HIGH RESOLUTION CERVICAL AUSCULTATION SIGNAL FEATURES REFLECT VERTICAL AND HORIZONTAL DISPLACEMENT OF THE HYOID BONE DURING SWALLOWING

by

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Millions of people around the globe suffer from dysphagia (swallowing difficulties) that can lead to malnutrition, aspiration, pneumonia and death. Videofluoroscopy is considered to be the gold standard for assessing and diagnosing dysphagia. In recent years, swallowing cervical auscultation has been suggested as a noninvasive screening method. However, many questions remain open about the physiological source of swallowing auscultation signals. Therefore, the aim of this study is to compare the maximum displacement of the hyoid bone extracted from the videofluoroscopy images during 31 swallows to the signal features extracted from the cervical auscultation recordings captured with a tri-axial accelerometer and a microphone. For cervical auscultation recordings, we have considered features in the time, frequency, and time-frequency domains. From the videofluoroscopy images, we measured the maximal vertical and horizontal displacement of the hyoid bone normalized to an anatomic reference across subjects. Our results have produced several interesting observations. First, the vertical displacement of the anterior part of hyoid bone is related to the entropy rate of the superior-inferior swallowing vibrations and to the kurtosis of the swallowing sounds. Second, the vertical displacement of the posterior part of the hyoid bone is related to the bandwidth of the medial-lateral axis of the swallowing vibrations. Third, the horizontal displacement of the posterior part of the hyoid bone is related the spectral centroid of the superior-inferior swallowing vibrations. Fourth, the horizontal displacement of the anterior part of the hyoid bone is related to the peak frequency of the medial-lateral swallowing vibrations. Fifth, a patient's sex is not associated with either vertical or horizontal displacements of the hyoid bone. Sixth, the airway protection scores were associated with the vertical displacement of the posterior part of the hyoid bone, and the command swallow characteristic also affects the maximal horizontal displacement of the posterior part of the hyoid bone. Additional associations between the patients' characteristics and auscultations signals were also observed. High resolution cervical auscultation may offer a noninvasive alternative to the screening of dysphagia and offer additional diagnostic information.

Keywords: Cervical auscultation features, dysphagia, hyoid displacement, signal processing, swallowing.

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PREFACE

First, I would like to sincerely thank my advisor for his education, his patience, and his understanding during my master studies. Second, I would like to thank our collaborators in this study for their help, knowledge, and patience. Third, I am also deeply grateful to my colleagues who provided me help, assistance, inspiration, encouragement, and support. Fourth, I wish to thank my family for their wisdom, for believing in me, supporting me, and guiding me even when I failed. Lastly, I want to express great appreciations to all my teachers of my academic life who taught me and stimulated my curiosity and to my committee members for their time and interest.

1.0 INTRODUCTION

1.1 SWALLOWING AND SWALLOWING DIFFICULTIES

Swallowing is a vital biomechanical process that enables feeding and hydration of the human body [1]. It is a complex mechanism that involves the synchronized movement of 20 muscles [2]. When food enters the mouth, it is masticated and transformed into a bolus through the action of the teeth and saliva. The bolus is then propelled into the pharynx. A biological sensor detects the bolus and urges the brain to swallow, making the vocal folds close. The epiglottis then covers the larynx in order to make the bolus pass into the esophagus, that in turn leads to the digestive system. Thanks to the epiglottis, the bolus cannot move into the larynx which would lead to the lungs [1], [2], [3], [4], [5]. Figure 1 shows the mechanism operable in healthy swallowing.

Since swallowing is a complicated process that involves muscles, synchronized movements, and neural control, it is sometimes wrongly executed [2]. Dysphagia most often occurs in older individuals having experienced a heart attack, muscular disease, or neurological condition such as a stroke [7]. Swallowing difficulties are broadly named dysphagia coming from the Greek terms "dys", meaning a "disorder" or "illness", and "phagos", meaning "eat" or "swallow" [7]. There are two types of dysphagia: oropharyngeal dysphagia (related to the mouth and the throat) and esophageal dysphagia (related to the esophagus) [2].

The symptoms of dysphagia are choking, pain during swallowing, aspiration, malnutrition, and pneumonia. In the United States, 10 million people each year are diagnosed with dysphagia [8], [9]. Fifty percent of older adults and people with neurological conditions suffer from oropharyngeal dysphagia [7], and as many as 62% of people with dysphagia die in the year following onset of stroke or a similar condition [10].

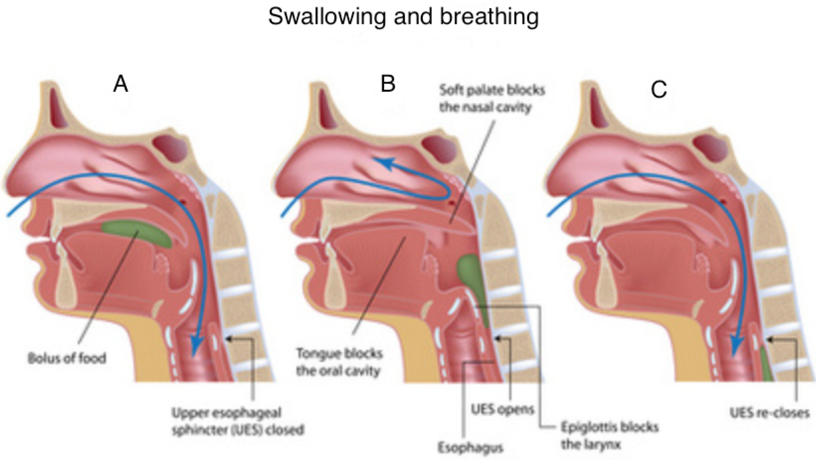

Figure 1: Healthy swallow mechanism [6].

1.2 DIFFERENT WAYS TO DIAGNOSE DYSPHAGIA

The method of diagnosis for dysphagia can take many forms depending on the resources available and the patient's symptomatology. Both noninstrumental, clinical examinations, and sophisticated imaging studies using endoscopic or x-ray (videofluoroscopy or VF) instrumentation are commonplace, with the latter methods serving as the gold standards for identification of oropharyngeal kinematic impairments, airway protection deficits, and disordered transfer of swallowed material to the digestive system [2], [11]. The effectiveness of clinical evaluation is limited by the reliance on real-time observation. The examiner is blinded to any activity occurring once the mouth is closed, which is the case during the majority of swallowing activity [12]. Videofluoroscopy (VF) records real-time radiographic images of a swallow at an optimal temporal resolution to enable human judgment of kinematic events in relation to one another. Timing and completeness of airway closure, and consequences of impaired kinematics are among important observations that can be made with VF. VF is the gold standard diagnostic method, but it is not always available at the time that dysphagia is first suspected, is not feasible in some settings, and is too expensive to use as a screening method [12], [13], [14]. Moreover, VF data needs to be analyzed by a clinical expert [15] and involves the use of invasive ionizing radiation.

1.3 MOTIVATION FOR THIS RESEARCH

1.3.1 Prevalence of oropharyngeal dysphagia

1.3.1.1 Older adults 16 million older Europeans and 10 million older Japanese adults suffer from oropharyngea dysphagia [7], [16]. Overall, 30%-40% of people who are older than 65 years are affected by oropharyngeal dysphagia [17]. Seventeen percent of people between the age of 70 and 79 and 33% of people above the age of 80, who live independently in their own house, have dysphagia [18]. 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], [20]. Furthermore, 29% of people in these populations have to be tube fed [19], [20]. Finally, 60% and 80% of older people who suffer from Parkinson's and Alzheimer's, respectively, are affected by oropharyngeal dysphagia [7], [8].

1.3.1.2 Patients with neurological conditions People who suffer from neurological conditions frequently experience difficulty with swallowing. Up to 70% of patients with severe acute traumatic brain injuries and up to 50% of patients with severe chronic traumatic brain injuries are diagnosed with dysphagia. Many stroke patients also have oropharyngeal dysphagia, with 64-78% during the acute phase and 40-81% during the chronic phase [7], [21], [22]. Additionally, patients with Parkinson's disease are 52-82% more likely to have dysphagia [21], and 30-40% of patients who suffer from multiple sclerosis also have dysphagia [7], [22].

1.3.1.3 Patients with head and neck issues It is common that oropharyngeal dysphagia appears as a result of chemotherapy or surgery in the larynx area. Patients who have experienced radio chemotherapy, because of altered anatomy, mass effects, or cancer, are more than 44% more likely to be diagnosed with dysphagia after previous treatment for their illness [7], [23].

1.3.2 Current assessment issues

Dysphagia is a severe condition which has many causes and, if left untreated, can lead to death [7]. The majority of ways to assess dysphagia use X-rays and are therefore invasive and dangerous to the patient's health [21]. Examinations are expensive and not all hospitals can afford the equipment necessary for diagnosis patients [14], [24]. Moreover, some examinations are always reliable and require a specialist, which further increases the price of diagnosis [8].

1.3.3 Assessment methods

Less invasive methods to assess specific aspects of dysphagia have been investigated in previous studies, such as ultrasonography to assess soft tissue function [25], manometry to assess pressure generation and propagation from the oral cavity through the esophagus [26], [27], electromyography to assess the timing and sequence of muscle activation [28], and cervical auscultation (CA), which observes sounds emanating form the pharyngeal mechanism to infer swallow physiology [15], [29], [30], [31], [32], [33], [34], [35], [36]. Traditional CA of swallowing functions are performed using a stethoscope and, although an examiner can "hear" a swallow, it has repeatedly been shown to provide inconsistent information leading to subjective interpretations by the examiner. This subjectivity is due to variations in instrument design (stethoscopes are not designed to assess pharyngeal sounds) and limitations of the human auditory system. High-resolution cervical auscultation (HRCA), based on recordings of swallowing vibrations and sounds using accelerometers and microphones, has been proposed and investigated as an affordable, noninvasive, and automated system. High-resolution cervical auscultation can be used to screen 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. More recently, 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.

A previous study suggested that swallowing kinematics, in particular hyoid bone movement, could be a physiological component of swallowing producing some HRCA signal features [37]. It has been found that the weak accelerometry signals recorded from a dual-axial accelerometer are linked to a small hyoid bone excursion [37]. Other studies have explored the possibility that the

HRCA acoustic time features are associated with the laryngeal vestibule closure and re-opening, with the opening of the upper esophageal sphincter (UES), and with contact of the base of the tongue to the posterior pharyngeal wall during bolus propulsion [38]. These studies have also found associations between HRCA signals and the position of the hyoid bone at the beginning and end of a swallow, the maximal excursion of the hyoid bone, and that both the closure and opening of the laryngeal vestibule and UES opening are correlated to acoustic swallowing sounds [38]. Other studies have shown that HRCA signal features are affected by the head position commonly used as dysphagia compensations, especially the chin-tuck maneuver [36].

However, the question still remains open regarding which physical events during swallowing cause the swallowing vibrations and sounds. We wondered if the vertical and horizontal hyolaryngeal displacement would affect the swallowing sounds and swallowing vibrations measured in three directions: superior-inferior, anterior-posterior, and medial-lateral. Therefore, we sought to compare HRCA signal features in the time, frequency, and time-frequency domains to the maximal vertical and horizontal hyoid bone displacement during swallowing as measured with VF. We hypothesized that both acoustic and tri-axial accelerometer HRCA signals would be strongly associated with vertical and horizontal displacement of both the anterior and posterior tips of the body of the hyoid bone. We further hypothesized that, as in prior studies, our methods would confirm that other swallow and participant factors (e.g. sex, PA score, command or not, age) would be associated with hyoid bone maximal displacement, and associated HRCA signals.

This research will study a device that records the vibrations resulting from movement of the hyopharyngeal mechanism. The hyoid bone is an important structure that helps to close the airway and propel the bolus into the esophagus during swallowing [2], [8], [15], [35], [36]. Over time, a tri-axial accelerometer may be able to diagnose abnormal swallows and suggest possible ways to treat them. The device of swallowing accelerometry has three axes: The Anterior-Posterior axis (AP), the Superior-Inferior axis (SI), and the Medial-Lateral axis (ML) [15]. No studies, to our knowledge, have tried to find a relationship between the features extracted and the magnitude of the vertical and horizontal displacement of the hyoid bone measured during swallowing. This relationship could give us information regarding the efficiency of the use of the tri-axial accelerometer in analyzing swallowing. Our study will focus on the ability of the tri-axial accelerometer to find dependency between the vertical and horizontal displacement of the hyolaryngeal complex during deglutition, as measured on videofluoroscopy videos, and the considered features in the time, frequency, and time-frequency domains. We will try to prove that the device signals can be linked to the horizontal and vertical magnitude of displacement of the hyoid bone during pharyngeal swallowing.

After further studying features that have been extracted from the tri-axial accelerometer, we hope to be able to develop this method as a diagnostic tool. This means that the medical examination would no longer require a specialist, as the device produced could be used by general practitioners.

In the long term, if the device should prove to be efficient in the assessment of dysphagia, this discovery could be very useful in patient care. This device is not very expensive, and can therefore be purchased readily by hospitals, which would reduce the waiting time for patients in need of assessing. Also, some patients, such as stroke patients or patients with Parkinson's disease, could ask for frequent verification of their swallows, even if they do not have any symptoms, in order to screen for dysphagia. Moreover, this device is not invasive and could also, after diagnosis, be used as a way to follow the progress of a patient's condition.

1.4 RECORDING DEVICE

1.4.1 Accelerometry

A widely used accelerometer in scientific applications is the MEMS accelerometer [39]. 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, in this study fixed to the neck of the patient. The other plate is suspended above the fixed one [39], as shown in Figure 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 [39].

This device is usually used to measure the speed of an object or to record its motion; however, by increasing the bandwidth of the accelerometer, it can record signals with larger frequencies [40], [15], [35], [36], [41], [42], [43].

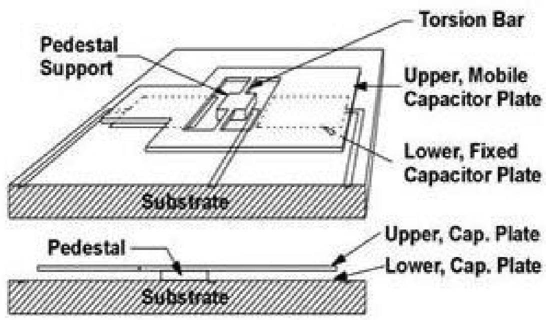

Figure 2: MEMS accelerometer constitution [44].

1.4.2 Microphone

A microphone typically used is an electret condeser microphone [40], [45]. This microphone is made of a polarized film that moves when it is contacted by the sound waves as shown in Figure 3. This movement modifies the electric field of the device, thus producing the signal [45]. The electret condeser 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 [40], [15], [36].

Due to the microphones' polarized film, the orientation is very important [46]. 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 electric output due to the orientation of the polarized microphone [45], [46]. This way noise rejection can be increased, and therefore can affect the predetermined signal recording. To counter that disadvantage, the device is transformed into a contact microphone and thereby directly fixed to the desired object, which in our study is the neck of the patient [45]. Thus, the contact microphone will not record ambient noise and unwanted signals; rather, only sounds that originate from the object which has been fixed to the device will be detected by the contact microphone [45].

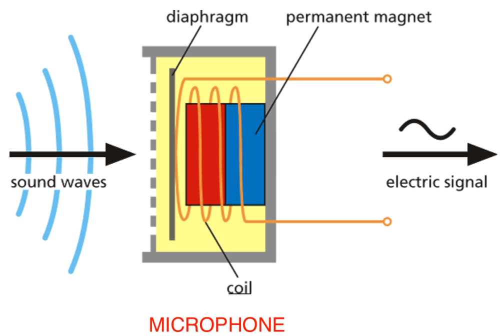

Figure 3: Functioning of a microphone [47].

1.5 THESIS STRUCTURE

Chapter 2 will describe all the necessary background about swallowing and dysphagia. First, we will introduce the mechanics of a normal swallowing, then, the different types of dysphagia and their symptoms will be expressed. Lastly, we will describe the different ways to diagnose patients and possible treatments. Chapter 3 will explain how the data has been selected and interpreted. We will demonstrate first how we have denoised the swallowing vibrations and sounds. Second, we will show which features in the time domain, frequency domain, time-frequency domain, and information-theoretic features have been extracted from swallowing vibrations and sounds. Third, we will show how we have extracted the maximal displacement of the hyoid bone using videofluoroscopy. Chapter 4 will present our results. Different mean values of the extracted features from swallowing sounds and vibrations and the mean values of the different maximal displacement of the hyoid bone considered will be discussed. Second, the dependence between all the maximal displacement and some of the extracted features from the swallowing vibrations and sounds will be discussed. Lastly, how each patient's characteristics can affect the maximal displacement of the hyoid bone and the extracted features from the swallowing sounds and vibrations will be presented. In chapter 5 we will present a discussion of the results and their impact. Chapter 6 will conclude with an overall discussion of the significance of our findings, the limitation of our research, and potential future studies.

2.0 BACKGROUND

2.1 SWALLOWING MECHANISM

Swallowing is a vital bio-mechanical process that is necessary for nourishing and hydrating the human body. It is a complex action involving around 20 muscles that necessitate neurological coordination with breathing [2]. Figure 4 depicts the deferent parts of the mouth and the throat involved in the swallowing process. Food masticated in the mouth and broken down by the saliva and the teeth forms a bolus that will be expelled into the pharynx. Then, a biological sensor in the pharynx detects the bolus and sends a signal to the brain that the swallow needs to be initiated. The vocal folds close and the epiglottis covers the larynx in order to prevent the bolus from entering into the trachea which leads to the lungs. Therefore, the bolus can only enter into the esophagus and proceed to the stomach [1], [3], [4]. The swallowing process has three different stages: the oral preparatory stage, the oropharyngeal stage, and the esophageal stage [24].

2.1.1 Oral preparatory stage

This stage consists mostly of preparing the bolus for swallowing, as depicted in Figure 5. When the food arrives in the mouth, the teeth will break down the food to give it an appropriate form that is easy to swallow. The saliva also helps to form a cohesive bolus by helping to mix the food. The movements of the tongue gather food that could stick in the cheeks or between the teeth. The formed compact bolus is then propelled into the oropharynx, due to the contractions of different muscles in the oral cavity [24], [48].

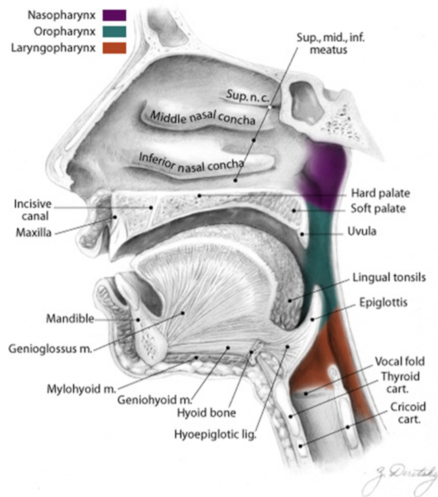

Figure 4: Diagram of a cross-section of the human head and neck [49].

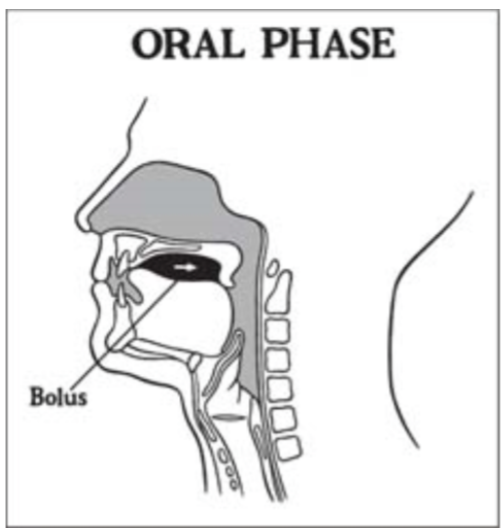

Figure 5: Oral stage of the swallowing mechanism [50].

2.1.2 Oropharyngeal stage

The oropharyngeal stage is composed of involuntary and reflex mechanisms triggered by special biological sensors as depicted in Figure 6. During this stage, the bolus has to pass into the larynx in order to go to the stomach to be digested at the end of the swallowing process. It is by consecutive and coordinated contractions and relaxations of different muscles that the bolus can be propelled through the pharynx. The pharyngeal phase is voluntarily triggered, while the rest of the process is automatically mediated [51]. The soft palate, by elevating itself, will close the nasopharynx in order to to prevent the bolus from coming back up towards the nose. Then, the larynx is pulled up by the suprahoid muscles to prevent the entry and overflow of the bolus into the airway. Finally, the epiglottis moves to cover the larynx that leads to the lungs, in order to completely prevent the bolus from entering into the airway. The upper esophageal sphincter stays contracted until the entire bolus has entered into the esophagus [24], [48]. The peristalsis creates gradient pressure to make the bolus pass through the esophagus [52], [53].

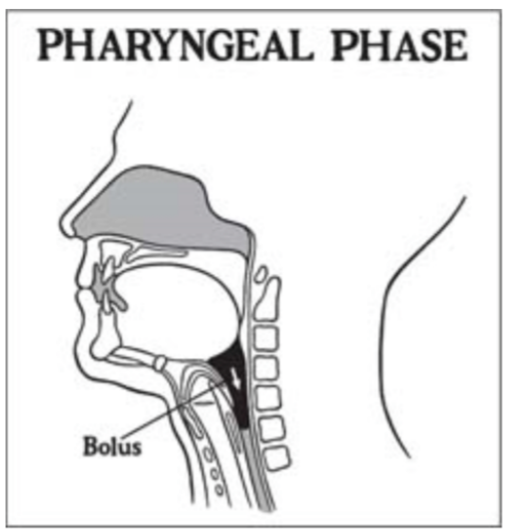

Figure 6: Oropharyngeal stage of the swallowing process [50].

2.1.3 Esophageal stage

The bolus is, at the beginning of this phase, entering into the esophagus. Then, it needs to go to the stomach to be digested. The upper esophagus forces the bolus to pass into the esophagus.

Then, the lower esophagus sphincter relaxes, in order to allow and facilitate the propulsion of the bolus until it arrives at the end of the esophagus, as shown in Figure 7. Thusly, the two esophageal sphincters protect people from regurgitating food. This stage is completely voluntary [3]. The swallowing mechanism can take between 8 and 20 seconds [24], [48].

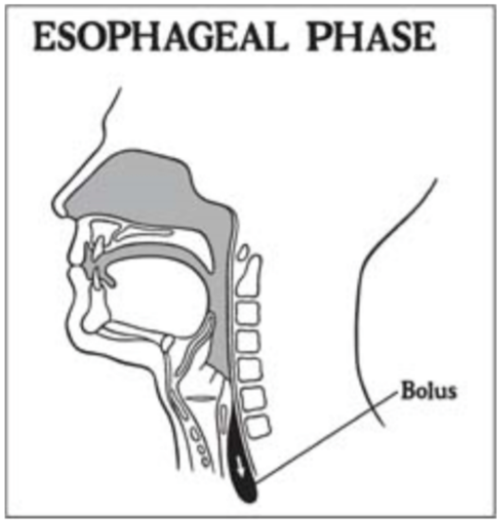

Figure 7: Esophageal stage of the swallowing process [50].

2.2 ROLE OF THE HYOID BONE IN THE SWALLOWING PROCESS

The precise timing of muscular contractions requires intricately coordinated neurological responses to ensure the complete anterograde propulsion of swallowed material and closure of the upper airway to prevent aspiration into the respiratory system [1], [3]. A hypothesized biological sensor in the pharynx detects the bolus and receives multiple sensorimotor feedback and feedforward signals emanating from the brainstem central pattern generator and peripheral activity, resulting in a pharyngeal response that typically begins at the time the bolus enters the pharynx [3]. Displacement of the hyolaryngeal complex, a key component of the pharyngeal stage, repositions the laryngeal inlet, the entrance to the airway, anteriorly and superiorly, pushing it away from the path of the oncoming bolus while also distending the upper esophageal sphincter which has momentarily relaxed from its tightly-closed resting posture due to vagal inhibition [54].

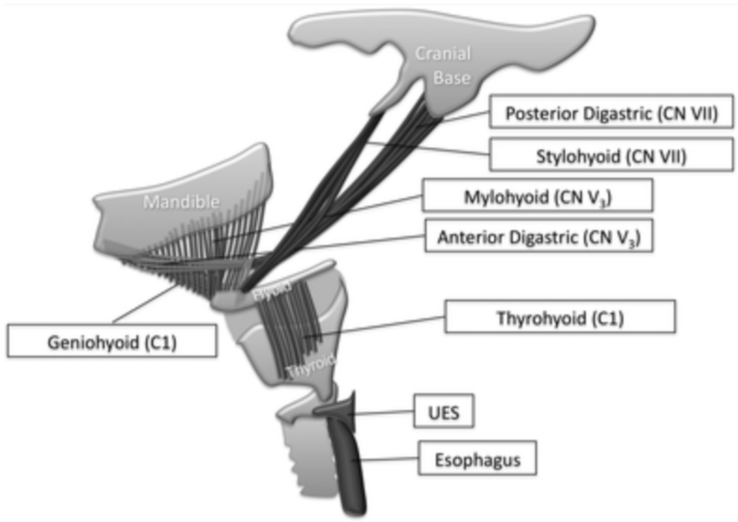

Figure 8: Diagram of the hyolaryngeal structure showing the suprahyoid muscles with their attachment [55].

This hyolaryngeal displacement also repositions the epiglottis over the laryngeal inlet while the larynx collapses at the level of the vocal folds, thus preventing the bolus from entering the airway leading to the lungs [3]. These pharyngeal events ensure delivery of the bolus, which then enters into the digestive system while preventing aspiration of material into the airway, an event that leads to immediate complications such as airway obstruction, and more insidious outcomes such as aspiration pneumonia, a significant contributor to morbidity and mortality in people with oropharyngeal swallowing disorders, also known as dysphagia [3], [4], [5], [56].

As shown in Figure 8, the hyoid bone has two main functions during the swallowing process. First, the movement of the hyoid bone makes the epiglottis cover the airway in order to avoid aspiration. Second, the forward movement of the hyoid bone, shown in Figure 9, helps to widely open the esophagus to allow the bolus to be propelled into the digestive area [1], [3]. So, during the swallowing process the hyoid bone moves upward and forward to accomplish its two main functions that guarantee a healthy swallow.

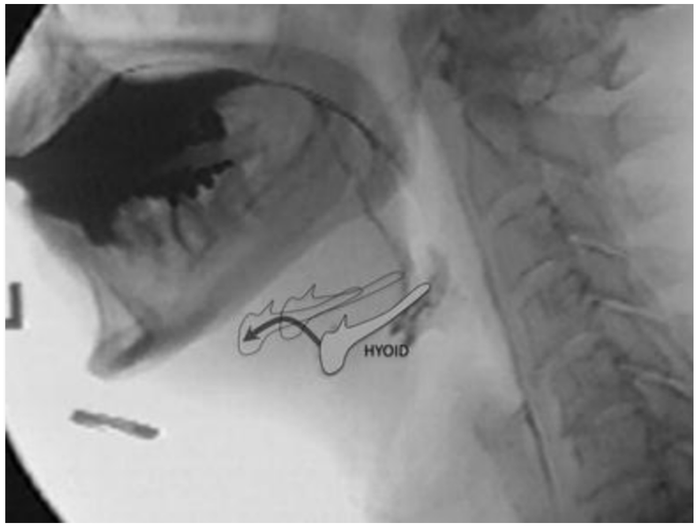

Figure 9: Hyoid bone upward and forward movement during swallowing process as seen under videofluoroscopy [55].

2.3 DYSPHAGIA

The complex mechanism of swallowing can sometimes be wrongly executed and can lead to a condition named dysphagia (Greek term “dys” means disorders or ill and “phagos” meaning eat or swallow) [7].

Patients who have dysphagia experience difficulty with swallowing. Two types of dysphagia exist: oropharyngeal dysphagia, related to the mouth and the throat, and esophageal dysphagia, which is related to the esophagus. People affected by oropharyngeal dysphasia can have difficulties in forming and safely moving the bolus, formed from food mashed and saliva, from the mouth to the stomach. Esophageal dysphagia is mostly caused by structural abnormalities or motor dysfunction [2], [16], [57].

There are different causes of swallowing abnormalities [24]. First, when the bolus enters in the pharynx if the larynx is still open (the epiglottis doesn’t cover the airway) the bolus can then enter into the airway. Second, liquids and food can also enter into the airway somewhat if the larynx does not close completely or if it somehow closes in a delayed fashion, and is therefore non-synchronous with arrival of the bolus. Lastly, if the volume of the material exceeds the volume of the laryngeal cavity, that results in the overflow of the bolus into the larynx [2].

2.3.1 Symptoms

2.3.1.1 Aspiration and penetration Aspiration is one of the most common symptoms of dysphagia. It occurs when mashed food, liquids or secretions enter into the larynx or other lower respiratory organs, such as the lungs. 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 [2], [11]. People who suffer from dysphagia can also have pharyngeal residue that overflows into the larynx after swallowing, if the larynx is open. There is a scale named penetration aspiration score (PA score) that characterizes the swallow from 1, for healthy swallows, to 8, for the most abnormal swallows [58]. A PA score of 3, for example represents a swallow in which the bolus enters into the airway, yet remains above the vocal folds. A PA score of 8, however, describes a situation when the bolus enters into the airway and passes below the vocal folds, yet the patient fails to react in order to to eject the bolus from the airway [58].

2.3.1.2 Choking This is the mechanical response to aspiration. Liquid that has entered into the airway must be expelled from it [11]. Some biological sensors that detect liquids or food into the airway make the patient choke. The choking reflex tries to reject the bolus from the airway by expelling air from the lungs.

2.3.1.3 Pneumonia Pneumonia is the third leading cause of death in Japan and the first leading cause for older Japanese [59]. This is the main cause of death in cases of dysphagia. It is caused by infection of the lungs after aspiration and inhalation of the bolus (food, liquid, or secretions). Pneumonia is a severe disease that causes difficulties in swallowing and breathing. Patients experience fast breathing, shortness of breath, and heartburn. They also often feel weak and tired, and can experience nausea, fever, and vomiting [11], [60].

2.3.1.4 Malnutrition and dehydration Dysphagia can cause difficulties and pain during swallowing, and as a consequence some patients stop eating. Some patients are ashamed to eat in front of others, and 36% of nursing home patients avoid eating with others [7]. Twenty-five percent of patients who have a stroke suffer from malnutrition and dehydration due to dysphagia [7]. Their malnutrition leads to an important loss of weight that makes the patient weaker and less able to combat the possible pneumonia. Moreover, it is difficult for some patients to form a compact bolus in their mouth and to swallow it entirely. They pocket food in their cheeks and cannot successfully gather all food particles from the mouth to form and successfully propel a bolus into the esophagus. Other patients spill food or liquids out of their mouth during mastication [17], [60]. All of these difficulties can lead to malnutrition and dehydration.

2.3.1.5 Other symptoms Other symptoms include heartburn and sensations of food getting stuck in the throat, chest, or behind the sternum. While choking, which is a mechanical reflex against aspiration, they also can experience regurgitation of food or stomach acid into the throat [7]. In Table 1 the different symptoms linked to the two types of dysphagia are represented.

Table 1: Different symptoms related to the two types of dysphagia: the oropharyngeal dysphagia (related to the mouth and the throat) and esophageal dysphagia (related to the esophagi) [7], [11], [17], [59], [60].

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

2.4 WHAT CAUSES DYSPHAGIA

There are different causes for dysphagia that can be classified in three categories: neurological conditions, structural and mechanical disorders, and a condition of the neck or head [7], [11], [21], [60].

2.4.1 Patients with neurological diseases

Neurological diseases can cause dysphagia because muscles involved in the swallowing process are less controllable by the brain. Moreover, the sensors that should detect the bolus in the pathway may not detect it at all or may detect it with an important delay. Therefore the epiglottis cannot be closed in time, which would provoke the entry of the bolus in the airway. Strokes represent one of the most important neurological causes for oropharyngeal dysphagia [7]. People who had suffered from severe acute traumatic and chronic traumatic brain injuries are more likely to have esophageal dysphagia [22]. Another infamous neurological cause is Parkinson's disease. Furthermore, patients who have dementia, severe amyotrophis sclerosis, or advanced occulopharyngeal muscular dystrophy are 80-100% more likely to suffer from dysphagia [7], [61]. Another neuromuscular disease is achalia, also named cardio spasm or esophageal aperistalsis. This disease is the failure of the lower esophageal sphincter (LES) muscle to relax. The consequences are low intra-esophageal pressure and dilatation or compression of the esophagus. These can create functional obstruction. Hypercontractile esophagus is another neuromuscular condition that can cause dysphagia [7].

2.4.2 Patients with head or neck diseases

Patients who have cancer, lymphoma, or a mass in the neck can suffer from dysphagia. The mass can occupy space and apply pressure on the pathway of the bolus, narrow the esophagus and the larynx, and make the swallowing mechanism more difficult. A surgical treatment to remove the mass can make the dysphagia even more severe. During the operation the surgeon will have to cut some links between the tumor and the muscles. This action can weaken the muscles involved in the swallowing process. Moreover, the weakened muscles cannot protect the larynx any more. So, previous surgeries in the neck or the head can be an important cause of dysphagia [7], [8].

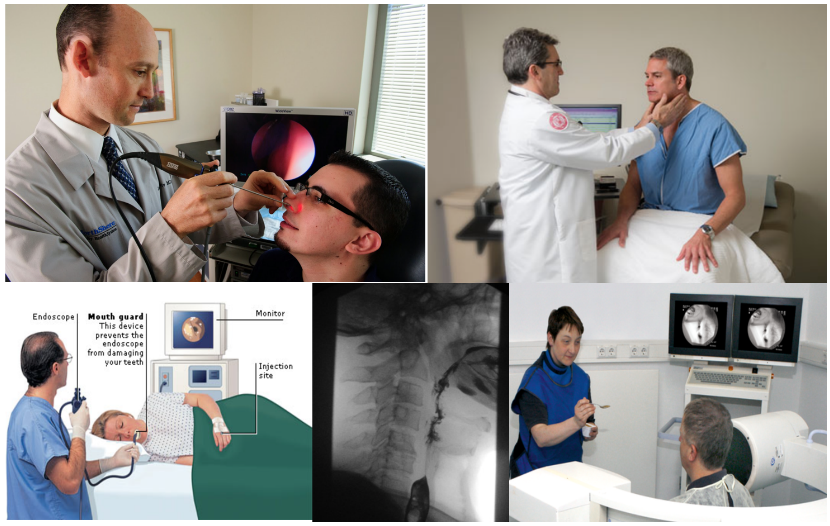

Figure 10: Different examination to diagnose dysphagia from the top right to the bottom left : a nasopharyngoscopy, a physical examination, an endoscopy, a barium study, and a videofluoroscopy [62], [63], [64], [65], [66].

2.4.3 Mechanical causes

Mechanical causes, such as obstruction or structural impairments, can be detected from endoscopy or barium studies and can usually be treated easily. These impairments are due to inflammations of the tissues. Some connective tissue diseases cause dysphagia, such as systemic sclerosis that can affect badly the organs from the stomach to the intestine [7]. Fifty to eighty percent of patients who undergo systemic sclerosis suffer from esophageal dysphagia [7].

2.5 HOW TO ASSESS DYSPHAGIA

Different techniques for diagnosing dysphagia exist. Some are more appropriate for oropharyngeal dysphagia and some for esophageal dysphagia. Most of the efficient ways to determine that the patient suffers from dysphagia are invasive and expensive.

2.5.1 Physical examination

The aim of this examination is to identify whether the patient may have a neurological disorder, speech issues, weakness in the muscles involved in the swallowing and/or speech processes, head or neck injuries, or trauma. Following an examination performed by a specialist, it is possible to evaluate the possible severity of the condition. During the physical examination, the specialist first checks the chest which can reveal signs of infection or increased secretions that can notify one of the most common symptom of dysphagia, a severe aspiration. Then, the specialist checks if the lips and the jaw are closed during swallowing. He/she also examines mastication, saliva production, and tongue mobility and strength [21], [60].

The first additional component is the speech evaluation conducted by a speech language pathologist. This examination will provide information about muscles involved in the swallowing process that may be too weak to perform efficiently during swallowing. This may also reveal the presence of a cognitive disorder caused by brain lesions. The conclusion of the speech evaluation can also help to select the treatment needed by the patient for treating his/her dysphagia [40], [67]. If the voice is wet that can be a cause of a long term aspiration. On the contrary, if a patient has a weak raspy voice it could be caused by a vocal fold pathology [21], [24].

The second component is the neurological exam. Neurological disorders diagnosed as Parkinson's, or the prior occurrence of stroke, can both cause dysphagia, in fact 52% of Parkinson's patients suffer from dysphagia [21], [22], [24], [60], [67]. Finally, during the last exam, the specialist examines the head and the neck to verify the absence of lymph node masses, or goiter. The specialist also takes note to whether previous surgery has been performed on the neck or the head, and inspects the oral cavity, including both the teeth and the tongue [7], [21].

2.5.2 Barium study

Barium study (as shown in Figure 10) is a radiographic (X-ray) examination of the esophagus and pharynx. It is usually one of the first examinations conducted by the doctor when he/she suspects structural obstruction. The patient drinks a barium sulfate suspended in a liquid that will highlight the esophagus and pharynx. This examination evaluates motility better than endoscopy. However, in order to conduct the procedure, the patient needs to be cooperative since he/she has to stay immobile on the X-ray table, which may prove difficult for patients suffering from Parkinson's. This examination requires the use of X-rays, which may be harmful when patients are exposed to them for long periods of time [7], [21].

2.5.3 Nasopharyngoscopy

During a nasopharyngoscopy, the doctor inserts a flexible tube that has a light and a camera at the extremity into the patient's nose. The tube can reach up the vocal box and so the doctor can observe the nose, the back of the tongue, the throat, the epiglottis, and the vocal folds. That way, the specialist can determine whether there is an obstruction in this area, structural lesions or masses. He can also evaluate the laryngeal sensitivity to contact. However, the tube cannot go lower than the vocal folds and therefore cannot enter the trachea [21]. This exam evaluates the structural problems of the first part of the respiratory system and is therefore useful in diagnosing oropharyngeal dysphagia. During this examination the patient is given local anesthesia and therefore the pharynx may sometimes become anesthetized itself, and thusly not react as desired. This can sometimes lead to improper diagnosis. This examination is useful only for oropharyngeal disphagia and not always accurate [7], [21].

2.5.4 Endoscopy

2.5.4.1 Nasoendoscopy During the examination (as shown in Figure 10), the specialist inserts a fiberoscopy or video-endoscope through the nose. This device offers a direct visualization of the mucosa of the oral cavity, the pharynx and the larynx. It is one of the most accurate ways to diagnose structural intra-cavity lesions and mucosa abnormalities. During this examination, the patient may be asked to swallow colored liquids or dyed food. The camera can evaluate whether there is a delay in initiating the pharyngeal swallow or not. Moreover, colored residues in the subglottic airway and their accumulated secretions can provide indirect evidence of aspiration. The flexible tube used during nasoendoscopy can reach the epiglottis, which, as previously explained, plays an important role in the swallowing process. This device also has a pulse stimulus that can be applied on the pharyngeal membrane to assess its sensation. Stroke patients have reduced sensations in the hypopharynx [21], [60].

2.5.4.2 Gastroendoscopy

Gastroendoscopy can assess esophageal mucosa and detect infections and erosions. But barium study is more efficient in evaluating the motor functions or the subtler structures [7], [21].

2.5.5 Manometry

Manometry is a test that evaluates the motor function of the esophagus. During examination, the doctor inserts a catheter that has multiple electronic pressure sensors inside the nose which can advance along the stomach. Usually, this test is performed if no abnormalities have been found in the barium test. When this examination is performed alone, it can only offer indirect evidence of pharyngeal weakness [7]. The tube that is inserted in the nose can measure esophageal contractions and assess upper and lower esophageal responses during swallowing thanks to multiple sensors in different sections of the tube [7], [21], [60]. Only 25% of the patients with non structure abnormalities are diagnosed to have motor function abnormalities, however [68].

2.5.6 pH monitoring

During testing, a thin tube is inserted into the patient's nose and passes into the esophagus where it will record the pH level. This examination will assess the frequency of acid reflux entrance into the esophagus and how long it stays there. The patient has to keep this tube inserted for a 24 hour period to record information which can be inconvenient for patients and also contraindicated for patients with Parkinson's [7], [21], [69].

2.5.7 Videofluoroscopy

Videofluoroscopy, as shown in Figure 10 and 11, is one of the most accurate ways to assess and diagnose dysphagia. It allows the doctor to assess functional abnormalities of the oral and pharyngeal swallowing mechanisms. During examination, the patient is asked to swallow different types and quantities of liquid (in a spoon, cup, or with a straw) or eat different types and quantities (cookies or viscous liquid) of food. Then, using X-ray technologies, the physician obtains lateral projections of the patients so that he can see the oral cavity and the proximal esophagus. The video is saved on a tape so that the doctor can re-analyze and slow down the film to be more accurate in his verdict [7], [21], [48], [60], [68].

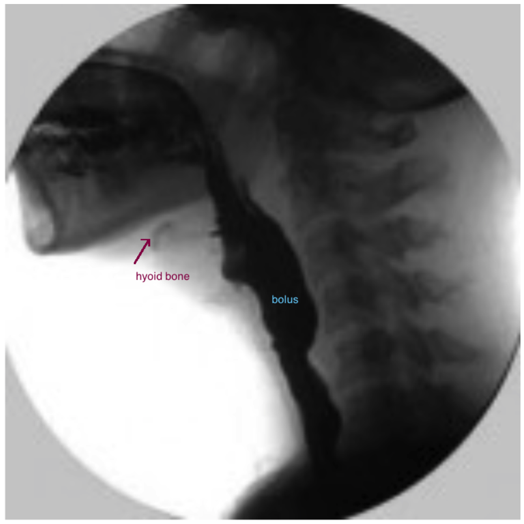

Figure 11: Videofluoroscopy of a patient during swallowing and the position of the hyoid bone that moves during swallowing.

This examination allows the doctor to assess the delay or inability to initiate swallowing, aspiration, nasopharyngeal regurgitation, and residue. During the test, the patient may be asked to swallow in different postures (lying down or with their head rotated) or using a maneuver. This way, the examination can gauge the efficiency of possible treatment. Videofluoroscopy cannot, however, assess the strength of the muscle involved in the swallowing process during pharyngeal contraction. Moreover, this type of examination uses X-rays that may be harmful in case of long term exposure [7], [8], [21], [48], [60], [68].

2.5.8 Manofluorography

Manofluography is a combination of manometric data and videofluoroscopic observation. This technique requires an expert to synchronize manometry and videofluoroscopy. When the synchronization is good, the addition of the videofluoroscopy to the manometry can overcome the weakness and disadvantages of manometry. For example, it allows the sensors to be more clearly localized at a given moment during the examination [21], [60].

2.5.9 Brief summary

The first type of examination that the doctor usually offers to a patient is the barium study, which is a good way to diagnose orpharyngeal dysphagia and can identify whether there is a structural obstruction present. Endoscopy may also be suggested to the patient since it is an accurate way to evaluate lesions and mucosa abnormalities. Manometry can assess the strength of pharyngeal contraction. The most common test is videofluoroscopy, which evaluates the motor function of muscles involved in the swallowing mechanism and can determine whether or not aspiration is present. Videofluoroscopy can be also improved by combining manometry but this technique adds additional complexity [7], [21], [60].

2.6 TREATMENT FOR DYSPHAGIA

Different treatments can manage dysphagia or help to feed a patient. Some treatments are severe, like surgery, while some are less extreme such as rehabilitation, physiotherapy, and specialized daily diets. Each patient's severity and the different causes (neurological or structural) of dysphagia require specialized treatment [48], [70], [71], [72].

2.6.1 Postural techniques

Postural techniques can be done to increase muscles' strength or to help closing or opening specific parts of the swallowing system while the patient is drinking or feeding in order to principally avoid aspiration or choking. Lying down or on one side can increase the flow of the bolus through the pharynx during swallowing and can reduce the amount of residues in the oropharyngeal system. Turning or tilting the head increases the size of the upper esophageal sphincter and the amount of the bolus swallowed. Therefore, these techniques can decrease the pharyngeal residue and risk of aspiration and can be added to oral sensory awareness techniques, in order to be more efficient. Moreover, they can be used during videofluoroscopy examination to test their efficiency and to assess how much the head should be turned [36], [48], [70], [73], [74].

2.6.2 Swallowing maneuvers

In order to make swallowing easier, patients can be asked to practice swallowing maneuvers that are supposed to help different openings to increase their ability to let the flow pass or to help different closings to avoid letting fluid pass. The chin down maneuver, shown in Figure 12, consists of putting the chin closer to the chest and swallowing from that position. This maneuver will narrow the larynx and so counterbalance the delay of the epiglottis closure. The patient will be more able to control the bolus and to reduce the risk of aspiration. During the Mendelssohn maneuver, the patient places their hand on their throat at the highest point that his larynx reaches during swallowing. Then, they squeeze the muscles in the back of the tongue intensely and as long as possible to keep the voice box at his highest point. Then, the patient must let the larynx come back to its resting position. This maneuver will increase the tongue control and decrease the amount of residue in the pharynx and the throat. The Valsalva maneuver, as shown in Figure 12, increases the laryngeal opening during swallowing and reduces the risk of aspiration. During this maneuver, the patients will hold their breath after taking a deep breath while keeping their lips opened. All these maneuvers can be completed by adding a position such as the chin tuck maneuver with head turned, to increase the efficiency according to specific needs of each patient [48], [70], [72], [73], [74].

2.6.3 Diet modification

A daily diet modification is specific to each patient depending on the severity and the symptoms they have. For example, if the patient feels pain while swallowing thick food, an appropriate diet could consist of purees [71]. Patients that have a lot of gastroesophageal reflux are asked to avoid chocolate, coffee, fatty food, and acidic or sour food. Patients that have very severe dysphagia and inability to eat can be fed intravenously [48], [71], [78].

2.6.4 Oral sensory awareness techniques

There are a lot of different strategies and exercises to increase sensory awareness of the oral cavity. The cheek push strategy, mouth rise, and strong hold food strategies all increase sensory awareness in the oral cavity and reduce oral residue by avoiding pocketing food or liquid in the cheeks and increasing chewing skills. The multiple strategy is an exercise that can be followed on videofluoroscopy. It consists of swallowing multiple times before eating again to be sure that nothing

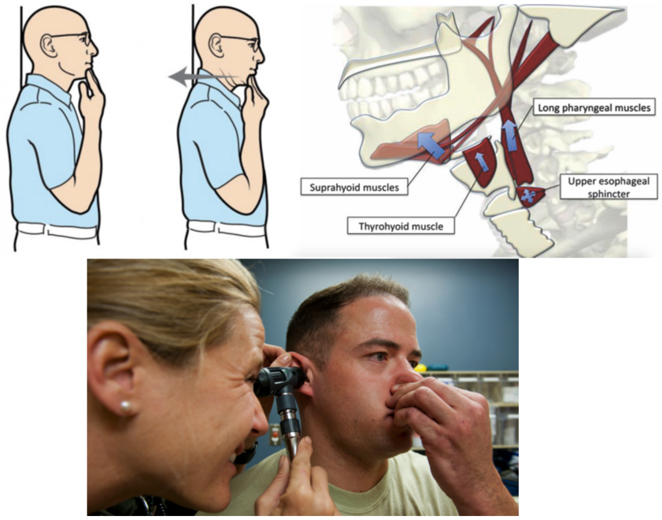

Figure 12: Different maneuvers helping to swallow more efficiently and a sagital view of the swallowing system. From top right to bottom left: the chin tuck maneuver [75], swallowing system [76], the Valsalva maneuver [77].

remains in the mouth. This strategy helps to avoid residue in the oral cavity and increase the control of the bolus. This method can be extended to alternating solid and liquid swallows. After masticating and swallowing the food, the patient is asked to swallow liquid in order to catch all the food residues that remain in the mouth. This exercise also reduces the risk of aspiration that is due to the delay on initiating the swallow. Some strategies such as the cold lips rub, the warm lip rub, the soft lips pressure, or the tongue tickle are more focused on rehabilitation of certain muscles. They are supposed to increase the strength of the lips and the tongue. That way the bolus is easier to form. The thermal-tactile stimulation, the textured, sour, cold, and small bolus strategies can also increase significantly the sensory awareness. There are also some medical devices that help the patient to practice their exercises to increase the strength of the different muscles involved in the swallowing process. These devices could be used for example on the tongue [70], [79].

2.6.5 Electrical stimulation

In order to improve, during swallowing, the efficiency of weak muscles involved in the swallowing mechanism, doctors can decide to apply electrical stimulations to increase the muscles' strength. Electrodes stimulate different parts of the throat and the oral cavities. The muscles should respond to this stimulation by contraction [70].

2.6.6 Prosthetics

Prosthetics can be implanted during surgery to improve the swallowing mechanism. The glossectomy prosthesis improves swallowing and reduces aspiration. A patient takes less time to swallow and can eat more varied consistencies of food. A prosthesis can improve swallowing, but could also damage speech and articulation. Therefore compromises must be made [70], [80].

2.6.7 Surgical treatment

Some patients who suffer from chronic oral or pharyngeal dysphagia have to undergo surgery. The cricopharyngeal myotomy (cutting of the upper esophageal sphincter (UES)) would eliminate the resistance of the UES during swallowing and increase outflow. Another surgery that can be done is suspension of the thyroid cartilage. It is supposed to improve the laryngeal elevation which will help swallowing [48], [70].

2.7 PREVIOUS CONTRIBUTIONS

Recently, noninvasive methods to assess dysphagia have been suggested such as electromyography/bioimpedance [28], and cervical auscultation [40], [15], [29], [30], [31], [32], [33], [34], [35]. High-resolution cervical auscultations based on recording of swallowing vibrations and sounds could potentially lead to an affordable, noninvasive, and automated system that can assess dysphagia. For example, the chin-tuck maneuver, which consists of dropping the chin towards the chest during swallowing, has been shown to affect swallowing vibrations but not sounds [35]. Another contribution has compared the vibrations among the different directions of the tri-axial accelerometer [15]. This study has concluded that there exists, among signals from the three axes of the accelerometer, dissimilarities on the degree of predictability, the disorder behavior in the time-frequency domain, and the variability of the amplitude [15]. However, no studies have proved how the swallowing auscultation signal could be linked to the physical process of swallowing.

In this study, we have considered a relationship between the features extracted from the cervical auscultation recordings and the vertical and horizontal displacement of the hyoid bone during swallowing. The results of this study are aimed to reveal some physiological sources of swallowing cervical auscultation signals, and in this particular case, we considerer the hyoid bone movement. This study is meant to be a preliminary work that can comparatively align cervical auscultation recordings with other clinical tools used in the dysphagia management.

3.0 METHODOLOGY

3.1 DATA ACQUISITION

For this study we monitored 31 single swallows (without swallowing maneuverer) of a thin bolus with barium liquid (50% water at room temperature with 50% barium sulfate, Varibar thin liquid with less than 5 cps viscosity) from a spoon collected from 25 patients (13 females, 12 males, mean age: 60 ± 12 years) undergoing a videoflourscopy exam at the University of Pittsburgh Medical Center. All these swallows were considered to be safe swallows, that is, they were rated to have a penetration-aspiration scale of one or two [58].

Table 2: Patient distribution and characteristics of the considered swallows.

characteristics	the sample of our data
number of swallows	31
number of patients	25
female	13
male	12
age range	44 to 86 years old
volume of the bolus	spoon
PA/SPA score	1 or 2
single or multiple swallow	single swallow

Cervical auscultation signals were recorded using two different sensors. A tri-axial accelerometer (ADXL 327, Analog Devices, Norwood, Massachusetts) was attached to the anterior of the patient's neck [40]. The signals extracted from the tri-axial accelerometer sensors were recorded into a National Instruments 6210 DAQ at a sampling rate of 40 kHz with the LabVIEW Program Signal

Table 3: Distribution of swallowing as dependent of the characteristics of patients.

number of swallows	command	not command	total
	5	26	31
	white origin	other origin	total
	25	6	31
	PA=1	PA=2	total
	15	16	31

Express (National Instruments, Austin, Texas) [40], [15]. The tri-axial accelerometer was powered by a 3 Volt power supply (model 1504, BK Precision, Yorba Linda, California). The signal was then passed through a bandpass filter from 0.1 to 3000 Hz with an amplification gain of 10 (model P55, Grass Technologies, Warwick, Rhode Island) [40], [15]. A microphone (model C 411L, AKG, Vienna, Austria) was also placed next to the accelerometer to record swallowing sounds. The microphone was powered by the model B29L power supply (model B29L, AKG, Vienna, Austria) and set to line impeded with a volume of 9 while the resulting voltage signal was sent to the previously mentioned DAQ.

3.2 PRE-PROCESSING CERVICAL AUSCULTATION RECORDINGS

First, to determine the start and end times of each swallow, the fluoroscopic videos associated with cervical auscultation were analyzed by a speech language pathologist. By analyzing the videos frame-by-frame, the start and end times of the swallows were identified on the fluoroscopic videos and applied to the signals of the cervical auscultation. To determine the start time of the swallow, the specialist identifies the time when the bolus is seen at the extremity of a ramus of the mandible; the end time is set when the hyoid bone returns to its initial position [15], [41].

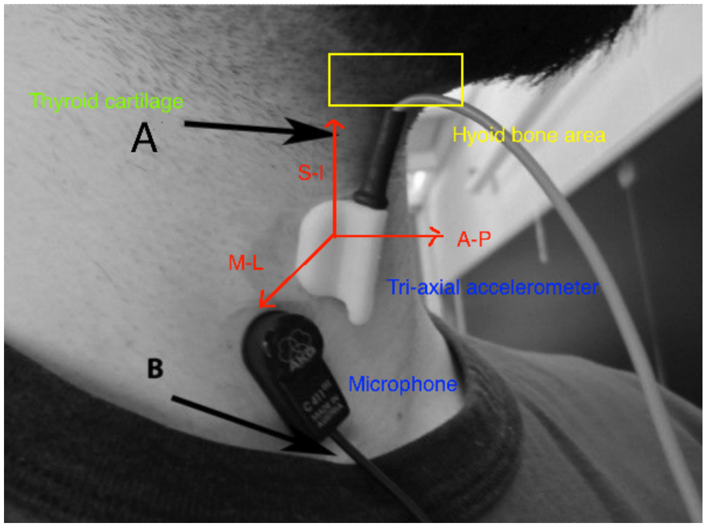

Figure 13: Placement of the tri-axial accelerometer and its different axis and the associated microphone A indicates the thyroid cartilage and B the suprasternal notch. A and B are used as reference to place the devices [40].

In order to reduce the mechanical, electrical, and thermal noise inherent in the accelerometer device, each segmented swallow signal is filtered by a finite impulse response filter (FIR) [41]. Second, low-frequency components associated with head movements are removed using a fourth-order splines approximation algorithm [15], [42], [43]. Finally, wavelet denoising was used via a tenth-order Meyer wavelet to remove any additional noise.

3.3 FEATURE EXTRACTION

In order to determine if the signals characterize the distance (vertical, horizontal, or combined) of hyolaryngeal displacement during swallowing with good accuracy, several features in different domains were extracted from four cervical auscultation signals (superior-inferior vibrations, anterior-posterior vibrations, medium-lateral vibrations and swallowing sounds) [41], [81], [82], [83], [84], [85]. According to previous studies [81], [82], [83], [84], the time domain, frequency domain, and time-frequency domain features are explained as follows: After denoising the signal collected from the tri-axial accelerometer, several features in different domains have been extracted from each swallow signal according to each respective axis in order to analyze them and determine whether the signals provide an accurate characterization of the distance (vertical, horizontal, combined) of hyolaryngeal displacement during swallowing.

3.3.1 Time domain features

These features in the time domain can describe the behavior of the signal where X=$\{x_1, x_2, ..., x_n\}$ is the vector of the signal [41], [81], [82], [83], [84], [85].

- Mean of the Amplitude of the signal:

  $$\mu_x = \frac{1}{n}\sum_{1}^{n} x_i \tag{3.1}$$

  The mean of the amplitude (μ_x) represents the unbiased estimation of the signal.

- Unbiased estimation of the standard deviation:

  $$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{1}^{n}(x_i - \mu_x)^2} \tag{3.2}$$

  The unbiased estimation of the standard deviation (σ_x) gives information about the fluctuation of the signal around the mean value. The lower the unbiased deviation is, the closer the positive amplitudes of the signal are to the mean.

- Skewness: Skewness (ζ_x) quantifies how the amplitudes of the signal are symmetric.

  $$\zeta_x = \frac{\frac{1}{n}\sum_{1}^{n}(x_i - \mu_x)^3}{\{\frac{1}{n}\sum_{1}^{n}(x_i - \mu_x)^2\}^{\frac{3}{2}}} \tag{3.3}$$

  If the distribution is symmetric, the skewness is equal to zero. The skewness is positive if the distribution is asymmetric and the right-hand tail (with high values) is longer or bigger, whereas the skewness is negative if the left-hand tail is bigger or longer.

- Kurtosis: Kurtosis (γ_x) measures, excepting the effect of dispersion resulting from the unbiased standard deviation, the disposition of mass probabilities around the mean. This qualifies how the amplitude peaks or flattens in comparison with a normal distribution. It is computed as follow:

  $$\gamma_x = \frac{\frac{1}{n}\sum_{1}^{n}(x_i - \mu_x)^4}{\{\frac{1}{n}\sum_{1}^{n}(x_i - \mu_x)^2\}^2} \tag{3.4}$$

If the distribution has narrow high value peaks close to the mean that quickly decrease into peaks of very small amplitude with heavy tails, the kurtosis value is high. A low value indicates a flat distribution with thin tails.

3.3.2 Frequency domain features

In order to extract and analyze the frequency domain feature we have computed the Fast Fourier Transform [41], [81], [82], [83], [84], [85].

- Peak frequency (p) is the frequency of the maximum power.

  $$p = arg_{f \in [0, f_{max}]} \; max \; |FX(f)|^2 \tag{3.5}$$

  with f_{max} is the maximum frequency of the signal, according to the preprocessing
  $f_{max} = 3000 Hz$.
  $|FX(f)|$ represents the Fourier transform of the signal.

- Spectral centroid:

  $$\hat{f} = \frac{\int_0^{f_{max}} f |FX(f)|^2 df}{\int_0^{f_{max}} |FX(f)|^2 df} \tag{3.6}$$

  The spectral centroid ($\hat{f}$) indicates the frequency of the mass of the spectrum.

- Bandwidth:

  $$BW = \sqrt{\frac{\int_0^{f_{max}} (f - \hat{f})^2 |FX(f)|^2 df}{\int_0^{f_{max}} |FX(f)|^2 df}} \tag{3.7}$$

  The bandwidth (BW) indicates the range of frequencies of the signal.

3.3.3 Information-theoretic features

Information-theory studies the quantity, the redundancy, and the storage of the information about a signal. Information-theoretic features are common to use in order to characterize biological signals [41], [81], [82], [83], [84], [85].

- Normalized Entropy Rate:

  Entropy is used to compare the degree of regularity between each respective axis (PA, SI, ML). First, X is normalized so we have subtracted μ_x from X and then divided by σ_x. Second, the normalized X is quantized into ten equally spaced levels. Then, these equally spaced levels give the vector X'=$\{x'_1, x'_2, ..., x'_n\}$, where the x'_i are sequences of consecutive points (of length N). Then the series of integers is computed as follows [13], [14], [15]:

$$w_i = x'_{i+N-1}.10^{N-1} + x'_{i+N-2}.10^{N-2} + ... + x'_i \tag{3.8}$$

  giving us the vector

$$W_H = \{w_1, w_2, ...w_{n-N+1}\} \tag{3.9}$$

  Third, we evaluate the Shannon entropy ($\Delta_{(H)}$) as follows:

$$\Delta_{(H)} = \sum_{q=0}^{10^{H-1}} PW_H(q)ln(PW_H(q)) \tag{3.10}$$

  The normalized entropy rate (H_{nor}) is defined as follows:

$$H_{nor} = \frac{\Delta_{(H)} + \Delta_{(H-1)} + \Delta_{(1)}perc(H)}{\Delta_{(1)}} \tag{3.11}$$

  where perc is the percentage of coded integers that only occurred once. So, the entropy rate is $\rho = 1 - min(H_{nor})$. If the calculated entropy is close to 0, it means that the distribution is highly regular. If it is close to 1, it means that the distribution is random.

- Lempel-Ziv Complexity (LZC):

  The Lempel-Ziv complexity determines the predictability of the signal. The signal X is previously transformed into a binary sequence by quantizing the signal into 100 equally spaced levels. Then this quantization of X is decomposed into k blocks [7], [10]. Therefore k reprensents the number of unique sequences in the decomposed signal. Finally the LZC is defined as [7], [10]:

$$LZC = \frac{k\ log_{100}\ n}{n} \tag{3.12}$$

  where n is the length of the pattern and the logarithm base of 100 is coming from the 100 levels of quantized.

3.3.4 Time-frequency domain

The time-frequency domain gives information simultaneous in both time and frequency. For that we apply a ten-level discrete Meyer wavelet decomposition to the signal [41], [81], [82], [83], [84], [85].

- Wavelet entropy:

  Wavelet entropy (WE) has been used in previous studies to qualify whether a signal is disordered or not. The decomposition give us $W_x = [a_{10}\ d_{10}\ d_9 ... d_1]$ where a_{10} is the approximation signal and d_k the k^{th} level of the detail signal. We then compute the energy for the approximation signal as follows:

  $$E_{a_{10}} = \|a_{10}\|^2 \tag{3.13}$$

  where $\|.\|$ is the euclidean norm.

  $$E_{d_k} = \|d_k\|^2 \tag{3.14}$$

  for k integer from 1 to 10.

  The relative energy is defined as:

  $$Er_{li} = \frac{E_{li}}{E_T} * 100\% \tag{3.15}$$

  where l_i can be a_{10} or d_k.

  Then the total energy is defined as:

  $$E_T = E_{a_{10}} + \sum_{k=1}^{10} E_{dk} \tag{3.16}$$

  and the wavelet entropy qualifies also the disorder propriety of the signal. It is defined as follows:

  $$WE = -\frac{Er_{a_{10}}}{100} * log_2(\frac{Er_{a10}}{100}) - \sum_{k=1}^{10} \frac{Er_{dk}}{100} * log_2(\frac{Er_{dk}}{100}) \tag{3.17}$$

3.3.5 Summary of the extracted features

In summary, we first extracted features from the time domain, which included: the mean value of the signal, the standard deviation that characterizes the fluctuation of the signal around the mean, the skewness that quantifies the symmetry of the signal, and the kurtosis that quantifies the signal's peakedness in comparison to a normal distribution. Also the information-theoretic features

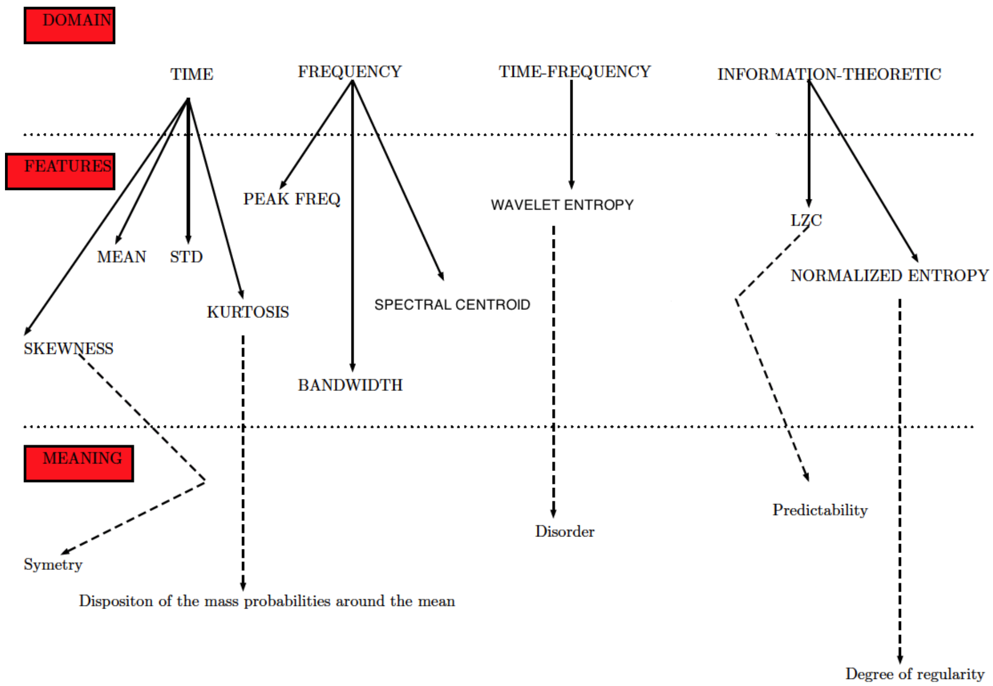

Figure 14: Summary of the extracted features from the signal of the tri-axial accelerometer.

such as the normalized entropy rate, which quantifies the regularity of a signal, and the Lempel-Ziv complexity (LZC), which determines the predictability of the signal were computed. Second, in the frequency domain, the bandwidth, the spectral centroid that indicates the frequency of the mass of the spectrum, and the peak frequency that shows the frequency at the maximum power were calculated from cervical auscultation recordings. Third, in the time-frequency domain, we extracted the wavelet entropy to quantify whether the signal is disordered or not. All the extracted features are depicted in Figure 14.

3.4 ANALYSIS OF VIDEOFLUOROSCOPY IMAGES

The coordinates of the hyoid bone are located in each videofluoroscopic image, as shown in Figure 15. The hyoid bone is denoted in yellow (anterior and posterior part linked). The upper and lower extremity of the pink segment represent C2 (second cervical) and C4 (fourth cervical), respectively. The length of C3 (third cervical) is depicted by the blue line.

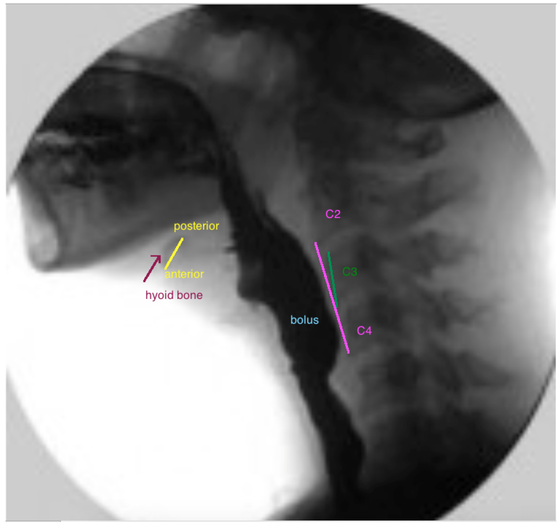

Figure 15: Position of the hyoid bone, C2-C4 and C3 on a videofluoroscopic image.

As some patients move their head during the videofluoroscopy exam, a geometric transformation is applied to the hyoid bone motion in order to avoid the influence of head motion on the hyoid bone displacement.

For the first videofluoroscopic image, we made the segment C2-C4 vertical, as shown in Figure 16. The black segment C2-C4 represents the first position of the second and the fourth cervical on the first image. To make it vertical, we measured the length of C2-C4. Then, we added the length of C2-C4 to the vertical coordinate of C4. The horizontal coordinates of C2 were made equal to the horizontal coordinate of C4. This transformation is shown in Figure 16 with the new vertical red segment of C2-C4. The second step is to extract the angle Theta between the original position of C2-C4 segment (in black) and the new vertical one (in red). Then, the rotational angle, calculated previously, is applied to the original hyoid bone segment of the first image (HA-HP in black in Figure 16). The new rotated hyoid bone segment is represented in black as HA'-HP', and its coordinates become the new coordinates of the hyoid bone for the first videofluoroscopic image.

For the second videofluoroscopic image, because of head movement during the examination, the segment C2-C4 and the hyoid bone segment (HA-HP) may have moved as shown in green in Figure 16. First, we measure the distance d between the previous coordinates of C4 (in red) and the new one (in green). Then, we apply a translation of this distance d on the hyoid bone segment. Second,

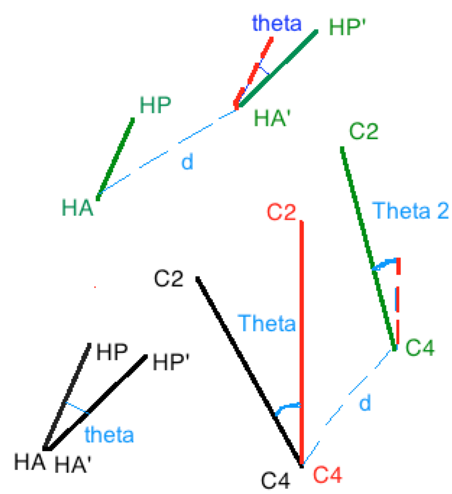

Figure 16: Adjusting the hyoid bone to the displacement of C2-C4.

we extract the angle Theta2 between the C2-C4 segment in green and the previous vertical C2-C4 in red. We rotate by Theta2 the previously translated hyoid bone segment. The new coordinates of the rotated and translated hyoid bone segment (HA'-HP' in green) are saved as the coordinates for the second videofluoroscopic image.

We apply this method to each of the videofloroscopic images. Thus we may obtain coordinates of the hyoid bone independently of possible head movement during videofluoroscopic examination. The maximal horizontal displacement of the anterior part of the hyoid bone is the difference between the maximum and minimum of the horizontal coordinates of the anterior part of the hyoid bone (HA). We calculated in the same way the horizontal displacement of the posterior part of the hyoid bone and the vertical displacement of both the anterior and posterior parts of the hyoid bone. Lastly, sometimes patients can stand closer to the videofluoroscopic camera of the videofluoroscopy than others, and so their hyolaryngeal complex is enlarged in the images. Then, the displacement has to be normalized by a physical unit of measurement. For this we have chosen the length of C2-C4 [86], and accordingly divided all the hyoid bone displacements by the length of C2-C4.

3.5 STATISTICAL ANALYSIS

To examine the association between measures of displacement, participant characteristics, and swallowing conditions, we fit a series of linear mixed models with each of the displacement measures as the response variable; each of the participant characteristics and swallowing conditions, both individually and together as the independent variable(s); and a participant random effect to account for multiple measurements from the same participant. We fit a series of similar models with each of the individual high resolution cervical auscultation (HRCA) signal features, one at a time, as independent variables to examine the associations between displacement measures and HRCA signal features. Finally, we adjusted the said models for participant's characteristics and swallowing conditions as covariates to examine independent associations between the same. SAS version 9.3 (SAS Institute, Inc., Cary, North Carolina) was used for all analyses.

4.0 RESULTS

4.1 VALUES OF THE EXTRACTED FEATURES FROM THE SWALLOWING VIBRATIONS AND SOUNDS AND THE MAXIMAL DISPLACEMENT OF THE HYOID BONE

Table 4 depicts the values of horizontal and vertical displacement of the anterior part of the hyoid bone and the horizontal and vertical displacement of the posterior part of the hyoid bone, relative to the C2−C4 length. Table 8 depicts considered feature values for cervical auscultation recordings.

Table 4: Mean and standard deviation of the vertical and horizontal maximum displacement of both anterior and posterior part of the hyoid bone relative to the C2−C4 length.

Maximum displacement		Values
anterior	horizontal	0.357 ± 0.067
	vertical	0.411 ± 0.172
posterior	horizontal	0.380 ± 0.069
	vertical	0.404 ± 0.162

4.2 RELATION BETWEEN THE MAXIMAL DISPLACEMENT OF THE HYOID BONE AND THE PATIENT CRITERION

Table 5 depicts the relationship between each maximal displacement and different patients' characteristics such as sex, age, and race. In addition, the command Yes/No characteristic represents whether a patient is asked to swallow or whether he/she swallows by him/herself instinctively. Finally, we have studied only two PAS scores (i.e., PAS=1 and PAS=2) [58]. All '+' signs denote that there exists a relationship between the criterion and the displacements of the hyoid bone and all '−' signs represent no dependency between the hyoid displacement and considered characteristics. Only the displacement of the posterior part of the hyoid bone is affected by the PAS score or the command Yes/No characteristics. The vertical displacement of the posterior part of the hyoid bone is 0.19 units more for a PAS score of 1 than for a PAS score of 2. The horizontal displacement of posterior part of the hyoid bone is 0.072 less for a command swallow than for a non-command swallow.

Table 5: Relationships between displacement of the hyoid bone and patient's characteristics. $\Delta_{ant(x)}$ stands for the maximal horizontal displacement of the anterior part of the hyoid bone. $\Delta_{ant(y)}$ stands for the maximal vertical displacement of the anterior part of the hyoid bone. $\Delta_{post(x)}$ stands for the maximal horizontal displacement of the posterior part of the hyoid bone. $\Delta_{post(y)}$ stands for the maximal vertical displacement of the posterior part of the hyoid bone.

Patient characteristics	$\Delta_{ant(x)}$	$\Delta_{ant(y)}$	$\Delta_{post(x)}$	$\Delta_{post(y)}$
Sex	−	−	−	−
Age	−	−	−	−
Race	−	−	−	−
Command Yes/No	−	−	+	−
PAS score	−	−	−	+

4.3 RELATION BETWEEN THE EXTRACTED FEATURES FROM THE SWALLOWING VIBRATIONS AND SOUNDS AND THE MAXIMAL DISPLACEMENT OF THE HYOID BONE

Table 6 depicts the dependency between some of the features extracted from cervical auscultation signals and the maximal displacement of the hyoid bone in different directions. The horizontal maximal displacement the anterior part increases by 0.004 units when the peak frequency of the ML axis increases.

The vertical displacement of the anterior part increases when the entropy rate of the SI axis and the kurtosis of the swallowing sounds increases (2.231 units and 0.003 units, respectively). The horizontal displacement of the posterior part decreases by 0.002 units when the spectral centroid of the SI axis increases. The vertical displacement of the posterior part of the hyoid bone decreases by 0.0005 when the bandwidth of the ML axis increases.

Table 6: Maximum displacement and its dependent features extracted from the tri-axial accelerometer.

Signal	Extracted features	$\Delta_{ant(x)}$	$\Delta_{ant(y)}$	$\Delta_{post(x)}$	$\Delta_{post(y)}$
ML	Bandwidth	$-$	$-$	$-$	$+$
	Peak frequency	$+$	$-$	$-$	$-$
SI	Spectral centroid	$-$	$-$	$+$	$-$
	Entropy rate	$-$	$+$	$-$	$-$
SS	Kurtosis	$-$	$+$	$-$	$-$

4.4 RELATION BETWEEN THE EXTRACTED FEATURES FROM THE SWALLOWING VIBRATIONS AND SOUNDS AND THE PATIENTS CRITERION

Table 7 depicts the dependency between the features extracted from cervical auscultation recordings and patient/swallow characteristics: sex (i.e., female compared to men), age, race (i.e., white versus other), command Yes/No, and PAS scores (i.e., 1 versus 2). The values represent a dependency between the patient's characteristics and the extracted features. They represent the slope of the general trend between the two dependent variables. A negative value represents a decreasing general trend and a positive value stages for an increasing general trend. For example, the bandwidth and the spectral centroid of the ML axis are linked to the PAS score. The spectral centroid is lower by 31.60 when the PAS score is 1 compared to the PAS score of 2, and the bandwidth is lower by 83.21 when the PAS score is 1 compared to a PAS score of 2.

Table 7: Relationships between extracted features from cervical auscultation recordings and clinical variables.

Signal	Extracted features	Sex	Age	Race	Command Yes/No	PAS score
AP	Wavelet entropy	–	–	–	−0.768	–
ML	Kurtosis	–	–	14.236	–	–
	Spectral centroid	–	–	–	–	31.599
	Bandwidth	–	–	–	–	83.208
SS	Kurtosis	–	–	19.533	–	–
	Spectral centroid	–	–	19.773	−17.825	–
	Wavelet entropy	–	–	1.179	–	–

Table 8: Mean and standard deviations of considered feature values. AP represents the anterior-posterior axis, ML the medial-lateral axis and SI the superior-inferior axis of swallowing vibrations. SS represents swallowing sounds.

Extracted features	SI	ML	AP	SS
Time domain:				
Standard deviation	0.036 ± 0.018	0.011 ± 0.006	0.029 ± 0.014	0.032 ± 0.018
Skewness	-0.417 ± 1.125	0.135 ± 0.903	0.614 ± 1.281	-0.338 ± 1.316
Kurtosis	13.021 ± 13.529	12.951 ± 13.348	12.175 ± 10.060	11.919 ± 14.187
Normalized entropy rate	0.926 ± 0.026	0.944 ± 0.019	0.925 ± 0.029	0.904 ± 0.042
Lempel-Ziv complexity	0.233 ± 0.060	0.197 ± 0.057	0.220 ± 0.058	0.279 ± 0.071
Frequency domain:				
Peak frequency	9.694 ± 4.116	10.460 ± 7.568	11.330 ± 15.077	9.885 ± 12.703
Bandwidth	61.643 ± 46.661	94.796 ± 89.831	84.707 ± 54.732	51.759 ± 22.390
Spectral centroid	37.173 ± 23.724	43.369 ± 29.115	43.584 ± 33.284	36.498 ± 17.811
Time-frequency domain:				
Wavelet entropy	1.025 ± 0.654	0.973 ± 0.654	0.877 ± 0.736	1.054 ± 0.821

5.0 DISCUSSION

5.1 HYOID MAXIMAL DISPLACEMENT AND THE PATIENT CHARACTERISTICS

In general, our results depict larger displacements in the vertical direction than in the horizontal direction. The maximal vertical displacements are similar to those found in a previous study and said to be a reference for young healthy swallow of an ultra thin liquid barium [86]. Our sample age is from 44 to 86 so we can extend the reference results for not young and healthy swallow of a thin liquid barium. The maximal horizontal displacements that we found can represent a reference for healthy participants swallowing thin liquid barium since the hypotenuse values of the displacement have similar values compared to Molfenter's study [86].

Our results highlight that the maximal displacement of the anterior and posterior part of the hyoid bone, vertically and horizontally, has no correlation with race, sex, or age. In previous papers, it has been found that the horizontal displacement of the hyoid bone depends on the age [86], [87], [88]; however, our results did not show age dependency. The range of our patients' age is 44–86 years old. Therefore, our lack of young patients from 18 to 43 may have affected our ability to detect the effects of age on the maximal hyoid bone displacement.

In concordance with previous studies, our results agree that hyoid bone displacement does not depend on sex [86], [89]. Since men are usually taller than women, our methods along with those of Molfenter [86], that adjusted absolute linear measures of distance between anatomic structures using participants' own anatomic referents, demonstrate that the difference in the hyoid displacement arises out of difference in height between participants and not of the patient's sex [86], [89]. The effect of the difference of size between sexes on the hyoid bone displacement is canceled by the normalization of C2−C4 length [86], [89]. However, it still remains as an open question whether another possible normalization that would also cancel the size effect on the hyoid bone displacement. We are currently investigating other anatomic scalars to determine if this is the case and the extent to which other, more convenient scalars might prove as accurate while being clinically expedient in order to judge hyoid displacement during videofluoroscopy.

The horizontal maximal displacement of the posterior part of the hyoid bone only seems to depend on whether the patient has been commanded to swallow or not. Prior studies have documented that the command swallow condition alters several temporal aspects of swallow physiology when compared to a natural uncued swallowing condition in healthy participants [90], [91], [92]. However, our sample contains only five commanded swallows out of 31. Moreover, despite our patients producing PAS scores of 1 and 2 which are healthy PAS scores, all of our patients were referred because of suspected dysphagia. The use of healthy people without suspicion of dysphagia could produce a different result.

Vertical displacement of the posterior landmark of the hyoid was associated with PAS scores, but the range of PAS scores that we investigated was narrow (PAS scores of 1 and 2). Our conjecture is that because a score of 1 represents no laryngeal penetration and 2 represents shallow, transient laryngeal penetration, hyoid vertical movement may be associated with more timely laryngeal closure. However, conclusions regarding this result cannot be made.

5.2 FEATURE EXTRACTION FROM CERVICAL AUSCULTATION RECORDINGS

According to the results shown in Table 8, the amplitude of the recorded signals is narrowly distributed around their mean values, as all four different recordings exhibited small standard deviation values. This is further demonstrated by high kurtosis values. The distribution of signal amplitude values is symmetric since the skewness values are low for all signals considered. Each signal has close peak and spectral centroid values, but all have different bandwidth values. As in a previous study, the wavelet entropies are almost the same and close to one [15]. We can conclude that all signals considered have approximately the same level of disorder. All the extracted features are in the same range as it has been found for safe swallows of thin bolus [15], [35].

5.3 HYOID BONE DISPLACEMENT AND CERVICAL AUSCULTATION RECORDINGS

The maximal vertical displacement seems to be related to features from the superior-inferior, medial-lateral vibrations and from swallowing sounds. First, the vertical displacement of the anterior part seems to affect the entropy rate of the SI axis vibrations, and the kurtosis of the swallowing sounds. In other words, the vertical displacement of the anterior part may affect how the swallowing sounds are peaked or flat compared to normal distribution and how a signal is regular or random [15]. When the vertical displacement of the anterior part increases the swallowing sounds tend to be less peaked, since the kurtosis increased by 0.003 units, and the signal from the SI axis seems to be more regular since the entropy rate increases by 2.231 units. Second, when the vertical displacement of the posterior part increases the bandwidth of the ML axis vibrations seems to decreased by 0.002 units. Therefore, a larger vertical displacement of the posterior part results in a signal spread on a smaller frequency range.

The horizontal displacement is dependent on features from the SI and ML vibrations. First, the horizontal displacement of the anterior part of the hyoid bone seems to depend on the peak frequency ML vibrations. For a larger maximal horizontal displacement of the anterior part of the hyoid bone, the maximal frequency of ML vibrations decreases. Second, when the maximal horizontal displacement of the posterior part of the hyoid bone increases, the median of the difference between the upper and lower frequencies of the SI vibrations decreases (by 0.002 units).

5.4 EXTRACTED CERVICAL AUSCULTATION FEATURES AND PATIENT CHARACTERISTICS

In a previous study, it has been found that sex slightly affects some features from the AP, SI vibrations and from the swallowing sounds [40], [36]. However, according to a previous study, age seems to not significantly affect swallowing vibrations [40]. In our study, we have found that sex also does not affect swallowing vibrations or sounds. This slight difference between results may be explained by the smaller sample of men and women we have (13 females and 12 males), compared to their study (28 females-27 males) [40]. Hence, sex effects may still remain as an open question, and future studies should investigate sex effects on a larger sample of female and male participants.

Age seems to have no effect on swallowing vibrations or sounds. In a previous study, they have found that age affects some swallowing vibrations and sounds features but their sample were divided in four age groups (18−29, 30−41, 42−53, 54−65) [93]. However, our sample age range is 44−86 years old. Hence, we lack young participants from 18 to 40 years of age to examine similar age effects on swallowing sounds and vibrations.

Our results also showed that race impacted some extracted features from swallowing vibrations and sounds. However, previous studies have found no racial differentiation in swallow physiology and our sample is very small and not racially diverse, therefore it does not provide any evidence regarding race effects.

In our study, we focused on safe swallows (PAS score < 3). A PAS score of 1 represents a healthy swallow without material penetrating the airway [58], [94]. A PAS score of 2 represents the case when the bolus remains above the vocal folds before being totally ejected from the airway into the esophagus [58], [94]. Nevertheless, even this narrow range of PAS score seems to demonstrate an influence on some features from the ML vibrations. For a PAS score of 2, the signal of the ML sensor has a significantly larger spectral centroid and bandwidth (31.59 and 83.21 units more) than for swallows with PAS scores of 1. This result may be explained by the ejection of material from the airway producing additional signal information in the ML vibrations and in the median of the range of those frequencies. Hence, future studies should investigate whether the other PAS scores from 3 to 8 could affect swallowing vibrations and sounds, and whether it would be possible to classify the different PAS scores according to the dependent features from the swallowing sounds and vibrations.

A higher value of wavelet entropy for a command swallow than for a non-command swallow indicates a more ordered signal for a command swallow than for a non-command swallow. So, a command swallow seems to have more disordered AP vibrations than a non-command swallow. Additionally, the swallowing sounds of command swallows have lower spectral centroid values than for non-command swallows. However, it should be stated that our sample has only five non-command swallows out of 31 swallows. Therefore, the difference between command and non-command swallows still remains an open question.

6.0 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

In this study, we have analyzed the relationship between hyoid bone displacement during swallowing and signal features extracted from the swallowing vibrations and sounds. We have considered 31 swallows and obtained the time, frequency, and time-frequency domain features. The results showed relationships between the extracted features and each displacement of the hyoid bone considered (vertical and horizontal for both anterior and posterior part of the hyoid bone). We have also verified the dependency of all the different maximal displacements of the hyoid bone on specified patient's characteristics such as sex, age, ethnicity and commend swallows. Finally, we have found dependency between the different patient's characteristics and the extracted features from cervical auscultation recordings.

6.2 FUTURE WORK

This study has provided good information on the physical causes of swallowing vibrations and sounds, but some questions still remain open. First, as mentioned earlier, we have found no dependency between the hyoid bone movement and the sex of the patients since we have normalized the maximal hyoid bone displacement of the hyoid bone by the length C2-C4. Since our work and other studies have found no link between the maximal displacement of the hyoid bone and the sex of the patients when normalizing by C2-C4, it would be interesting to study if another possible normalization would cancel the sex affect. For example, we could study the statistical differences between measuring the hyoid bone maximal displacement and normalizing by the length of C2-C4 and normalizing by the length C3. It would be also necessary to study the influence of sex on swallowing vibrations and sounds on a larger sample to verify our results in comparison with the results found in the previous study [40]. Second, our sample has only 5 command swallows out of 31. A future study could, with a larger and more equitable sample of data, study the effect of whether the swallow is commanded or not on the swallowing vibrations and sounds. Furthermore, we have found differences in swallowing vibrations and sounds for the two different penetration aspiration scales considered (1 and 2). In future research, it would be interesting to study the potential differences in swallowing vibrations and sounds for other values in the penetration-aspiration scale, raging from 1 to 8. It may be possible to classify the different PA scores thanks to the extracted features from the swallowing sounds and vibrations. So, the high resolution cervical auscultation could surrogate the videofluoroscopy in order to assess the seriousness of the dysphagia of the patient.

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