more complex signal, lower values indicate a more predictable less complex signal.
Entropy rate (ρ_{ML}, ρ_{AP}, ρ_V)	Quantifies the regularity of a signal when a relationship among consecutive data points is anticipated.
Peak frequency (f_{pM}, f_{pAP}, f_{pV})	The maximum spectral power.
Spectral centroid ($\hat{f}_{ML}$, $\hat{f}_{AP}$, $\hat{f}_{ML}$)	The frequency that divides the spectral power distribution into two equal parts.
Bandwidth (BW_{ML}, BW_{AP}, BW_V)	The difference between the uppermost and lowermost frequencies/range of frequencies in the signal.
Wavelet entropy (Θ_{ML}, Θ_{AP}, Θ_V)	Measures the degree of time-frequency based order-disorder of the signal; high values represent disordered behavior with significant equivalent contributions from all frequency bands (e.g. random process).

3.3.5 Statistical tests

In order to discover the association between the displacement of the hyoid bone and the HRCA signal features, we fitted a series of linear mixed models with each displacement (anterior or posterior) in 3 directions (horizontal, vertical, hypotenuse) as a response variable, and HRCA signal features, one at a time, as independent variables. SAS version 9.3 (SAS Institute, Inc, Cary, North Carolina) was used for these analyses.

4.0 RESULTS

Table 4.1 depicts the feature values for cervical auscultation recordings. Table 4.2 shows the values of the horizontal, vertical, and hypotenuse displacements of the anterior and posterior aspects of the hyoid bone normalized by the C3 length. Table 4.4 shows the relationship between HRCA features and displacement of the aspects of the hyoid bone in different directions. Positively and negatively correlated features are indicated.

The horizontal displacement of the anterior aspect of the hyoid bone is negatively correlated with skewness of the SI signal and the peak frequency of the ML signal. It is positively correlated with the peak frequency of the microphone signal, with small coefficients (-0.024, -0.004, 0.001 respectively).

The vertical displacement of the anterior aspect of the hyoid bone is negatively correlated with wavelet entropy, the Lempel-Ziv complexity of the AP signal, and the peak frequency of the ML signal. While the rise of wavelet entropy and peak frequency reflect little decrease of displacement (0.104 unit and 0.009 unit), one unit increase of Lempel-Ziv complexity reflects a 1.190 units decrease of vertical displacement. One unit of displacement refers to the length of C3.

The hypotenuse displacement of the anterior aspect of the hyoid bone is associated with several AP (skewness, wavelet entropy, Lempel-Ziv complexity), SI (skewness, Lempel-Ziv complexity, kurtosis) and ML (peak frequency) features. Among them, Lempel-Ziv complexity of the AP and SI signals are the most influential. A one unit increase of Lempel-Ziv complexity in the AP direction results in a decrease of 1.200 units of vertical displacement, whereas a one unit increase of Lempel-Ziv complexity in the SI direction results in an increase of 1.740 units of vertical displacement.

The horizontal displacement of the posterior aspect of the hyoid bone is associated with the skewness and peak frequency of the SI signal, peak frequency of the ML signal, and the standard deviation of the microphone signal. While other features have little influence on the value of displacement, the standard deviation increases one unit per every 2.880 units of displacement.

The vertical displacement of the posterior aspect of the hyoid bone is related to several features (AP: skewness, wavelet entropy, Lempel-Ziv complexity; SI: skewness, Lempel-Ziv complexity; ML: peak frequency; MIC: bandwidth). Lempel-Ziv complexity in the AP and SI directions has the most notable relationship (-2.380 units and 1.071 units respectively).

The hypotenuse displacement of the posterior aspect of the hyoid bone is associated with wavelet entropy (2.750 units) of the AP signal, Lempel-Ziv complexity (0.940 unit) of the SI signal, and standard deviation (5.041 units) of the microphone signal.

While the peak frequency of the ML signal is associated with displacements in all directions, the coefficients are small (≤ 0.130). Lempel-Ziv complexity in the AP and SI directions, and the standard deviation of the microphone signal have a robust influence on the horizontal and hypotenuse displacement of the anterior aspect of the hyoid bone and vertical displacement of the posterior aspect of the hyoid bone.

The relationship between hyoid bone displacement and clinical features of patients is shown in Table 4.3. The hypotenuse of displacement of both the anterior and posterior hyoid landmarks were significantly correlated with participant age (with p-value equals to 0.040 and 0.016 respectively) and there were no other correlations.

Table 4.1: Mean and standard deviation of considered features. AP means anterior-posterior, ML medial-lateral, SI superior-inferior, MIC microphone

Extracted features	**SI**	**ML**	**AP**	**MIC**
Time Domain Features				
Standard deviation (σ)	0.0450 ± 0.0400	0.0140 ± 0.0130	0.0240 ± 0.0250	0.0190 ± 0.0180
Skewness (ξ)	-0.317 ± 2.91	0.124 ± 3.87	0.582 ± 4.89	-0.629 ± 2.54
Kurtosis (γ)	35.5 ± 75.4	44.3 ± 150	65.2 ± 182	29.6 ± 84.7
Information-Theoretic Features				
Lempel-Ziv complexity (LZC)	0.233 ± 0.0830	0.190 ± 0.0790	0.175 ± 0.0720	0.238 ± 0.0730
Entropy rate (ρ)	0.904 ± 0.0470	0.943 ± 0.0340	0.934 ± 0.0350	0.921 ± 0.0350
Frequency Features				
Spectral centroid ($\hat{f}$)	86.2 ± 82.2	83.0 ± 171	121 ± 176	60.5 ± 151
Peak frequency (f)	20.3 ± 49.2	19.3 ± 128	19.8 ± 61.0	14.2 ± 78.5
Bandwidth (BW)	100 ± 63.4	147 ± 152	162 ± 153	96.6 ± 108
Time-Frequency Features				
Wavelet entropy (Θ)	0.969 ± 0.738	0.648 ± 0.624	0.823 ± 0.729	0.830 ± 0.679

Table 4.2: Mean and standard deviation of the vertical, horizontal, hypotenuse displacement of anterior and posterior of the hyoid bone related to C3 dimension

Displacement/length of C3		**Values**
Anterior	**horizontal**	0.761 ± 0.260
	vertical	1.08 ± 0.403
	hypotenuse	1.35 ± 0.385
Posterior	**horizontal**	0.861 ± 0.275
	vertical	1.05 ± 0.369
	hypotenuse	1.39 ± 0.358

Table 4.3: Relation between displacement of hyoid bone and clinical variables. 'ant(pos)_h(v/hp)_C3' means anterior (posterior) horizontal (vertical/hypotenuse) displacement of hyoid bone related to C3, '+'means related

Clinical variable	**ant_h_C3**	**ant_v_C3**	**ant_hp_C3**	**pos_h_C3**	**pos_v_C3**	**pos_hp_C3**
Stroke						
Sex						
Age			+			+

Table 4.4: Relation between displacement of hyoid bone and HRCA features. 'ant(pos)_h(v/hp)_C3' means anterior (posterior) horizontal (vertical/hypotenuse) displacement of hyoid bone related to C3, '+' means positively correlated, '-' means negatively correlated

	HRCA Features	**ant_h_C3**	**ant_v_C3**	**ant_hp_C3**	**pos_h_C3**	**pos_v_C3**	**pos_hp_C3**
AP	**Skewness**			-		-	
	Wavelet Entropy		-	-		-	+
	LZC		-	-		-	
AP	**Skewness**	-		-	-	-	-
	LZC			+		+	+
	Kurtosis			+			
	Peak Frequency				-		
ML	**Peak Frequency**	-	-	-	-	-	-
MIC	**Peak Frequencey**	+					
	Standard Deviation				+		+
	Bandwidth					-	
	Spectral Centroid						-

5.0 DISCUSSION

5.1 FEATURE EXTRACTION FROM CERVICAL AUSCULTATION RECORDING

One component of this study analyzed the relationship between features extracted from different axes of HRCA signals. We found that four signals (AP vibrations, SI vibrations, ML vibrations and swallowing sounds) had low standard deviations, low skewness and high kurtosis. This implies that the signals were evenly distributed around the mean value with small variation. All four signals were relatively regular and predictive with low Lempel-Ziv complexity and high entropy rates. All features had low peak frequency, large bandwidth, and spectral centroid around 88 Hz (with AP slightly higher). This suggests that the signals reflected similar levels of structure. Wavelet entropy of SI, AP, and swallowing sound were close to one, with the ML signal slightly smaller. The results from the extracted features are consistent with previous research [18, 75].

5.2 HYOID BONE DISPLACEMENT AND CERVICAL AUSCULTATION RECORDINGS

Research suggests that vertical displacement of the hyoid bone contributes to airway protection and UES opening [76, 77]. Therefore, we sought to determine whether there was a relationship between hyoid bone displacement and HRCA signal features.

The vertical displacement of both the anterior and posterior aspects of the hyoid bone were highly correlated with Lempel-Ziv complexity features, which suggests that the vertical displacement of the hyoid bone influences the complexity and predictability of the AP and SI signal. As the vertical displacement increased, the Lempel-Ziv complexity of the AP signal became smaller and the Lempel-Ziv complexity of the SI signal became larger. In other words, the AP signal became more organized in swallows with greater vertical hyoid displacement while the SI signal became more complex and less predictable. It is possible that greater hyoid vertical displacement during swallowing, which in turn produces greater superior traction forces on the UES and airway closure mechanism, generates more organized HRCA signals than reduced displacement which is often observed in patients with various forms of dysphagia. This observation may represent a significant advancement toward the use of noninvasive technology to monitor swallowing function since reduced hyoid displacement is a well-known source of impaired airway protection and UES opening. The hypotenuse displacement had the same effect on the SI and AP signals as the vertical displacement because the hypotenuse is a combination of horizontal and vertical, and therefore increases the SI signals unpredictability.

Previous research shows a correlation between HRCA swallowing sounds and UES opening [34]. The increases in horizontal and hypotenuse displacement of the posterior aspect of the hyoid bone in the current study resulted in an increase in the standard deviation of swallowing sound. This may be related to the opening of the UES and a reflection of the ability of high resolution acoustic recordings, in lieu of traditional use of stethoscopes to observe sounds, to identify key aspects of swallow physiology that the human auditory system and/or stethoscopes are not designed to observe or transmit.

Finally, we observed that the peak frequency of the ML signal appeared to be related to the displacements of the hyoid bone in all three directions. However, the coefficients were small (≤ 0.013) compared to other features. Therefore, it is not clear whether the ML signal is currently a useful reference for hyoid bone displacement.

5.3 HYOID DISPLACEMENT AND PATIENT CHARACTERISTICS

Results from this study indicated that vertical hyoid bone displacement is greater than horizontal displacement and is approximately the length of C3. This visually salient observation during diagnostic testing with VF may provide clinicians with an objective estimate of adequate hyoid displacement during the examination, and enable quicker intervention for impaired hyoid displacement.

Results revealed that horizontal displacement of the posterior aspect of the hyoid bone is greater than that of the anterior aspect, while the vertical displacements of the anterior and posterior aspects are approximately the same. This finding suggests that the anterior and posterior aspects of the hyoid bone move at different magnitudes during swallowing and reflect the rotational aspects of hyoid body displacement.

Consistent with prior research, our study showed that HRCA signals of hyoid bone displacement were not influenced by sex or stroke history [78, 79]. Our study did not find an association between hyoid bone displacement between swallows of small and larger volume boluses. This contrasts with earlier studies that found an association between greater hyoid bone displacement and larger bolus volumes [80, 81]. However, since we did not systematically evaluate contrasting pairs of known large and small bolus volumes, this result may represent the artifact of a design limitation. Early studies demonstrated a dependency between age and horizontal hyoid bone displacement [78, 80], whereas our study only revealed age effects on hypotenuse displacement. One explanation for this contrast, and a limitation of the study, is that we did not include swallows for patients younger than 48 years old. Another limitation is the inclusion of only thin and nectar-thick liquids on single swallows. Future investigations should consider various bolus volumes and viscosities, multiple swallows, and swallows from older and younger patients to explore the relationship between hyoid bone displacement and HRCA feature signals.

6.0 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSION

In this study, we analyzed the relationship between hyoid bone displacement during swallowing and features extracted from HRCA signals. Our study confirmed that hyoid bone displacement can be inferred from HRCA features. The results revealed associations between vertical displacement and the AP and SI signals complexity and predictability. The variation of the Lempel-Ziv complexity of the AP and SI signals will allow us to estimate the vertical displacement of the hyoid bone. This finding is of clinical value given the relationship between vertical hyoid bone displacement, airway protection, and UES opening. We also equated vertical hyoid displacement to an anatomic scalar (C3) and identified a strong indication that vertical hyoid displacement was roughly the same as the height of C3. During clinical VF testing, clinicians are required to identify impairments and react to them immediately with appropriate treatment interventions. This finding could accelerate the deployment of intervention by providing immediate evaluation of the efficacy of trial interventions rather than current methods relying on post-examination visual inspection of the VF data which negates deployment of treatment efficacy trials during VF.

6.2 FUTURE WORK

This study has revealed the relationship between hyoid bone movement and swallowing vibrations and sounds. However, some questions remain open and there are a number of different ways to follow up the results presented in this paper.

To begin with, we have chosen C3 instead of the conventional C2-C4 as a normalization scale, which, as mentioned above, would be able to cancel the gender effect while bringing clinical benefit during impairment identification and quick decision making of treatment interventions. Future work should aim to replicate the result in other datasets in order to verify that it is a sufficient surrogate of C2-C4. Secondly, no correlation between hyoid bone displacement and age was found in this study due to the lack of young patients. Repeating the same experiment with younger subjects would verify our result and provide more general information among all population. Moreover, monitoring and controlling the bolus volume would be an important next step to do since earlier studies have revealed an important association between it and hyoid bone movement.

Besides, future study should also focus on finding out to what extent that Lempel-Ziv complexity of AP and SI signals and hyoid bone displacement are correlated. More importantly, an automated algorithm that can map from Lempel-Ziv complexity of AP and Si signals to the vertical displacement of hyoid bone would be of great value. Last but not least, it is of great interest to explore the association between HRCA signals and other swallowing kinematic events such as laryngeal vestibular closure, upper esophageal sphincter opening, and initiation of pharyngeal swallow to improve the use of HRCA assessment of swallowing and biofeedback during dysphagia therapy.

BIBLIOGRAPHY

[1] J. A. Logemann and J. A. Logemann, "Evaluation and treatment of swallowing disorders," 1983.

[2] A. J. Miller, "The neurobiology of swallowing and dysphagia," *Developmental Disabilities Research Reviews*, vol. 14, no. 2, pp. 77–86, 2008.

[3] J. L. Coyle and J. Robbins, "Assessment and behavioral management of oropharyngeal dysphagia." *Current Opinion in Otolaryngology and Head and Neck Surgery*, vol. 5, no. 3, pp. 147–152, 1997.

[4] J. A. Logemann, "The evaluation and treatment of swallowing disorders." *Current Opinion in Otolaryngology and Head and Neck Surgery*, vol. 6, no. 6, pp. 395–400, 1998.

[5] J. Robbins, S. Langmore, J. A. Hind, and M. Erlichman, "Dysphagia research in the 21st century and beyond: proceedings from dysphagia experts meeting, august 21, 2001," *Journal of Rehabilitation Research and Development*, vol. 39, no. 4, p. 543, 2002.

[6] P. Clavé, R. Terré, M. De Kraa, and M. Serra, "Approaching oropharyngeal dysphagia," *Revista Espanola de Enfermedades Digestivas*, vol. 96, no. 2, pp. 119–131, 2004.

[7] P. Leslie, M. J. Drinnan, I. Zammit-Maempel, J. L. Coyle, G. A. Ford, and J. A. Wilson, "Cervical auscultation synchronized with images from endoscopy swallow evaluations," *Dysphagia*, vol. 22, no. 4, pp. 290–298, 2007.

[8] D. Smithard, P. O'neill, C. Park, J. Morris, R. Wyatt, R. England, and D. Martin, "Complications and outcome after acute stroke," *Stroke*, vol. 27, no. 7, pp. 1200–1204, 1996.

[9] L. Trawitzki, R. Dantas, F. Mello-Filho, and W. Marques Jr, "Masticatory muscle function three years after surgical correction of class iii dentofacial deformity," *International Journal of Oral and Maxillofacial Surgery*, vol. 39, no. 9, pp. 853–856, 2010.

[10] I. J. Cook, "Diagnostic evaluation of dysphagia," *Nature Clinical Practice Gastroenterology and Hepatology*, vol. 5, no. 7, pp. 393–403, 2008.

[11] M. B. Nierengarten, "Evaluating dysphagia: current approaches," *Oncology Times*, vol. 31, no. 14, pp. 29–30, 2009.

[12] B. A. Mathers-Schmidt and M. Kurlinski, "Dysphagia evaluation practices: inconsistencies in clinical assessment and instrumental examination decision-making," *Dysphagia*, vol. 18, no. 2, pp. 114–125, 2003.

[13] R. D. Wilson and E. C. Howe, "A cost-effectiveness analysis of screening methods for dysphagia after stroke," *PM and R*, vol. 4, no. 4, pp. 273–282, 2012.

[14] P. Leslie, M. J. Drinnan, P. Finn, G. A. Ford, and J. A. Wilson, "Reliability and validity of cervical auscultation: a controlled comparison using video fluoroscopy," *Dysphagia*, vol. 19, no. 4, pp. 231–240, 2004.

[15] C. Steele, C. Allen, J. Barker, P. Buen, R. French, A. Fedorak, S. Day, J. Lapointe, L. Lewis, C. MacKnight *et al.*, "Dysphagia service delivery by speech-language pathologists in canada: results of a national survey," *Canadian Journal of Speech-Language Pathology and Audiology*, vol. 31, no. 4, pp. 166–177, 2007.

[16] H. S. Bonilha, K. Humphries, J. Blair, E. G. Hill, K. McGrattan, B. Carnes, W. Huda, and B. Martin-Harris, "Radiation exposure time during mbss: influence of swallowing impairment severity, medical diagnosis, clinician experience, and standardized protocol use," *Dysphagia*, vol. 28, no. 1, pp. 77–85, 2013.

[17] I. Zammit-Maempel, C.-L. Chapple, and P. Leslie, "Radiation dose in videofluoroscopic swallow studies," *Dysphagia*, vol. 22, no. 1, pp. 13–15, 2007.

[18] F. Movahedi, A. Kurosu, J. L. Coyle, S. Perera, and E. Sejdić, "Anatomical directional dissimilarities in tri-axial swallowing accelerometry signals," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 5, pp. 447–458, 2017.

[19] S. B. Leder and D. M. Suiter, "An epidemiologic study on aging and dysphagia in the acute care hospitalized population: 2000–2007," *Gerontology*, vol. 55, no. 6, pp. 714–718, 2009.

[20] S. L. Sherman, E. C. Lin, N. N. Verma, R. C. Mather, J. M. Gregory, J. Dishkin, D. P. Harwood, V. M. Wang, E. F. Shewman, B. J. Cole *et al.*, "Biomechanical analysis of the pectoralis major tendon and comparison of techniques for tendo-osseous repair," *The American Journal of Sports Medicine*, vol. 40, no. 8, pp. 1887–1894, 2012.

[21] J. E. Aviv, S. T. Kaplan, J. E. Thomson, J. Spitzer, B. Diamond, and L. G. Close, "The safety of flexible endoscopic evaluation of swallowing with sensory testing (feesst): an analysis of 500 consecutive evaluations," *Dysphagia*, vol. 15, no. 1, pp. 39–44, 2000.

[22] M. R. Spieker, "Evaluating dysphagia," *American Family Physician*, vol. 61, no. 12, pp. 3639–3648, 2000.

[23] J. M. Dudik, I. Jestrović, B. Luan, J. L. Coyle, and E. Sejdić, "Characteristics of dry chin-tuck swallowing vibrations and sounds," *IEEE Transactions on Biomedical Engineering*, vol. 62, no. 10, pp. 2456–2464, 2015.

[24] N. Reddy, E. Canilang, J. Casterline, M. Rane, A. Joshi, R. Thomas, and R. Candadai, "Noninvasive acceleration measurements to characterize the pharyngeal phase of swallowing," *Journal of Biomedical Engineering*, vol. 13, no. 5, pp. 379–383, 1991.

[25] N. P. Reddy, A. Katakam, V. Gupta, R. Unnikrishnan, J. Narayanan, and E. P. Canilang, "Measurements of acceleration during videofluorographic evaluation of dysphagic patients," *Medical Engineering and Physics*, vol. 22, no. 6, pp. 405–412, 2000.

[26] J. Lee, S. Blain, M. Casas, D. Kenny, G. Berall, and T. Chau, "A radial basis classifier for the automatic detection of aspiration in children with dysphagia," *Journal of NeuroEngineering and Rehabilitation*, vol. 3, no. 1, p. 14, 2006.

[27] J. Lee, C. Steele, and T. Chau, "Time and time–frequency characterization of dual-axis swallowing accelerometry signals," *Physiological Measurement*, vol. 29, no. 9, p. 1105, 2008.

[28] E. Sejdić, C. M. Steele, and T. Chau, "The effects of head movement on dual-axis cervical accelerometry signals," *BMC Research Notes*, vol. 3, no. 1, p. 269, 2010.

[29] P. Clavé and R. Shaker, "Dysphagia: current reality and scope of the problem," *Nature Reviews Gastroenterology and Hepatology*, vol. 12, no. 5, p. 259, 2015.

[30] O. Ekberg, S. Hamdy, V. Woisard, A. Wuttge-Hannig, and P. Ortega, "Social and psychological burden of dysphagia: its impact on diagnosis and treatment," *Dysphagia*, vol. 17, no. 2, pp. 139–146, 2002.

[31] M. Serra-Prat, G. Hinojosa, D. López, M. Juan, E. Fabré, D. S. Voss, M. Calvo, V. Marta, L. Ribó, E. Palomera *et al.*, "Prevalence of oropharyngeal dysphagia and impaired safety and efficacy of swallow in independently living older persons," *Journal of the American Geriatrics Society*, vol. 59, no. 1, pp. 186–187, 2011.

[32] K. W. Altman, G.-P. Yu, and S. D. Schaefer, "Consequence of dysphagia in the hospitalized patient: impact on prognosis and hospital resources," *Archives of Otolaryngology–Head and Neck Surgery*, vol. 136, no. 8, pp. 784–789, 2010.

[33] C. L. Lazarus, "Effects of chemoradiotherapy on voice and swallowing," *Current Opinion in Otolaryngology and Head and Neck Surgery*, vol. 17, no. 3, p. 172, 2009.

[34] A.Kurosu, J.Dudik, E. Sejdic, and J. L. Coyle, "Detection of swallowing physiological events from acoustic high resolution cervical auscultation signals in patients with stroke," *Under Review.*

[35] D. Zoratto, T. Chau, and C. Steele, "Hyolaryngeal excursion as the physiological source of swallowing accelerometry signals," *Physiological Measurement*, vol. 31, no. 6, p. 843, 2010.

[36] A. Devices, "Adxl322: small and thin 2g accelerometer data sheet," *Norwood, MA: Analog Devices*, 2005.

[37] J. M. Dudik, I. Jestrović, B. Luan, J. L. Coyle, and E. Sejdić, "A comparative analysis of swallowing accelerometry and sounds during saliva swallows," *Biomedical Engineering Online*, vol. 14, no. 1, p. 3, 2015.

[38] K. A. Norman, S. M. Polyn, G. J. Detre, and J. V. Haxby, "Beyond mind-reading: multi-voxel pattern analysis of fmri data," *Trends in Cognitive Sciences*, vol. 10, no. 9, pp. 424–430, 2006.

[39] J. L. Hiatt and L. P. Gartner, *Textbook of head and neck anatomy.* LWW, 2009.

[40] C. V. Hughes, B. J. Baum, P. C. Fox, Y. Marmary, C.-K. Yeh, and B. C. Sonies, "Oral-pharyngeal dysphagia: a common sequela of salivary gland dysfunction," *Dysphagia*, vol. 1, no. 4, pp. 173–177, 1987.

[41] W. J. Dodds, "The physiology of swallowing," *Dysphagia*, vol. 3, no. 4, pp. 171–178, 1989.

[42] J. Brush, "Recognizing dysphagia at meals," *iAdvance Senior Care*, 2007.

[43] G. Zaninotto, T. R. DeMeester, W. Schwizer, K.-E. Johansson, and S.-C. Cheng, "The lower esophageal sphincter in health and disease," *The American Journal of Surgery*, vol. 155, no. 1, pp. 104–111, 1988.

[44] P. J. Kahrilas *et al.*, "Gastroesophageal reflux disease," *JAMA-Journal of the American Medical Association-US Edition*, vol. 276, no. 12, pp. 983–988, 1996.

[45] S. M. Shaw and R. Martino, "The normal swallow: muscular and neurophysiological control," *Otolaryngologic Clinics of North America*, vol. 46, no. 6, pp. 937–956, 2013.

[46] E. Sforza, W. Bacon, T. Weiss, A. Thibault, C. Petiau, and J. Krieger, "Upper airway collapsibility and cephalometric variables in patients with obstructive sleep apnea," *American Journal of Respiratory and Critical Care Medicine*, vol. 161, no. 2, pp. 347–352, 2000.

[47] R. Warwick, P. L. Williams, and H. Gray, "Gray's anatomy," *Longman*, 1973.

[48] W. J. Dodds, E. T. Stewart, and J. A. Logemann, "Physiology and radiology of the normal oral and pharyngeal phases of swallowing," *AJR. American Journal of Roentgenology*, vol. 154, no. 5, pp. 953–963, 1990.

[49] O. Ekberg, "The normal movements of the hyoid bone during swallow," *Investigative radiology*, vol. 21, no. 5, pp. 408–410, 1986.

[50] J.-H. Leigh, B.-M. Oh, H. G. Seo, G. J. Lee, Y. Min, K. Kim, J. C. Lee, and T. R. Han, "Influence of the chin-down and chin-tuck maneuver on the swallowing kinematics of healthy adults," *Dysphagia*, vol. 30, no. 1, pp. 89–98, 2015.

[51] W. G. Pearson, S. E. Langmore, and A. C. Zumwalt, "Evaluating the structural properties of suprahyoid muscles and their potential for moving the hyoid," *Dysphagia*, vol. 26, no. 4, pp. 345–351, 2011.

[52] D. O. Castell and M. W. Donner, "Evaluation of dysphagia: a careful history is crucial," *Dysphagia*, vol. 2, no. 2, pp. 65–71, 1987.

[53] J. M. Dudik, "Cervical auscultation for the identification of swallowing difficulties," Ph.D. dissertation, University of Pittsburgh, 2015.

[54] R. Cedrine, Z. Zhenwei, K. Yassin, R. Mona, K. Atsuko, C. James L, P. Subashan, and S. Ervin, "High resolution cervical auscultation signal features reflect vertical and horizontal displacement of the hyoid bone during swallowing," *Under Review*.

[55] J. A. Logemann, P. J. Kahrilas, J. Cheng, B. Pauloski, P. J. Gibbons, A. W. Rademaker, and S. Lin, "Closure mechanisms of laryngeal vestibule during swallow," *American Journal of Physiology-Gastrointestinal and Liver Physiology*, vol. 262, no. 2, pp. G338–G344, 1992.

[56] S. K. Daniels, M. F. Schroeder, P. C. DeGeorge, D. M. Corey, and J. C. Rosenbek, "Effects of verbal cue on bolus flow during swallowing," *American Journal of Speech-Language Pathology*, vol. 16, no. 2, pp. 140–147, 2007.

[57] J. C. Rosenbek, J. A. Robbins, E. B. Roecker, J. L. Coyle, and J. L. Wood, "A penetration-aspiration scale," *Dysphagia*, vol. 11, no. 2, pp. 93–98, 1996.

[58] H. Grundy and H. Grundy, "Proceedings: The mechanism of" adrenaline reversal" in the anaesthetized cat and rabbit," *British Journal of Pharmacology*, vol. 55, no. 2, p. 282P, 1975.

[59] K. Murata, S. Ishikawa, and T. Sugioka, "Investigation of dysphagia symptoms and their association with subjective symptoms in inhabitants of an island," *Journal of General and Family Medicine*, vol. 14, no. 1, pp. 32–39, 2013.

[60] I. Jestrović, J. M. Dudik, B. Luan, J. L. Coyle, and E. Sejdić, "The effects of increased fluid viscosity on swallowing sounds in healthy adults," *Biomedical Engineering Online*, vol. 12, no. 1, p. 90, 2013.

[61] L. H. Riley III, R. L. Skolasky, T. J. Albert, A. R. Vaccaro, and J. G. Heller, "Dysphagia after anterior cervical decompression and fusion: prevalence and risk factors from a longitudinal cohort study," *Spine*, vol. 30, no. 22, pp. 2564–2569, 2005.

[62] B. D. Kulbersh, E. L. Rosenthal, B. M. McGrew, R. D. Duncan, N. L. McColloch, W. R. Carroll, and J. S. Magnuson, "Pretreatment, preoperative swallowing exercises may improve dysphagia quality of life," *The Laryngoscope*, vol. 116, no. 6, pp. 883–886, 2006.

[63] I. J. Cook and P. J. Kahrilas, "Aga technical review on management of oropharyngeal dysphagia," *Gastroenterology*, vol. 116, no. 2, pp. 455–478, 1999.

[64] S. L. Hamlet, R. L. Patterson, S. M. Fleming, and L. A. Jones, "Sounds of swallowing following total laryngectomy," *Dysphagia*, vol. 7, no. 3, pp. 160–165, 1992.

[65] J.-H. Leigh, W. H. Lee, H. G. Seo, G. J. Lee, Y. Min, K. Kim, J. C. Lee, and T. R. Han, "Influence of the chin-down and chin-tuck maneuver on the swallowing kinematics of healthy adults," in *Dysphagia*, 2014.

[66] M. V. Welch, J. A. Logemann, A. W. Rademaker, and P. J. Kahrilas, "Changes in pharyngeal dimensions effected by chin tuck," *Archives of Physical Medicine and Rehabilitation*, vol. 74, no. 2, pp. 178–181, 1993.

[67] J. M. Dudik, J. L. Coyle, and E. Sejdić, "Dysphagia screening: contributions of cervical auscultation signals and modern signal-processing techniques," *IEEE Transactions on Human-Machine Systems*, vol. 45, no. 4, pp. 465–477, 2015.

[68] E. Sejdić, V. Komisar, C. M. Steele, and T. Chau, "Baseline characteristics of dual-axis cervical accelerometry signals," *Annals of Biomedical Engineering*, vol. 38, no. 3, pp. 1048–1059, 2010.

[69] E. Sejdić, C. M. Steele, and T. Chau, "A method for removal of low frequency components associated with head movements from dual-axis swallowing accelerometry signals," *PLoS One*, vol. 7, no. 3, p. e33464, 2012.

[70] ——, "A procedure for denoising dual-axis swallowing accelerometry signals," *Physiological Measurement*, vol. 31, no. 1, p. N1, 2009.

[71] E. Sejdic, K. A. Lowry, J. Bellanca, M. S. Redfern, and J. S. Brach, "A comprehensive assessment of gait accelerometry signals in time, frequency and time-frequency domains," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 3, pp. 603–612, 2014.

[72] L. T. DeCarlo, "On the meaning and use of kurtosis," *Psychological Methods*, vol. 2, no. 3, p. 292, 1997.

[73] J. Hu, J. Gao, and J. C. Principe, "Analysis of biomedical signals by the lempel-ziv complexity: the effect of finite data size," *IEEE Transactions on Biomedical Engineering*, vol. 53, no. 12, pp. 2606–2609, 2006.

[74] A. Cohen and J. Kovacevic, "Wavelets: The mathematical background," *Proceedings of the IEEE*, vol. 84, no. 4, pp. 514–522, 1996.

[75] E. Zahnd, F. Movahedi, J. L. Coyle, E. Sejdić, and P. G. Menon, "Correlating tri-accelerometer swallowing vibrations and hyoid bone movement in patients with dysphagia," in *ASME 2016 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers, 2016, pp. V003T04A083–V003T04A083.

[76] I. J. Cook, W. J. Dodds, R. O. Dantas, M. K. Kern, B. T. Massey, R. Shaker, and W. J. Hogan, "Timing of videofluoroscopic, manometric events, and bolus transit during the oral and pharyngeal phases of swallowing," *Dysphagia*, vol. 4, no. 1, pp. 8–15, 1989.

[77] P. Jacob, P. Kahrilas, J. Logemann, V. Shah, and T. Ha, "Upper esophageal sphincter opening and modulation during swallowing," *Gastroenterology*, vol. 97, no. 6, pp. 1469–1478, 1989.

[78] S. M. Molfenter and C. M. Steele, "Use of an anatomical scalar to control for sex-based size differences in measures of hyoid excursion during swallowing," *Journal of Speech, Language, and Hearing Research*, vol. 57, no. 3, pp. 768–778, 2014.

[79] Y. Kim and G. H. McCullough, "Maximal hyoid excursion in poststroke patients," *Dysphagia*, vol. 25, no. 1, pp. 20–25, 2010.

[80] ——, "Maximum hyoid displacement in normal swallowing," *Dysphagia*, vol. 23, no. 3, pp. 274–279, 2008.

[81] R. Ishida, J. B. Palmer, and K. M. Hiiemae, "Hyoid motion during swallowing: factors affecting forward and upward displacement," *Dysphagia*, vol. 17, no. 4, pp. 262–272, 2002.