THE EFFECTS OF HEAD MOVEMENTS AND FLUIDS WITH INCREASING VISCOSITY ON SWALLOWING SOUNDS

by

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Cervical auscultation (CA) is an affordable, non-invasive technique for diagnosis of dysphagia (swallowing difficulties). CA involves swallowing characterization either via accelerometers or microphones. Though characteristics of the swallowing sound are well known, there is also need for a complete understanding of the baseline characteristics of the device, as well as any in influence of the head motion, age and gender. Also, the effects of fluid viscosity on swallowing accelerometry signals is well understood, there are still open questions about these effects on swallowing sounds. In order to examine these parameters, data was collected from 56 healthy participants. At first, they performed six different tasks with absence of swallowing, than they would complete five water swallows, five swallows of nectar-thick apple juice, and five swallows of honey-thick apple juice. These swallows were completed in neutral head and chin-tuck head positions. After pre-processing of collected signals, a number of features in time, frequency and time-frequency domains were extracted. Statistical test for baseline characteristic of swallowing sound showed that only the skewness and peak frequency did not possess statistical difference for all tasks. This results of the peak frequency indicates that head movement does not significantly affect the swallowing sound, and there is no need for removing those components. However, there is no observed gender, but age dependence was found in the swallowing sound. Nevertheless, participant's age should be considered in the future studies about swallowing sound. The same test was used for investigating influence dependence, and it demonstrated that significant influence of viscosity was found in most of the features. In general, features extracted from swallows in the neutral head position were affected more than swallows from the chin-tuck position. Furthermore, most of differences were found between water and fluids with higher viscosity. Almost no significant difference were found between swallows involving nectar-thick and honey-thick apple juices. Our results also showed that thicker fluids had higher regularity and predictability as demonstrated by the information theoretic features, and a lower frequency content as demonstrated by features in the frequency domain. Therefore, viscosity of fluids should be considered in future investigations involving swallowing sounds.

Keywords: Swallowing, swallowing sounds, viscosity, signal characteristics.

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PREFACE

At first, I would like to thank my adviser for his support, patient and guidance during the my masters studies. I would also like to thank to all my colleagues for great cooperation in data collection process and others who helped during the project. And I want to express great appreciation to committee members for their time.

1.0 INTRODUCTION

1.1 NORMAL DEGLUTITION AND SWALLOWING DIFFICULTIES

The human body requires certain daily amount of food and liquid which provides energy and nutrition. Deglutition (i.e. swallowing) is a critical for human beings and animals to maintain healthy and sustain alive. This is the process of making food and fluids pass from the mouth to the stomach. In order to achieve this transport, food and fluids from the mouth first go through the pharynx into the esophagus, while the epiglottis is shut [1]. This is a complex behavior which involves coordination of several anatomical structures in the oral cavity, pharynx, larynx, and esophagus [2, 3] which are either voluntary or automatic.

Dysphagia (swallowing difficulties) refers to any swallowing disorder [4], typically occurring in patients who suffer from a variety of neurological conditions (stroke [5], cerebral palsy [6], Parkinson's and other neurodegenerative diseases [7]), head and neck cancer and its treatment [8], iatrogenic conditions or trauma [9]. Dysphagia can also occur due to genetic predispositions or congenital craniofacial syndromes [10]. The signs and symptoms of dysphagia include subjective difficulty in swallowing food or liquids, choking or coughing before, during or after swallowing, due to impaired clearance of swallowed material from the throat into the digestive system, which can cause malnutrition [11], dehydration [12], failure of the immune system [13], psycho-social degradation [14, 15] and in general, a decreased quality of life [16]. A major consequence of dysphagia is aspiration of food and liquids into the airway past the vocal folds and into the respiratory system which leads to airway obstruction, pneumonia, with the increased risk of mortality resulting from both [17, 18].

1.2 TECHNIQUES FOR DIAGNOSIS OF DYSPHAGIA

The videofluoroscopic swallowing study (VFSS) and the fiberoptic endoscopic evaluation of swallowing (FEES) are the currently accepted imaging gold standards [4, 19]. These diagnostic methods are typically readily available in acute care hospitals, rehabilitation centers and outpatient clinics.

VFSS is an imaging technique which uses X-rays for recording the path of swallowed foods and fluids which are mixed with barium. This provides a sequence of images which show the anatomical movements and bolus path. According to the results of VFSS, a speech-language pathologist can identify abnormal swallowing function and the origins of abnormalities. The results of VFSS are believed to be the most reliable compared to other techniques [20]. The high price of equipment, long waiting lists, exposure to radiation and needs for specialist, however, are some of the drawbacks associated with this gold-standard technique. [21, 22].

FEES uses a flexible endoscope which is inserted into the patient's nose. In order to provide a downward view of the pharynx during swallowing, the endoscope should be positioned at the level of the soft palate [4]. Placing the endoscope above the soft plate provides observation of the elevation and retraction of the soft palate, whereas the endoscope placed behind the uvula provides observation of the pharynx immediately before and after the pharyngeal swallow. 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, when the pharyngeal phase is triggered, the pharynx is closed which makes its view unavailable until the pharynx relaxes after the swallow [4], and it is impossible to obtain information about the airway protection. Other disadvantages are that FEES can cause complications such as discomfort, gagging, vomiting, vaso-vagal syncope and complications such as laryngospasm [23], and also must be performed by a trained specialist.

Pulse oximetry is a non-invasive method which uses a probe attached to the finger, toe or earlobe for measuring arterial oxygen saturation level (SpO_2) or the percentage of hemoglobin that is saturated with oxygen, before, during, and after swallowing [24]. It is speculated that in the case of failure of the airway protector, the level of SpO_2 decreases. However, pulse oximetry can provide only information about airway invasion, and cannot provide other comprehensive analysis of dysphagia. The primary limitation of pulse oximetry is the inevitable time delay between the occurrence and detection of airway invasion.

Accelerometry is another non-invasive technique which uses sensor such as accelerometer, attached on the patients neck for recording vibrations of the swallows [25]. Studies showed that acceleromerty signals from healthy and abnormal swallows have certain waveform characteristic [26, 25] and also amplitude of the signal depends of the extent of laryngeal elevation [27], which is an important component of airway protection. A number of studies investigated accelerometer signal for diagnosing dysphagia [28, 29, 30]. Although only anterior-posterior (A-P) accelerometer direction were considered at the beginning, later studies about dual-axis accelerometer signal showed that superior-inferior (S-I) direction contains some information which is absent in A-P direction [29].

1.3 CERVICAL AUSCULTATION

A non-invasive method of screening for dysphagia known as cervical auscultation (CA) has gained popularity in recent years [20], although its ability to identify or predict specific features of dysphagia or guide intervention to alleviate risks associated with dysphagia have not been established [31]. CA usually involves investigating signals acquired via device such as stethoscopes or microphones [32, 33]. It has been shown that sound of the normal swallow and abnormal swallows are different [34], so CA with digital signal processing (DSP) techniques [33, 28], exploits this characteristic for investigating and developing the diagnostic technique. The primary advantage of CA is mobility, low cost, suitable for day to day monitoring and noninvasiveness. On the other hand, making decision and evaluation is subjective and often with low accuracy, but development of algorithms for automatic analysis, can make diagnostic conclusions more objective and significantly decreases the number of erroneous diagnoses. As in all noninvasive screening methods, one attraction of CA is low price and mobility for day-to-day monitoring [33] though its diagnostic value has yet to be established. CA as a tool for screening for dysphagia is still under investigation (e.g., [20, 33]).

1.4 RESEARCH OBJECTIVE

Objective of this research is to investigate baseline characteristic and the effects of fluids with increased viscosity on swallowing sound characteristics, using a microphone with frequency response form 10Hz to 16kHz. Considering baseline characteristic, our goal is to show the relationship between different head motions and whether there is age and gender dependence on the sound? However, we also want to show whether the viscosity of the fluids influence the swallowing sound? Investigation of this parameters is very important for clinical trail.

In order to be more familiar with the swallowing sound, it is important to investigate its baseline characteristic. For example, the chin-tuck head position is such that the head is tilted little forward. Swallowing with the head in this position is a common compensatory technique for those with dysphagia for protecting airwaves [35]. Sejdić *et al.* [36] showed that head motions in the accelerometer signal contains some components which could contaminate the swallowing signal, and later developed an algorithm for removing those components [37]. Thus, the same procedure should be investigated for the swallowing sound. So for the future investigation of the swallowing sound, it is important to examine these parameters.

Also, previous studies indicated that thicker liquids can reduce the amount of material that is aspirated when individuals aspirate thin liquids while swallowing [38] or subjectively improve swallowing symptoms in some individuals who have dysphagia with ordinary liquids so it would be informative to determine whether the effects of increased fluid viscosity on swallowing signal characteristics produces useful information that might add value to auscultation as a screening method [39, 40]. Though there is understanding of the effects of increased viscosity on swallowing accelerometry signals (e.g., [29]), the effects on swallowing acoustics are more challenging to understand. One challenge is that previous studies used microphones of a varying quality to acquire swallowing sounds. In [41], the authors used Sony ECM-C115 microphone with a frequency response from 50Hz to 15kHz to show that duration of the swallow signals are longer for thicker fluids. A similar trend was observed by Reynolds *et al.* [42] using an electret microphone Optimus (Radio-Shack/Tandy Corp, Model 333013), with a nonlinear frequency response form 70Hz to 16kHz. Another challenge to the usefulness of auscultation in dysphagia screening stems from the previously adopted microphones, which were not able to capture low frequency components of swallowing sounds. In our recent study [43], we showed that the swallowing sounds are centered at lower frequencies below 50 Hz and their bandwidth extends up to few hundred Hertz. These open challenges prompted us to conduct the current investigation.

In particular, we examine the signal characteristics in time, frequency and time-frequency domains, while participants completed different head movement tasks and swallows in neutral head-neck posture and the head-neck flexion (chin-tuck) position. To compare our results with the previous study about effects of increase fluid viscosity on swallowing characteristics [29], we also simultaneously collected dual-axis swallowing accelerometry signals.

1.5 THESIS STRUCTURE

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Chapter 2 will describe normal swallowing in humans, swallowing difficulties and treatment for people with swallowing difficulties. Chapter 3 will describe Protocol design and data acquisition process. Chapter 4 introduce data processing, pre-processing steps and mathematical explanation of the features which were considered. Chapter 5 will describe results of the study. Chapter 6 introduce discussion of the results from the Chapter 5. The conclusions and future work will be indicate in Chapter 7.

2.0 BACKGROUND

2.1 SWALLOWING IN HUMANS

Swallowing or deglutition is the first step in the process of transporting food and fluid from the mouth to the stomach [44]. In that step, broken food and fluid goes from the mouth into the pharynx then into the esophagus while shutting the epiglottis [1]. The epiglottis is a flap of connective tissue that is made of elastic cartilage at the base of the tongue, and it points upward most of the time except when food or fluid passes from the oral cavity into the esophagus [45]. This prevents the swallowed material from going into the airways, which can cause aspiration [46]. Swallowing is a complex physiological process which involves a series of complicated motor neural inputs which are either voluntary or reflexive [47].

Normal deglutition proceeds in four phases: oral preparatory phase, oral phase, pharyngeal phase and esophageal phase [48]. The following subsection discusses the four phases in detail. Anatomical structure of mouth and pharynx can be seen at Figure 2.1.

2.1.1 Oral Preparatory Phase

In the oral preparatory phase, food is chewed, mixed with saliva and formed into a cohesive bolus [49]. After the bolus is formed, the tongue creates a cup on its dorsal surface that entraps the bolus between it and the palate [49]. This phase involves activity of teeth, mandible and tongue and consists of two stages [50]. The first stage is the transport of the ingested food or liquid from the incisal area to the molar region of the oral cavity, and the second stage is mechanical breakdown

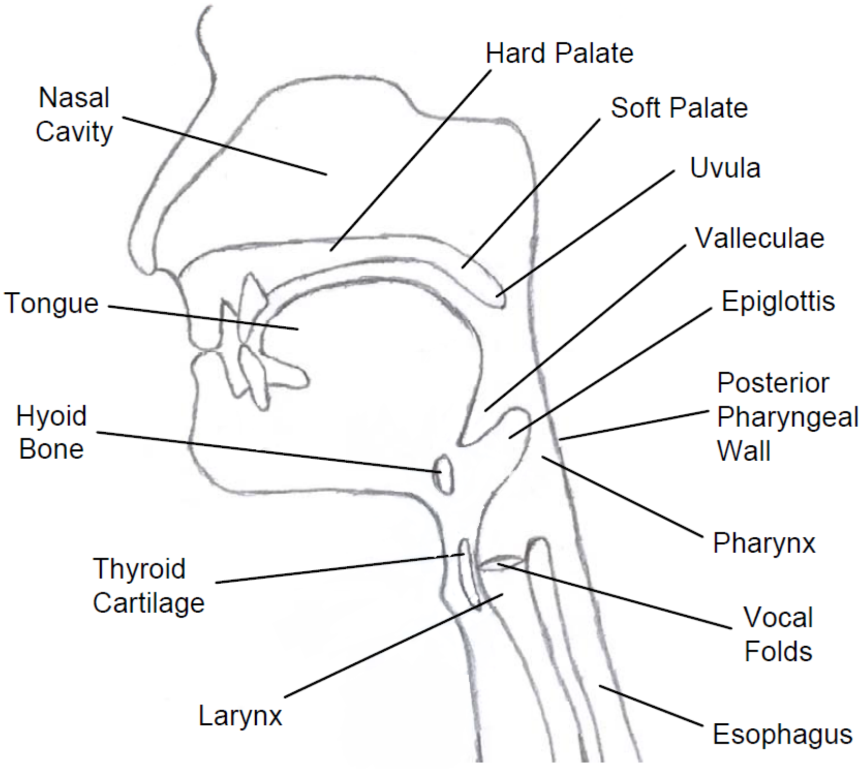

Figure 2.1: A sagittal view of the cervical region showing anatomical structures related to deglutition

of the food in order to make it in a swallowable condition. The second stage exists only when dealing with solid food where bolus formation needs the presence of saliva and food breaking, while in terms of fluids, this stage is absent. The oral preparatory phase contains only voluntary motor activity.

2.1.2 Oral Phase

During the oral phase, the tongue propels the bolus posteriorly to the point where the pharyngeal phase is triggered (Figure 2.2) [49]. It has been shown that in this phase the propulsion force provided by the tongue increases when the viscosity of the bolus is higher [51]. This phase also contain voluntary motor activity.

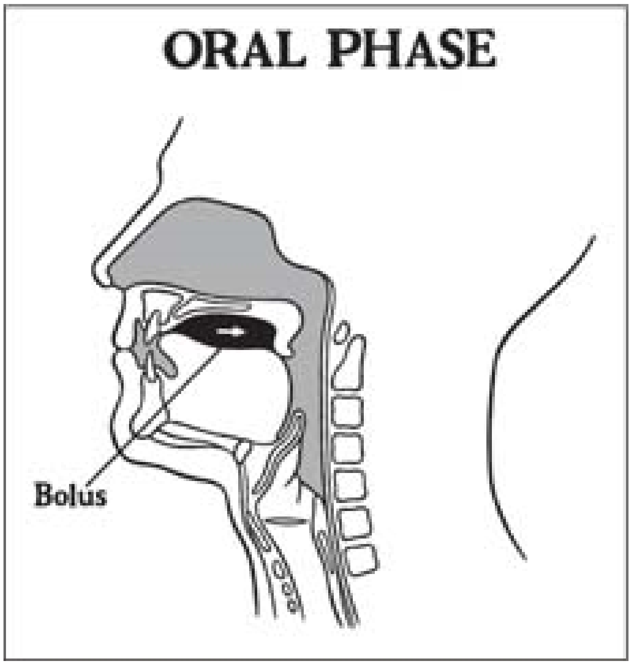

Figure 2.2: An oral phase of swallowing. This figure is adopted from [52]

2.1.3 Pharyngeal Phase

As the bolus reaches the pharynx, special sensory receptors activate the involuntary part of swallowing [25]. The reflex, which is mediated by the swallowing center in the medulla, causes the food to be further pushed back into the pharynx and esophagus by rhythmic but involuntary contractions of several muscles in the back of the mouth, pharynx, and esophagus [53, 54] (Figure

2.3). The oral phase is terminated and the pharyngeal phase starts when the bolus reaches between faucial arches and the point where the tongue base crosses the lower rim of the mandible [4]. The pharyngeal phase is partially voluntary. The part of the swallow, which is necessary to trigger the pharyngeal phase, is voluntary, while the rest phase proceeds automatically [25].

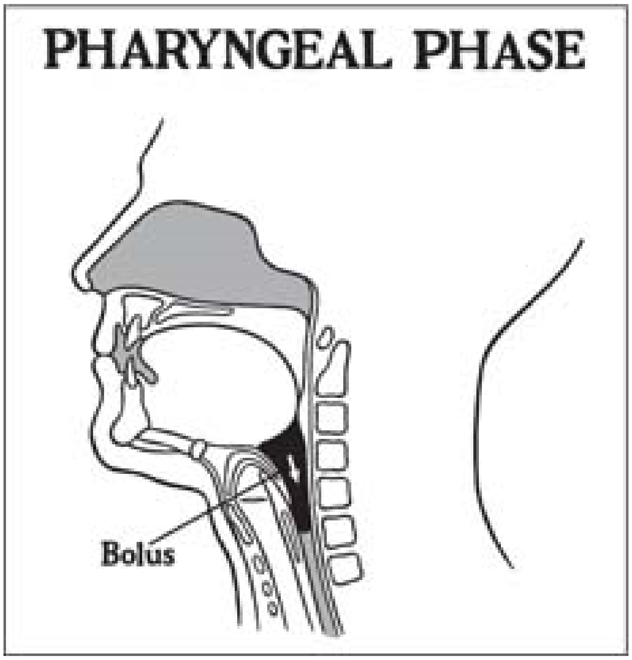

Figure 2.3: Pharyngeal phase of the swallowing. This figure is adopted from [52]

There are several actions which are characteristic for the pharyngeal phase:

- Mouth, nasopharynx, and larynx are blocked.
- Upper esophageal sphincter relaxes to open esophagus.
- Food moves through esophagus by pressure gradients created by peristalsis.
- The tongue base forms a ramp shape so that the bolus is directed into the pharynx.

2.1.4 Esophageal Phase

As food leaves the pharynx, it enters the esophagus, a tube-like muscular structure which leads food into the stomach due to its rhythmic contractions (Figure 2.4). The esophagus has two important sphincters, the upper and lower esophageal sphincters [55]. Under normal conditions they prevent food or saliva from being regurgitated toward the mouth [56]. In doing so, the esophageal sphincters serve as a physical barrier to regurgitated food [56]. The esophageal phase is totally voluntary [4].

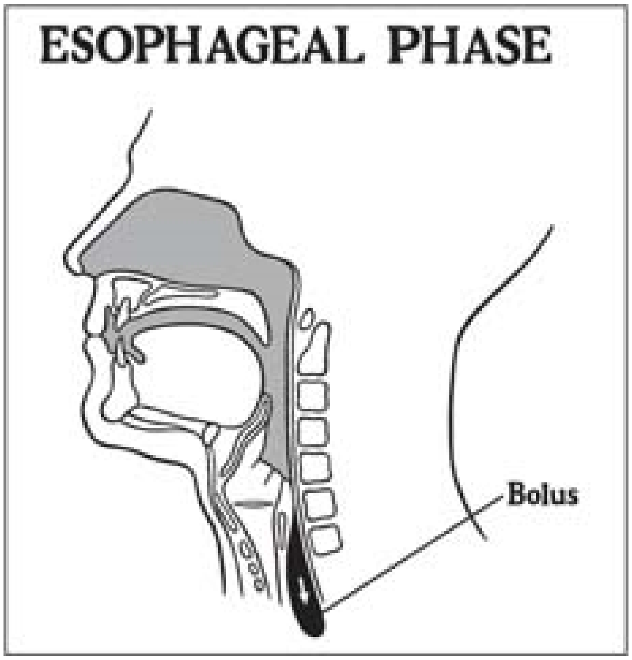

Figure 2.4: Esophageal phase of the swallowing. This figure is adopted from [52]

2.2 SWALLOWING DIFFICULTIES

Swallowing difficulties, or dysphagia, can occur for many reasons [57] and usually in elderly people. Swallowing difficulties is common following stroke, affecting 45% of all patients with stroke [5]. During the early days of an acute stroke, a patient's neurological condition can deteriorate, which usually affects swallowing. Consequently, the ability to swallow could change daily [58] which can cause many other medical conditions. One of those conditions is malnutrition [11]. Malnutrition usually leads to lethargy and ability to perform personal hygiene, to work and socialize [59]. The dehydration [12] can cause saliva to become thicker, which may be affected by breathing difficulties [60]. Another common condition is failure of the immune system [13]. All of these conditions leads to psycho-social degradation [14, 15] and in general a decreased quality of life [16].

Aspiration is a major problem of dysphagia [61]. Because of the jeopardized function of the airway protector, food and liquid enter above the vocal cords into the lungs [62] and hence can cause infection. About 20% of stroke patients with dysphagia develop aspiration pneumonia. Outcomes of aspiration pneumonia range from hospitalization to in the worst case death [18]. The overall mortality rate is from 20% to 50%. Some studies even reported a rate as high as 80% [63, 64, 65]. This very high rate of fatal consequence shows the great importance of early diagnosis of dysphagia.

2.3 TREATMENT FOR DYSPHAGIA

Treatment of dysphagia would mostly depend on the cause. One of the most common treatments is physical therapy which includes exercises for the swallowing muscles [66]. . If the problem is with the brain, nerves, or muscles, exercises would help patients with dysphagia to train muscles to work together to improve swallowing action. Another technique is to find a certain position which would make swallow more effective [67]. Studies showed that certain food and liquids make swallowing easier [68]. Another common therapy is diet modification aimed at increasing bolus viscosity, which not only makes swallowing easier, but also reduces the risk of aspiration pneumonia [69].

A technique for treatment of dysphagia which is the most important in clinical trails is swallowing in the chin-tuck position. The chin-tuck head position is the position when the head is tilted forward. Swallowing with the head in this position is a common compensatory technique for those with dysphagia for protecting the airways [35]. With the head in that position, the distances between the mandible, hyoid and thyroid decrease prior and during the swallow, which improves the closure of the larynx. The chin tuck has been found to significantly decrease the occurrence of aspiration [70].

2.4 PREVIOUSE CONTRIBUTION ABOUT CERVICAL AUSCULTATION

Cervical Auscultation (CA) describes several techniques and each of them uses different acoustic information. Auscultation with a laryngeal microphone provides a broad spectrum sound of muscle and fluid movement and breath exchange. Even though the frequency response characteristics of the different devices used in previous studies varied among models [38, 41, 42], it gave significant contribution for the future studies.

Acoustic analyses of the pharyngeal swallow have focused on either the mechanical or respiratory components. The idea was to make a correlation between mechanical sounds captured with device with specific physiological events during the pharyngeal swallow [34, 71]. Respiratory patterns surrounding normal and abnormal swallowing have been studied with contact microphones. These studies have found that for normal adults, respiratory apnea occurs during pharyngeal swallows [72, 73]. There is evidence to suggest that the respiratory pattern during swallowing is different for adults with dysphagia. It has been found that respiratory patterning is more variable, swallow apnea is less consistent, and aspiration occurs more frequently after the swallow [74].

However, the physiological origin of the swallow sound has not been clearly identified despite several attempts [75], so there is a need for more detailed investigation.

3.0 PROTOCOL DESIGN AND DATA ACQUISITION

3.1 SUBJECTS

In this study, data was collected from 56 healthy adults aged 18 to 65 years. All participants in the data acquisition process. had no previous history of neurological diseases, swallowing disorder, head, neck or spinal trauma, neck, brain or mouth cancer or abnormal brain activity. Each subject provided written consent as well as age, height and weight information. The study was approved by Institutional Review Board at the University of Pittsburgh.

Participants were divided in the four different groups according to their ages. First group were people aged from 18 to 29, second group were people aged from 30 to 41, third from 42 to 53, and the last group were people from 54 to 65. Table 3.1 shows participants' distribution over the gender and age.

Table 3.1: Participant distribution

Participants	**18-29**	**30-41**	**42-53**	**54-65**	**Total**
Male	12	8	3	6	29
Female	6	7	5	9	27
Age	22.6 ± 2.8	33.2 ± 2.8	46.0 ± 3.0	59.2 ± 3.6	38.9 ± 14.9

3.2 PROCEDURE

The experiment utilized two sensors. The dual-axis accelerometer (ADXL322, Analog Devices, Norwood, MA, USA) was powered with a 3V power supply (1504 DC/AC Power Supply, B&K Precision Corporation, Yorba Linda, CA, USA). Output of the accelerometer was passed through an amplifier (P55, Grass Technologies,Warwick, RI, USA), which provided 10 times amplification and band-pass filtering from 0.1Hz to 3000Hz. The two accelerometer axes were orientated in two directions, anterior-posterior (A-P) and superior-posterior (S-I). The second sensor, the contact microphone (AKG C411L, AKG Acoustics GmbH, Vienna, Austria) was powered by a power supply (model B29L, AKG, Vienna, Austria) and had frequency response from 10Hz to 18kHz. All signals were recorded using LabView software Signal Express (National Instruments, Austin, TX, USA) which provided 40kHz sampling rate, and recorded data was saved to a hard drive.

The sensors were attached to the subject's neck with double sided tape. The accelerometer was positioned below the thyroid cartilage as shown in Figure 3.1 and the microphone was positioned far enough from the accelerometer such that the two sensors would not come into contact.

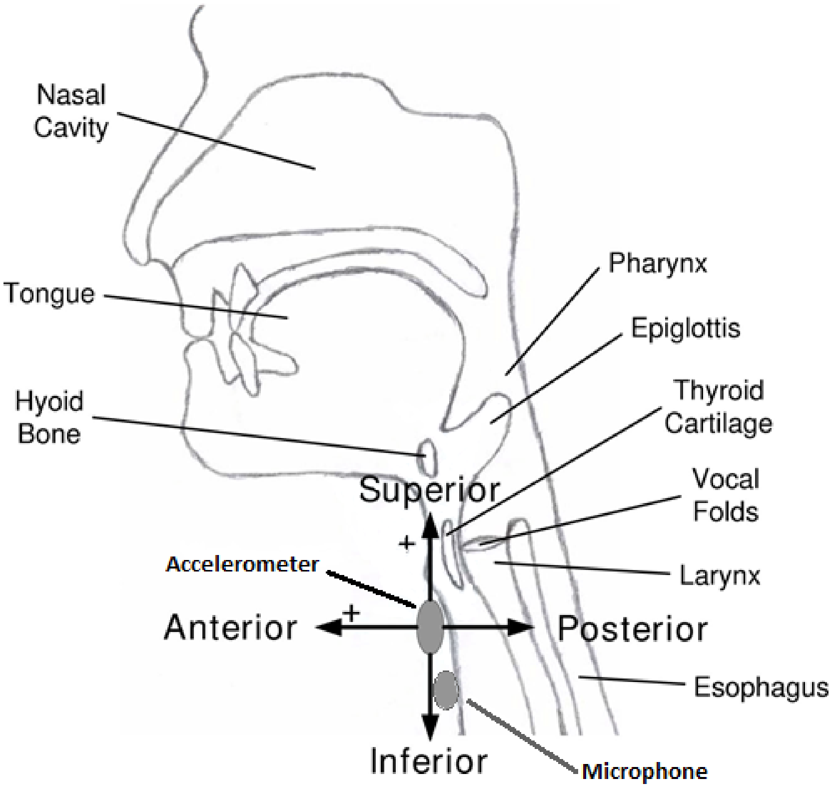

Figure 3.1: Position for accelerometer and microphone

The experimental procedure was divided into two parts and conducted in the same order for all participants. In the first part, we collected data for investigating the effects of head motions on swallowing sounds, while in the second part, the collected data was to be utilized for investigating the influence of viscosity on the swallowing sound characteristics.

3.2.1 Data Collection for Investigation of Baseline Characteristics

In this part of the experiment, the subject was asked to do six different tasks:

- one minute of resting
- 10 seconds of resting with holding breath
- tilt the head forward 10 times
- tilt the head backward 10 times
- tilt the head right 10 times
- tilt the head left 10 times

During these tasks, the subjects were asked to refrain from talking or swallowing.

3.2.2 Data Collection for Investigation of Influence of Viscosity on Swallowing Characteristics

This part of experiment contained two parts. First, participants completed bolus swallows in a neutral-head position, followed by the completion of swallows in a chin-tuck position. In both parts, the subject was asked to take five individual swallows of different fluids: water, nectar consistency and honey consistency apple juices. Thickened apple juices are commercially available products (Nestlé Health Care, Inc. Florham Park, NJ, USA). Nectar consistency and honey consistency apple juices are classified by the Australian Standard for Texture Modified Foods and Fluids, as Mildly Thick-Level 150 for nectar and Moderately Thick-Level 400 for honey-thick. All fluids were served chilled (3-5°C) in cups as a one bolus per cup. Participants were asked to complete the individual swallows of a single bolus at a time at a comfortable pace while consuming appropriate amounts of fluids. The volume of material swallowed was not controlled for.

4.0 DATA PROCESSING

Data processing consisted of two steps. In the first step, all collected signals were pre-processed according to previously proposed algorithm (e.g., [29]) in order to remove unwanted components from the original signal. After pre-processing, feature extraction on all signals was carried out.

4.1 PRE-PROCESSING

4.1.1 Pre-processing of Data for Investigation of Baseline Characteristics

In order to annul effects from the recording devices, a finite impulse response (FIR) filter, was created using AR coefficients from 18 baseline recordings, a method described in [76]. After filtering, the signals were denoised with 10-level discrete wavelet decomposition using the discrete Meyer wavelet with soft-thresholding. The global denoising threshold as proposed in [77] was used for wavelet denoising.

As the frequency response of the considered microphone is from 10 Hz to 18 kHz, the pre-processed signals were filtered with a 4 order, infinite impulse response (IIR) Butterworth high pass filter with cut off frequency of 10Hz to eliminate any spurious frequency components that may present as a side effect of pre-processing steps.

As an example, in the Figure 4.1 is presented original signal and and signal after all pre-processing steps for the 10 seconds hold breath task.

4.1.2 Pre-processing of Data for Investigation of Influence of Viscosity on Swallowing Characteristics

Figure 4.2 present an example of raw signal (water swallows in neutral head position). According to the picture, even signal is noisy, it is clearly visible 5 swallows. In the end, from this row signal, we should get 5 separate swallows, clear from noise and other unwanted elements.

All acquired signals were initially filtered with an FIR filter to annul the effects of the data acquisition equipment (Figure 4.3. The filters for swallowing accelerometry signals and swallowing sounds were designed according to the procedure outlined in [76] using 18 table-top recordings in a quiet room.

Next, we removed very low frequency components from the dual-axis accelerometry signals associated with head movements [37]. However, the swallowing sound was not affected by any head movements. Therefore, there was no need to perform such an operation for these signals.

Consequently, all signals were denoised with 10-level discrete wavelet decomposition using the discrete Meyer wavelet with soft-thresholding using the global denoising threshold, T_{den} defined

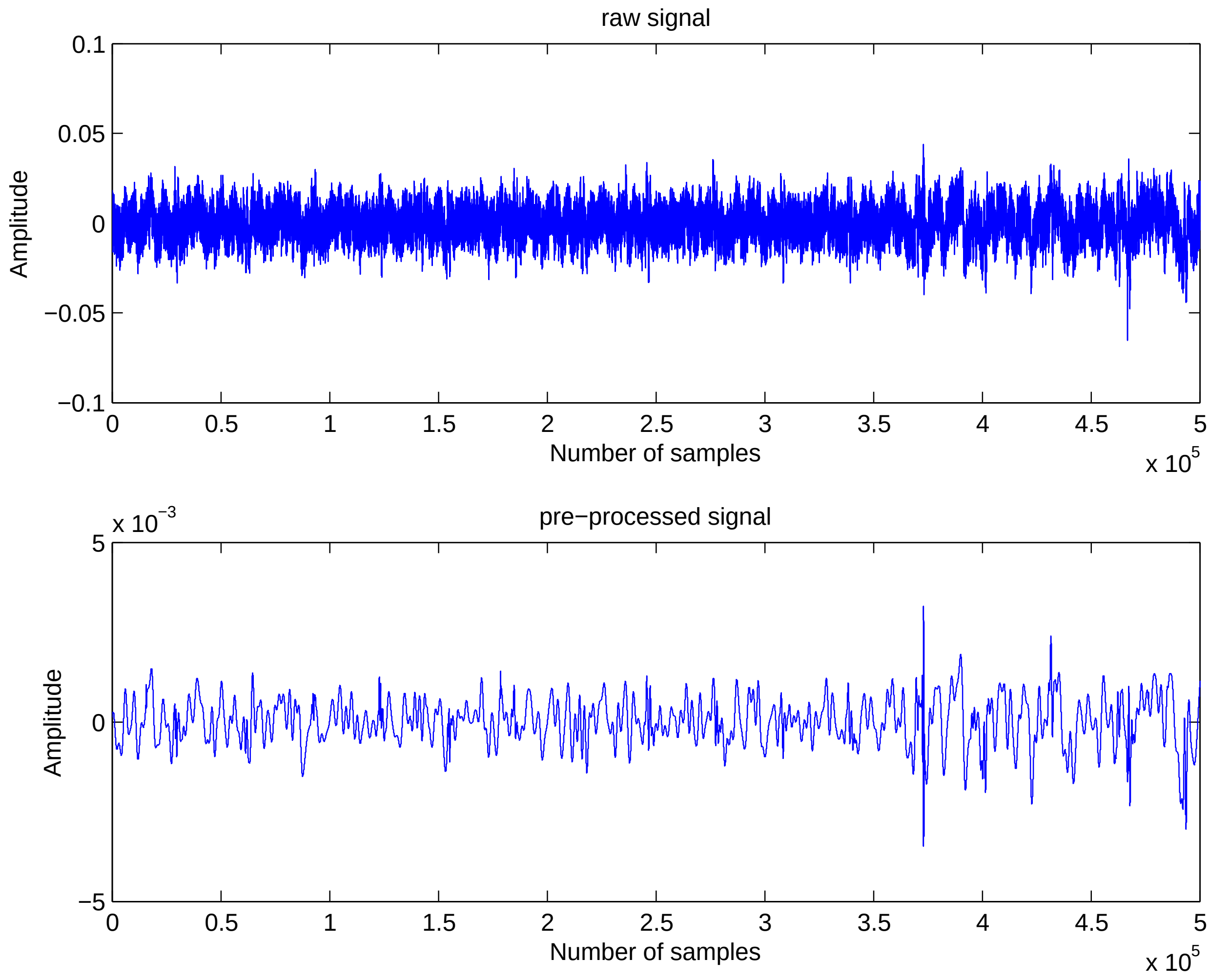

Figure 4.1: Original signal (above) and pre-processed signal (below)

as:

$$T_{den} = \frac{med(|d_1|)\sqrt{2\log n}}{0.6745}, \tag{4.1}$$

where d_1 represents wavelet coefficients at the first level, n is length of the signal and med is median operator [77]. Figure 4.4 present swallowing accelerometry signal and swallowing sound segmentation on separate swallows.

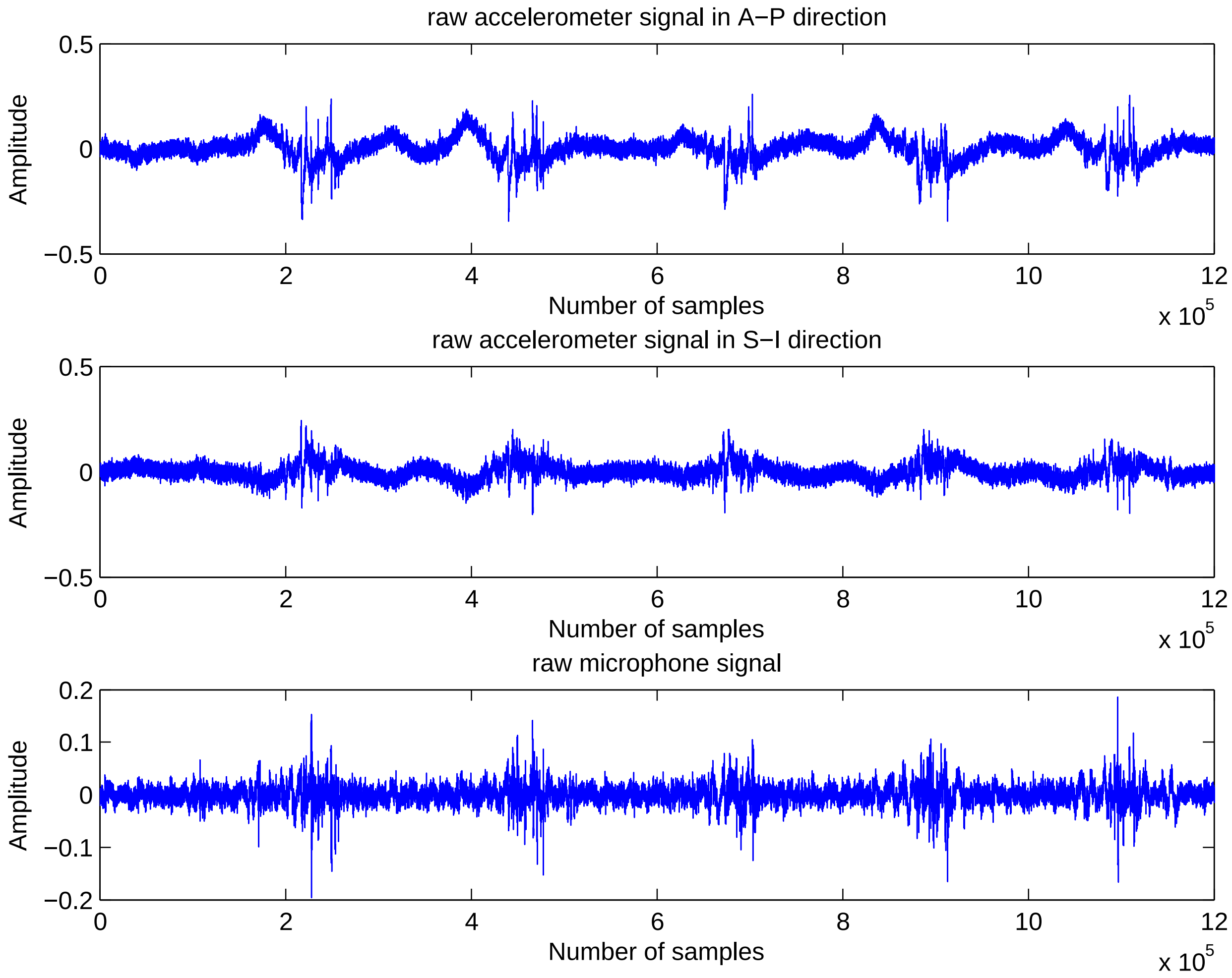

Figure 4.2: Raw swallowing accelerometry signal and swallowing sound

The last pre-processing step was the segmentation of signals carried out according to the sequential fuzzy c-means algorithm designed for dual-axis accelerometry signals [36]. All segmentation results were verified visually, if any of them were incorrect, swallows were segmented manually. Swallows which could not be segmented were excluded from the study. The time instances identified in this process as the beginning and the end of each swallow were then used to segment

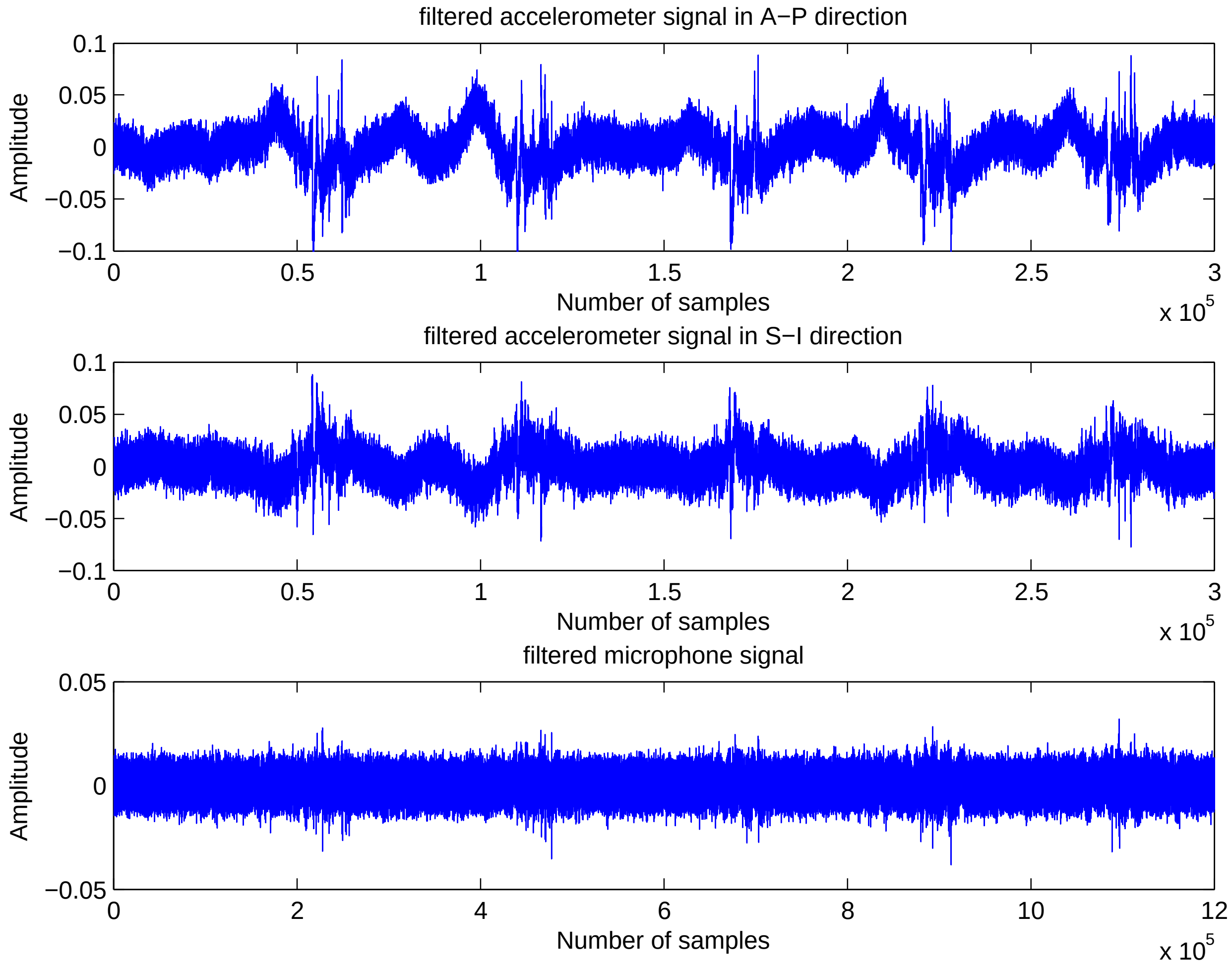

Figure 4.3: Filtered swallowing accelerometry signal and swallowing sound

the swallowing sound. As it is shown on the Figure 4.5, at the end we would have 5 separated swallows signals from both accelerometer direction and swallowing sound.

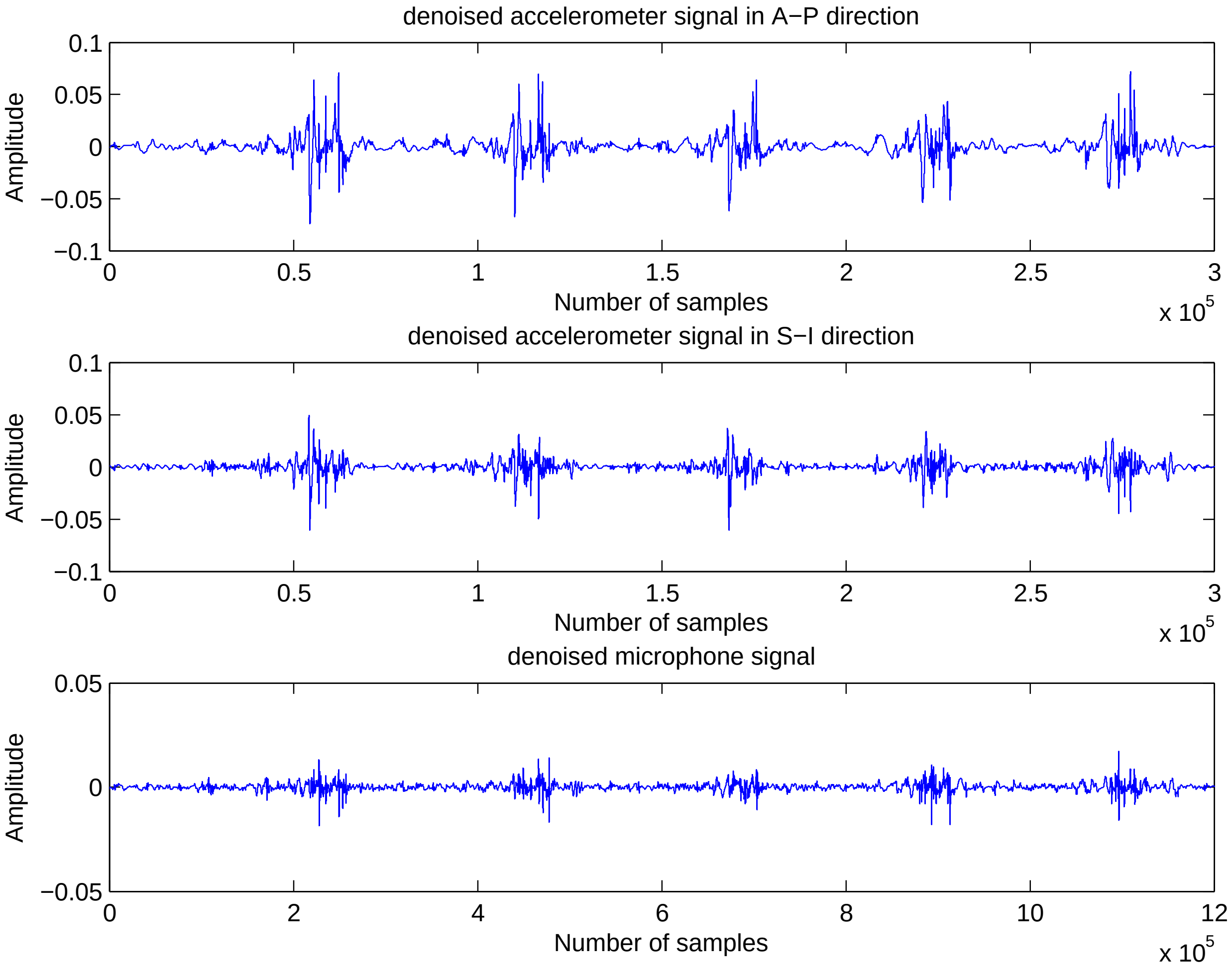

Figure 4.4: swallowing accelerometry signal and swallowing sound before segmentation

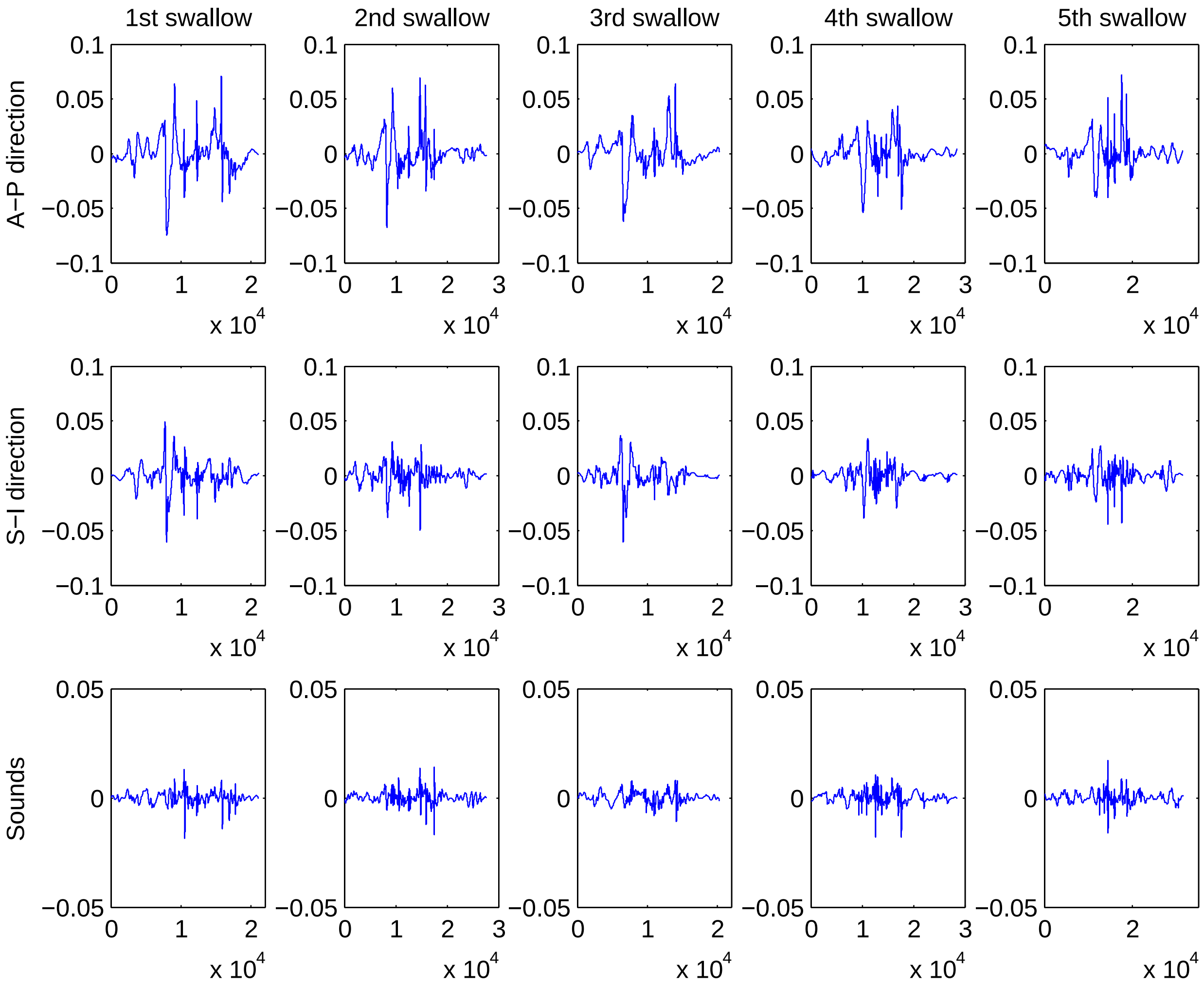

Figure 4.5: Pre-processed swallowing accelerometry signal and swallowing sound

4.2 FEATURE EXTRACTION

Each swallowing sound could be represented as a discrete time series, $M = \{m_1, m_2, ..., m_n\}$. Different signal features can be used to describe swallowing characteristics, and we summarize below the features considered in this study. The same set of features was considered for both swallowing sounds and dual-axis swallowing accelerometry signals.

4.2.1 Statistical Features

- The mean (average) value of a signal represents unbiased estimation of the amplitude of the signal. An equation for calculating the mean value is given as

$$\mu_m = \frac{1}{n}\sum_{i=1}^{n} m_i. \tag{4.2}$$

- The standard deviation is a measure of variation from the mean value. It can be obtained as

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(m_i - \mu_m)^2}. \tag{4.3}$$

- The skewness represents symmetry of a distribution of the signal [29]. It can be calculated as,

$$\nu = \frac{\frac{1}{n}\sum_{i=1}^{n}(m_i - \mu_m)^3}{(\frac{1}{n}\sum_{i=1}^{n}(m_i - \mu_m)^2)^{1.5}}. \tag{4.4}$$

- The kurtosis is a measure of the ”peakedness” of the probability distribution of a variable. For a high value of kurtosis, the distribution is sharp and narrow, with heavy tails. A low kurtosis value indicated a flat distribution peak and thin tails. Kurtosis is calculated as

$$\varpi = \frac{\frac{1}{n}\sum_{i=1}^{n}(m_i - \mu_m)^3}{(\frac{1}{n}\sum_{i=1}^{n}(m_i - \mu_m)^2)^2}. \tag{4.5}$$

4.2.2 Information-Theoretic Features

- The entropy rate [78, 79] quantifies the extent of regularity in a signal. It provides important information about swallows as an random process. Entropy rate is calculated in several steps. First, a signal M should be normalized to zero mean and unit variance. The normalized M is then quantized to 10 equally spaced levels. Those 10 levels are ranged from minimum to maximum and marked with integer numbers from 0 to 9. Then the quantized signal $\hat{M} = \{\hat{m}_1, \hat{m}_2, ..., \hat{m}_n\}$, with U consecutive points is coded as

  $$s_i = \hat{m}_{i+U-1} \cdot 10^{U-1} + ... + \hat{m}_i \cdot 10^0, \tag{4.6}$$

  where $i = 1, 2, ..., n-U+1$, and $S_i = \{s_1, s_2, s_{n-U+1}\}$ are coded integers. Because of the 10 quantization levels, 10 is used as a base. Using the Shannon entropy formula, the entropy is estimated as

  $$E(U) = -\sum_{k=1}^{10^{U-1}} P_{S_u}(k) \cdot lnP_{S_U}(k), \tag{4.7}$$

  where P_{S_u} is probability of observing k in S_u, approximated by the corresponding sample frequency. The entropy is then normalized using following formula

  $$\widehat{NE(U)} = \frac{E(U) - E(U-1) + E(1) \cdot \alpha}{E(1)}, \tag{4.8}$$

  where α is the percentage of the coded integers in S_i that occurred only once. Finally, the regulatory index as a measure of the entropy rate is calculated as

  $$\rho = 1 - min\widehat{NE(U)}. \tag{4.9}$$

  ρ takes value from 0 to 1, wherefor regulatory index is equal to 1 indicates maximum of regularity, while value of 0 represents maximum of randomness.

- The Lempel-Ziv complexity (L-Z) [80] provides information about predictability of the signal. To compute the L-Z complexity, a signal M should be first quantized into 100 equally spaced levels. Then this 100 levels are ranged from minimum to maximum values. In the next step, the quantized signal $A_1^n = \{a_1, a_2, ..., a_n\}$ was decomposed in L different blocks of the length $l - j + 1$, so that $A_1^n = \{\psi_1, \psi_2, ..., \psi_n\}$. Blocks are defined as

$$\Psi = A_1^n = \{a_j, a_{j+1}, ..., a_l\}, 1 \leq j \leq l \leq n \tag{4.10}$$

The first block is equal to the first element of the quantized signal. Other blocks are defined as

$$\Psi_{m+1} = A_{h_m+1}^{h_{m+1}}, m \in \mathbb{Z}^+ \tag{4.11}$$

where h_m is ending index for ψ_m. Finally, the L-Z complexity is calculated as

$$LZ = \frac{L \log_{100} n}{n} \tag{4.12}$$

4.2.3 Frequency Features

- The peak frequency of a signal is defined as

$$f_p = \underset{f \in [0, f_{max}]}{\text{argmax}} |F_M(f)|^2, \tag{4.13}$$

  where f_{max} is the highest available frequency in a signal and F_M represents the Fourier transform of a signal.

- The centroid frequency indicates position of the center of mass in the signal in the frequency domain [76]. For the signal, M, it is estimated as

$$f_c = \frac{\int\limits_0^{f_{max}} f |F_M(f)|^2 df}{\int\limits_0^{f_{max}} |F_M(f)|^2 df}. \tag{4.14}$$

- Bandwidth represents spectral spread and it is defined as

$$BW = \sqrt{\frac{\int_0^{f_{max}} (f - f_c)^2 \, |F_M(f)|^2 df}{\int_0^{f_{max}} |F_M(f)|^2 df}}. \tag{4.15}$$

4.2.4 Time-Frequency Features

- The relative energy was computed using a 10-level discrete wavelet decomposition of the signal with the Meyer wavelet [29, 81, 82, 83]. The energy at each decomposition level is computed using the Euclidean norm of decomposition coefficient vectors:

$$E_{a_{10}} = ||a_{10}||^2, \tag{4.16}$$

$$E_{d_i} = ||d_i||^2, \tag{4.17}$$

where a_{10} is the approximation signal and d_i is detail signal. The total energy was calculated as

$$E_T = E_{a_{10}} + \sum_{i=1}^{10} E_{d_i}, \tag{4.18}$$

Finally, percent of relative energy contribution from each decomposition level was computed as

$$E_{t_{a_{10}}} = \frac{E_{a_{10}}}{E_T} \times 100\%, \tag{4.19}$$

$$E_{t_{d_i}} = \frac{E_{d_i}}{E_T} \times 100\%, \tag{4.20}$$

for $i = 1, 2, ..., 10$.

- Wavelet entropy describes the information distribution in the time-frequency domain. Wavelet entropy was computed using 10-level wavelet decomposition and relative energy computed above, with following formula:

$$WE = -\frac{E_{t_{a_{10}}}}{100} \cdot log_2 \frac{E_{t_{a_{10}}}}{100} - \sum_{i=1}^{10} \frac{E_{t_{d_i}}}{100} \cdot log_2 \frac{E_{t_{d_i}}}{100}, \tag{4.21}$$

4.2.5 Data Analysis

For investigating baseline characteristics of the swallowing sound, the statistical differences between all different conditions were tested using the Kruskal-Wallis test [84]. Next, the Wilcoxon rank-sum test [85] was used for determining pairwise statistical differences between similar head motions. Namely, we examined the statistical differences between the 1 minute baseline and 10 seconds breath holding segments, forward and backward head tilts, and between right and left head tilts. Due to the clinical significance of the chin-tuck position, statistical differences between the 1 minute baseline and the forward head tilt position was examined as well. The Wilcoxon rank-sum test was also to examine sex effects. To examine the age effects on features, we employed a standard linear regression [86].

For investigating influence of viscosity on swallowing characteristics, it was used the Wilcoxon rank-sum test for determining pairwise statistical differences between different conditions.

5.0 RESULTS

5.1 RESULTS FOR BASELINE CHARACTERISTICS OF THE SWALLOWING SOUND

The Tables 5.4, 5.2 and 5.3 summarize mean values of the different features, expressed as mean ± standard deviation. We first examined the effects of head motions on all considered features. The Kruskal-Wallis test showed that only skewness (ν), peak frequency (f_p) and $d1$ relative energy level did not exhibit significant statistical differences between different tasks ($p > 0.05$).

Table 5.1: Time domain features for cervical auscultation signals. * denotes multiplication by 10^{-2}, ** denotes multiplication by 10^2.

Feature	**1 minute baseline**	**10 sec hold breath**	**tilt forward**	**tilt backward**	**tilt right**	**tilt left**
s^{**}	0.04 ± 0.01	0.04 ± 0.01	0.19 ± 0.04	0.14 ± 0.05	0.11 ± 0.02	0.12 ± 0.04
ν	-0.53 ± 0.22	-0.98 ± 0.93	-1.21 ± 2.42	-0.79 ± 0.75	0.13 ± 0.09	1.04 ± 0.71
ϖ^{*}	50.4 ± 29.1	7.91 ± 4.52	26.2 ± 8.95	16.3 ± 7.74	15.1 ± 5.75	6.51 ± 2.81
ρ	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01	0.99 ± 0.01
LZ^{**}	0.81 ± 0.08	1.86 ± 0.12	0.66 ± 0.08	0.96 ± 0.11	1.14 ± 0.09	1.14 ± 0.09

Pairwise comparisons between coronal tilts did not reveal significant differences for any of the features ($p > 0.05$). Pairwise comparison between sagittal tilts did not show statistical difference for standard deviation (σ), skewness, and entropy rate (ρ), as well as for all of the frequency-domain features ($p > 0.05$). Positive sagittal tilts showed higher mean value for kurtosis (ϖ) ($p = 0.02$) and lower mean value for Lempel-Ziv complexity (LZ) ($p = 0.04$) than the negative direction. While performing pairwise comparisons for the time-frequency domain features, we observed that the wavelet entropy (WE) and most of the relative energy levels were not affected by head motion ($p > 0.05$). The relative energy distribution was only statistically different between tilting forward and backward for the levels $d4$ and $d3$ ($p < 0.05$).

Table 5.2: Frequency domain features for cervical auscultation signals.

Feature	**1 minute baseline**	**10 sec hold breath**	**tilt forward**	**tilt backward**	**tilt right**	**tilt left**
f_p	14.8 ± 0.79	16.5 ± 0.97	20.6 ± 3.96	15.2 ± 1.44	16.7 ± 3.03	16.8 ± 3.71
f_c	131 ± 40.8	84.2 ± 27.3	434 ± 80.1	287 ± 56.9	325 ± 87.4	218 ± 83.3
BW	556 ± 151	239 ± 69.7	963 ± 154	782 ± 127	325 ± 158	499 ± 116

The pairwise comparison between 1 minute baseline and 10 seconds breath holding were not statistically different the standard deviation, skewness and entropy rate ($p > 0.05$). The 1 minute baseline showed higher mean value for kurtosis ($p << 0.01$) and lower mean value for L-Z complexity ($p << 0.01$) than the breath holding segments. The observation of frequency domain features for the same pairwise comparison shows that peak frequency was not statistically different between the 1 minute baseline and breath holding segments. However, the 1 minute baseline segment had higher mean value of centroid frequency (f_c) and bandwidth (BW) than the 10 seconds breath holding segments. The wavelet entropy and the relative energy in levels $a10$, $d3$ and $d2$, were not statistically affected ($p > 0.05$). Significant differences were found between the 1 minute baseline and 10 seconds breath holding segments for relative energy in the levels $d10$, $d9$, $d8$, $d7$, $d6$, $d5$, $d4$ and $d1$.

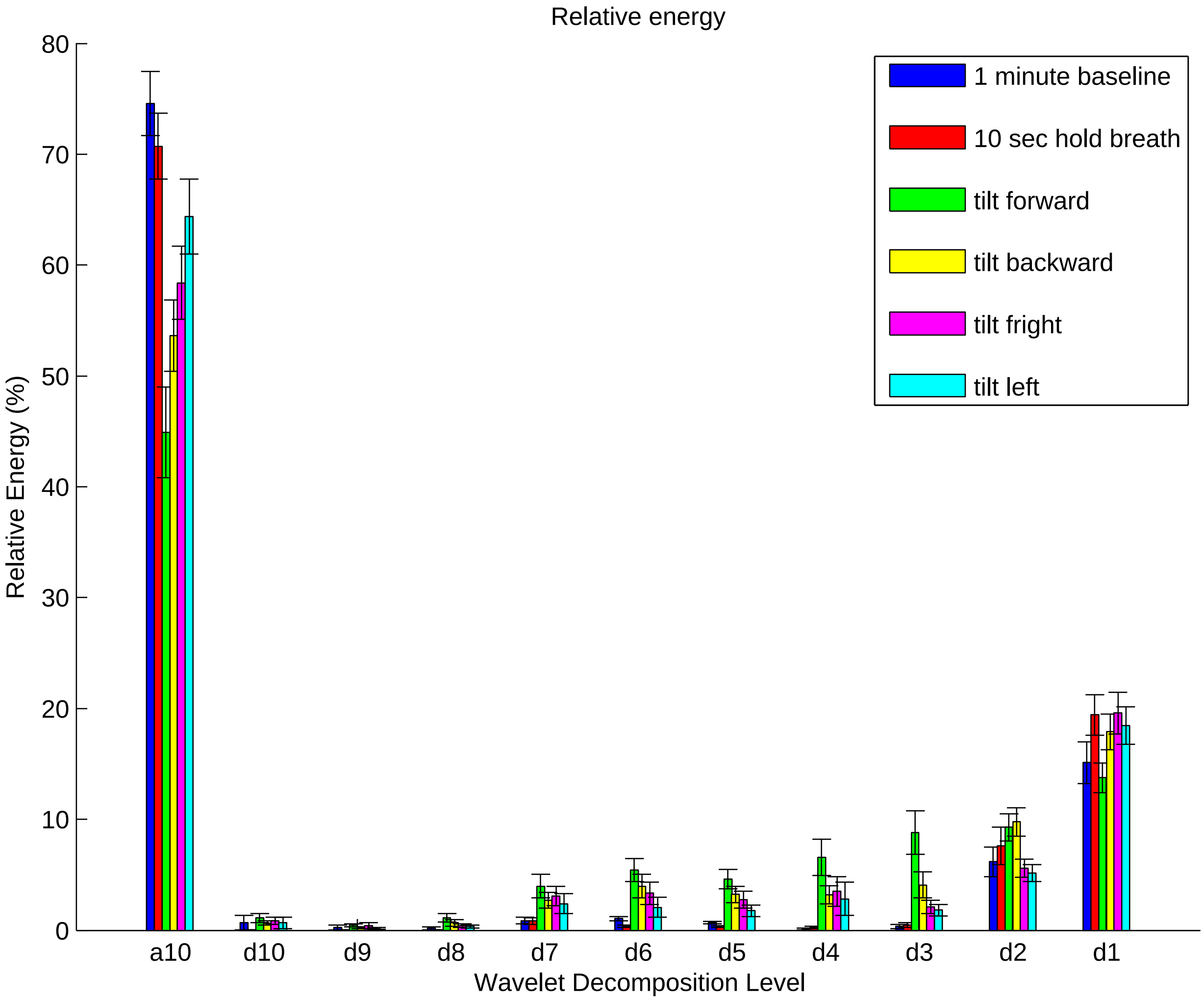

Figure 5.1: Mean relative energy per decomposition band.

Pairwise comparison between 1 minute baseline and head tilting forward did not show statistical difference for skewness, L-Z complexity, entropy rate, peak frequency and $d1$ relative energy level ($p > 0.05$), while all other feature show significant difference ($p << 0.01$).

Table 5.3: Time-frequency domain features.

Feature	**1 minute baseline**	**10 sec hold breath**	**tilt forward**	**tilt backward**	**tilt right**	**tilt left**
WE	0.93 ± 0.06	0.97 ± 0.06	1.85 ± 0.11	1.67 ± 0.09	1.44 ± 0.09	1.25 ± 0.09

Sex differences were not present for most of the features except for the skewness during the 1 minute baseline ($p = 0.02$) and kurtosis during tilting left ($p = 0.02$).

According to the results of linear regression, frequency and time frequency domain features do not depend on the subject's age for all of the head motions ($p > 0.05$). There is an observed age dependence of skewness and kurtosis for 10 seconds breath holding, tilting backward, tilting right and tilting left ($p < 0.02$) tasks. Standard deviation was affected with age for tilting backward, tilting right and tilting left, while L-Z complexity were affected for tilting backward and tilting right ($p < 0.02$).

5.2 RESULTS FOR INFLUENCE OF VISCOSITY ON SWALLOWING CHARACTERISTICS OF THE SWALLOWING SOUND

Results are presented as a mean value ± standard deviation. We analyzed 271 water swallows in neutral and 274 in chin-tuck position, 277 nectar-thick apple juice in neutral and 275 in chin-tuck position, and 273 honey-thick apple juice swallows in neutral and 273 in the chin tuck position.

5.2.1 Time Domain Features Results

Table 5.4 summarizes the time domain features from the swallowing sounds. The results showed that standard deviation (σ), skewness (ν) and kurtosis (ϖ) were not significantly different between the control condition (water) and the thickened liquid conditions in the chin-tuck position ($p > 0.05$). For the swallows in the neutral position, pairwise comparison between water and nectar-thick apple juice revealed statistically significant differences for standard deviation ($p = 0.03$) and skewness ($p = 0.01$). The skewness was significantly different between water and honey-thick apple juice ($p << 0.01$) as well as the kurtosis ($p = 0.02$). Next, we observed significantly higher entropy rates (ρ) for nectar-thick and honey-thick fluids in comparison to water for both head positions ($p << 0.01$). However, the L-Z complexity had statistically the highest values for water swallows for both head maneuvers ($p < 0.05$).

Table 5.4: Time domain features for swallowing sounds. * denotes multiplication by 10^{-2}

	Neutral position			Chin-tuck position		
Feature	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**
s^*	0.54 ± 0.03	0.42 ± 0.02	0.54 ± 0.03	0.54 ± 0.02	0.54 ± 0.02	0.54 ± 0.02
ν	-1.34 ± 0.22	-0.80 ± 0.20	-1.04 ± 0.34	-1.53 ± 0.41	-2.19 ± 0.59	-0.69 ± 0.43
ϖ	92.5 ± 17.1	96.1 ± 16.7	173 ± 43.1	157 ± 37.5	300 ± 57.7	227 ± 41.6
ρ^*	98.7 ± 0.04	99.0 ± 0.04	99.1 ± 0.06	98.1 ± 0.14	98.5 ± 0.10	98.7 ± 0.05
LZ^*	6.14 ± 0.15	5.78 ± 0.16	5.61 ± 0.18	7.45 ± 0.29	6.39 ± 0.26	5.98 ± 0.20

Table 5.5 summarizes the results for the swallowing accelerometry signals. The results showed that in the A-P direction of the accelerometer signal, standard deviation and kurtosis in the chin-tuck position were not affected by the fluid viscosity ($p > 0.05$). Water swallows in the neutral

position had the statistically highest values for standard deviation ($p < 0.01$) and the lowest values for kurtosis ($p < 0.03$). The skewness was statistically different between nectar-thick and honey-thick apple juice in neutral position ($p = 0.03$), and between water and honey-thick apple juice also in chin-tuck position. Furthermore, water swallows had statistically the lowest values for entropy rate ($p < 0.05$) and the highest values for the L-Z complexity ($p << 0.01$) in comparison to other two fluids in both head positions. Also, a pairwise comparison between nectar-thick and honey-thick swallows found significant differences for entropy rate ($p = 0.01$) and L-Z complexity ($p = 0.03$) in the head chin-tuck position.

Table 5.5: Time domain feature for swallowing accelerometry signals. * denotes multiplication by 10^{-2}

	Neutral position			Chin-tuck position		
Feature	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**
σ^* A-P	1.39±0.05	1.16±0.03	0.39±0.02	1.39±0.04	1.39±0.04	1.39±0.04
σ^* S-I	1.11±0.06	0.96±0.03	1.16±0.05	1.16±0.05	1.16±0.04	1.16±0.05
ν A-P	-0.73±0.22	-1.39±0.23	-0.74±0.21	-2.31±0.43	-2.24±0.49	-1.31±0.42
ν S-I	0.28±0.32	0.14±0.37	-0.49±0.39	-0.13±0.31	-0.69±0.29	-0.54±0.37
ϖ A-P	64.5±12.8	62.7±16.7	64.1±13.6	173±30.5	193±42.1	183±33.6
ϖ S-I	81.8±17.0	121±28.1	118±32.2	96.9±21.2	193±21.5	145±22.6
ρ^* A-P	98.8±0.04	99.1±0.02	99.1±0.04	98.5±0.07	98.8±0.06	99.1±0.04
ρ^* S-I	99.1±0.03	99.2±0.02	99.2±0.03	98.5±0.08	98.8±0.04	98.9±0.04
LZ^* A-P	5.46±0.12	4.97±0.12	4.92±0.14	6.26±0.19	5.44±0.17	4.83±0.14
LZ^* S-I	6.36±0.14	6.21±0.15	6.31±0.16	7.17±0.22	6.42±0.21	5.91±0.18

In the S-I direction, the fluid thickness did not have influence on L-Z complexity in the head neutral, and standard deviation and kurtosis in the chin-tuck position ($p < 0.05$). For skewness, nectar swallows showed a significant statistical difference in neutral position ($p < 0.02$), while in chin-tuck position water swallows has the lowest value ($p < 0.02$). The standard deviation was statistically different between water and nectar-thick ($p = 0.02$) as well as kurtosis between water and honey-thick ($p = 0.01$). Additionally, the entropy rate is observed to be significantly lower in water swallows than in the other two stimuli in both head position ($p << 0.01$). Water swallows showed a significantly higher value for the L-Z complexity in the chin-tuck position ($p < 0.05$), while a pairwise comparison between nectar-thick and honey-thick apple juices showed a difference for the entropy rate ($p = 0.02$).

Also, we compared the extracted features between two accelerometer axes. Kurtosis in both head positions did not exhibit a significant statistical difference ($p > 0.05$). The standard deviation in the neutral head position and skewness in the chin-tuck position showed statistical differences between swallows for all stimuli ($p << 0.01$). In the neutral position, skewness was statistically different between water and nectar-thick swallows ($p << 0.01$), while the standard deviation showed statistically difference for nectar-thick swallows in chin-tuck position ($p << 0.01$). The L-Z complexity and the entropy rate were different for all stimuli in both head positions ($p << 0.01$).

5.2.2 Frequency Domain Features Results

Table 5.6 summarizes the values of the considered frequency features for swallowing sounds. The centroid frequency and the bandwidth were not affected by the fluid viscosity in the chin-tick position ($p > 0.05$), while the peak frequency had statistically the highest values for water swallows in the chin-tuck position ($p < 0.04$). In the neutral head position, the peak frequency was statistically higher for water swallows than for honey-thick swallows ($p = 0.01$), while simultaneously the water swallows had smaller bandwidth values than the honey-thick swallows ($p = 0.02$). The water swallows also had the smallest values for the centroid frequency in comparison to the other two types of swallows ($p << 0.01$).

Table 5.6: Frequency domain features extracted from swallowing sounds.

	Neutral position			Chin-tuck position		
Feature	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**
f_p	26.6±4.93	16.7±1.96	8.68±1.69	24.3±3.82	17.9±2.19	13.5±1.71
f_c	446±45.4	464±51.6	493±65.7	739±66.1	802±69.5	767±73.4
BW	759±46.3	736±60.3	725±61.1	1161±68.5	1269±72.6	1236±71.8

The centroid frequency and bandwidth of the swallowing accelerometry signal in the A-P direction was not affected by fluid viscosity in the chin-tuck position ($p > 0.05$). However, in the A-P direction the centroid frequency and bandwidth has statistically the highest value for water swallows in the neutral position ($p << 0.01$). In the same direction, a pairwise comparison between water and honey-thick apple juice for the peak frequency showed differences in neutral position ($p = 0.006$), while in the chin-tuck position honey-thick swallows had statistically the lowest value ($p < 0.02$).

In the S-I direction, fluids did not impose any statistical differences on the centroid frequency in chin-tuck position, nor or the bandwidth in the neutral position ($p < 0.05$). The peak frequency was statistically different only between water and nectar-thick swallows in the head-neutral position ($p = 0.03$), and between water and honey-thick swallows in the chin-tuck position ($p < 0.01$). However, also in the S-I direction, the centroid frequency exhibited differences between water and honey-thick swallows in the neutral head position ($p = 0.01$), while water swallows had smaller bandwidth values than the nectar-thick swallows in the chin-tuck head position ($p = 0.02$).

Table 5.7: Frequency domain feature for swallowing accelerometery signals.

	Neutral position			Chin-tuck position		
Feature	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**
f_p A-P	2.93±0.42	2.10±0.10	2.08±0.21	2.80±0.26	2.49±0.49	2.14±0.19
f_p S-I	6.09±0.44	5.57±0.48	5.12±0.29	5.83±0.46	5.72±0.49	5.28±0.62
f_c A-P	80.5±9.11	51.3±6.92	57.5±7.67	120±13.5	130±14.3	140±15.3
f_c S-I	63.2±8.33	59.5±10.4	62.4±10.1	105±11.6	110±10.7	108±8.89
BW A-P	141±14.1	100±9.78	112±12.2	215±15.7	244±17.9	243±17.6
BW S-I	94.8±9.89	89.7±9.23	85.8±11.1	174±13.3	225±15.9	218±15.8

While comparing statistical differences between the A-P and S-I directions, we found significant differences for the peak frequency for all stimuli in both head positions ($p << 0.01$). Furthermore, the centroid frequency is different for nectar-thick and honey-thick swallows in both head positions ($p < 0.03$). The bandwidth was significantly different between the two directions for all stimuli ($p < 0.04$) in the neutral head position. Lastly, the bandwidth was significantly smaller for the S-I direction for water swallows in the chin-tuck position ($p = 0.02$).

5.2.3 Time-Frequency Domain Feature

The relative energy decompositions are presented in Figures 5.2-5.4, while the wavelet entropy results for both swallowing sounds and accelerometry signals are summarized in Table 5.8.

The wavelet analysis of the swallows showed that the viscosity of fluids had a major impact on the time-frequency structures of these signals. Let us first consider the swallowing sounds. From Figure 5.2, it is obvious that majority of the energy is concentrated on the first a10 level for both

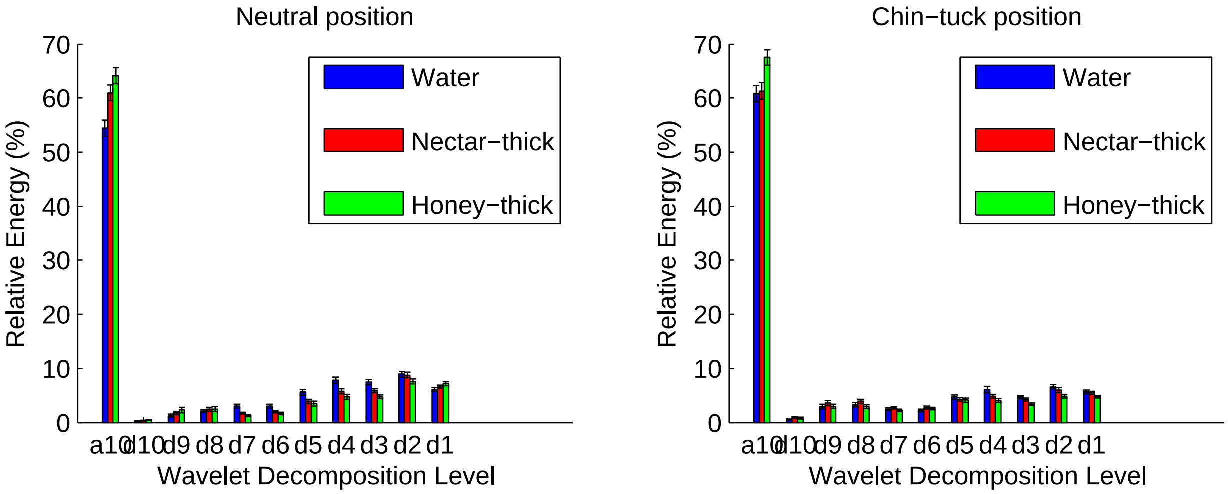

Figure 5.2: Mean relative energy per decomposition band for swallowing sounds.

head maneuvers. Levels d10 and d9 in the neutral head position, and d8, d7, d6, d5,and d1 ($p > 0.05$) in the chin-tuck position were not affected by viscosity of the fluids. In both head positions, water swallows had the statistically lowest value in the a10 level. However, water swallows had a higher energy concentration than the other two stimuli in the most of higher frequency levels (d8, d7, d6, d5, d4, d3,and d1 ($p < 0.04$)) in the neutral head position. Also, nectar swallows were statistically different from other stimuli for levels d4, d3 and d2 ($p < 0.03$). In chin-tuck head position, nectar swallows are shown to have statistical difference from other fluids in levels a10 and d3 ($p < 0.01$), while water swallow has the lowest value at level d10 ($p < 0.01$). A pairwise comparison between water and honey-thick apple juice revealed significant differences for levels d4 and d2 ($p << 0.01$), while water and nectar-thick apple juice were significantly different for the level d9 ($p = 0.01$). Lastly, the wavelet entropy had a smaller value for the fluids with higher viscosity in the neutral head position ($p < 0.02$), while in the chin-tuck position, nectar swallows exhibited a significant difference from the other two swallows ($p < 0.02$).

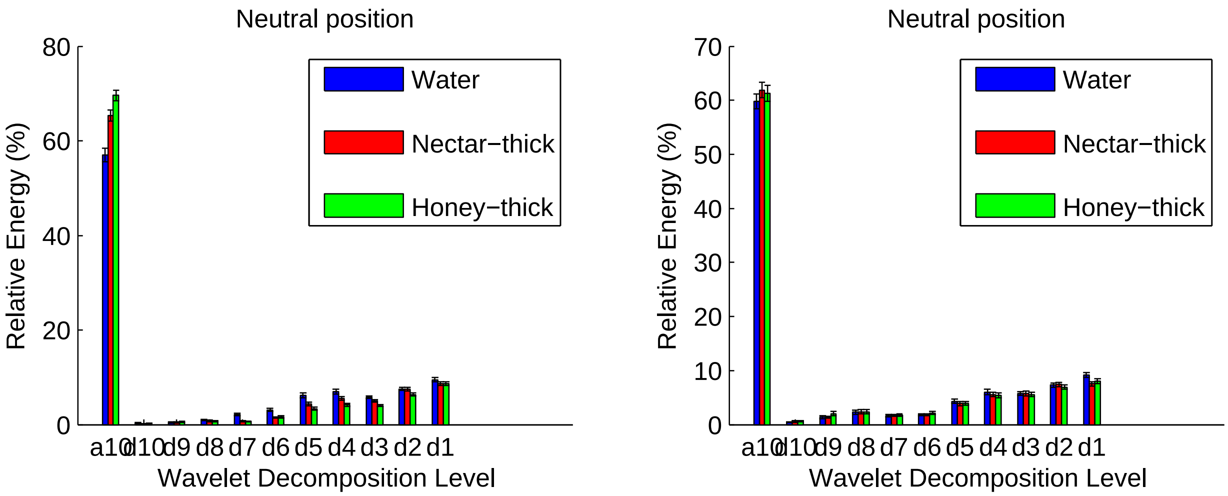

Figure 5.3: Mean relative energy per decomposition band for swallowing accelerometry signals in the A-P direction.

Contrary to the previous study on swallowing accelerometry signals [30], a significant influence of fluid viscosity was noticed on the swallowing accelerometry signals from both directions. First, let us consider the relative energy decomposition of the swallowing accelerometry signals in the A-P direction. Similar to the swallowing sounds, most of the energy is concentrated in the a10 level for all fluids. Additionally, water swallows have the statistically lowest energy concentration in the a10 level ($p << 0.01$), which was not the case at higher frequencies, where water swallows had mostly higher energy concentration for both head maneuvers and both axes. The results for the A-P direction showed that the d10 and d9 levels in the neutral position and most of the levels in chin tuck position were not affected with viscosity of fluids. In the neutral head position, all stimuli showed a significant difference in the levels a10, d4 and d3, while water swallows exhibited higher energy concentrations in the d8, d7, d6, and d5 levels ($p < 0.01$). Nectar-thick apple juice swallows revealed a significant difference in the d2 level ($p < 0.03$) for the neutral head position. In the chin-tuck head position, water swallows showed significant difference in level d1 ($p < 0.05$),

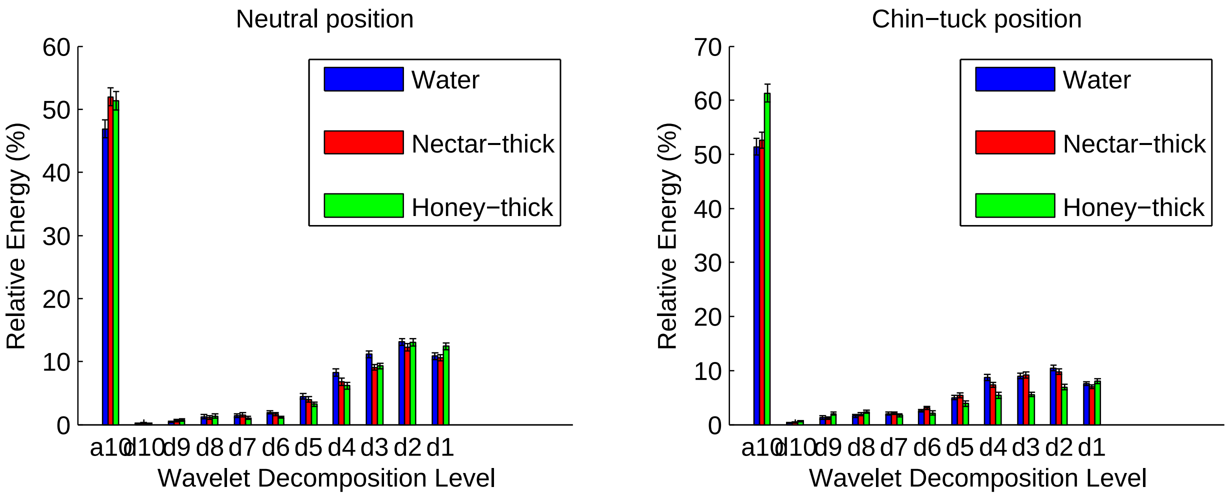

Figure 5.4: Mean relative energy per decomposition band for swallowing accelerometry signals in the S-I direction.

Table 5.8: Wavelet entropies for swallowing sounds and accelerometry signals.

	Neutral position			Chin-tuck position		
Feature	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**	**Water**	**Nectar-thick apple juice**	**Honey-thick apple juice**
WE	1.81±0.04	1.65±0.04	1.51±0.04	1.67±0.04	1.69±0.05	1.51±0.05
WE A-P	1.78±0.04	1.55±0.04	1.39±0.03	1.71±0.04	1.65±0.04	1.65±0.04
WE S-I	1.91±0.03	1.81±0.03	1.79±0.03	1.87±0.04	1.91±0.04	1.96±0.04

while a pairwise comparison between water and nectar-thick showed significant difference in the d10 level ($p = 0.01$). Lastly, in the A-P direction, the wavelet entropy had a significantly lower value for fluids with higher viscosity in the neutral position ($p < 0.02$). The wavelet entropy was not affected by viscosity in the chin-tuck position ($p > 0.05$).

In the S-I direction, levels d9, d6, and d2 in the neutral head position, and most of the levels in chin-tuck position did not show a significant statistical difference between stimuli. Water swallows were significantly different from other fluids in the a10, d10, d8, d7, d4 and d3 levels in the neutral position $(p < 0.04)$, and in the d9 level in the chin-tuck position $(p << 0.01)$. A pairwise comparison between water and honey-thick apple juice exhibited significant differences for the level d5 and d1 $(p < 0.01)$ in the neutral position and for the levels d10 ($p = 0.01$) in the chin-tuck position. A pairwise comparison between water and honey-thick apple juice showed a significant difference in level d10 ($p = 0.01$) in chin-tuck head position, while pairwise between nectar-thick and honey-thick apple juice in level d1 ($p < 0.01$) in neutral position. Also, the wavelet entropy had statistically the highest value for water swallows in the S-I direction ($p < 0.02$).

The relative energy distribution between the two axes were significantly different between each other. Levels a10, d10, d9, d8, d7, d5, d3 and d2 in the neutral position and levels a10, d4, d3 and d2 in the chin-tuck position showed difference between two axes for all three stimuli $(p << 0.01)$. Furthermore, swallows based on nectar-thick and honey-thick apple juices were also different between axes for the d1 level in the neutral head position and for the d5 level in the chin-tuck position $(p < 0.01)$. The relative energy distribution for water swallows was significantly different between two axes when considering the d5 level in the neutral position, and the levels d9, d8, d7 and d1 in the chin-tuck position $(p < 0.01)$. However, the d4 level in the neutral head position and the levels d10 and d6 in the chin-tuck position were not significantly different between two axes ($p > 0.05$).

6.0 DISCUSSION

6.1 DISCUSSION FOR BASELINE CHARACTERISTICS OF THE SWALLOWING SOUND

A lower mean value for the Lempel-Ziv complexity implies higher predictability. In this case, as we completed a pairwise comparison between sagittal tilting tasks, a lower values denotes that tilting forward produces a more predictable signal than tilting in the backward direction. Also, kurtosis describes "peakness" of the amplitude probability distribution of the signal. A higher mean value of the kurtosis for the tilting forward task than for the tilting backward task means that tilting backward contains more variant amplitudes in the sound signal. However, the behavior of the sensors on the skin during motion needs to be considered. During backwards movement, the sensor moves with the skin over the cricoid cartilage and produces a sound. This behavior likely explains higher kurtosis and higher predictability of tilting forward compared to tilting backward.

A lower kurtosis value for breath holding segments than for the 1 minute baseline task implies that the 1 minute baseline task contains less components of the different amplitudes (loudness) than that the baseline task. The microphone attached on the subject's neck can also record sounds from the carotid artery [87]. Studies have shown that the heart rate increases and becomes more prominent while holding breath in comparison to the resting state [88]. These heart rate changes can potentially provide more signal components, which can explain the results for kurtosis, as well as the lower result of L-Z complexity for 1 minute baseline to the 10 seconds holding breath task. A lower mean value of he Lempel-Ziv complexity for the 1 minute baseline implies that task tends to be a more well defined pattern than the 10 seconds breath holding task, which is expected since the cervical auscultation signal for the 10 seconds breath holding task can change over time as the heart rate increases. A higher value for the centroid frequency during the 1 minute baseline than during the 10 second breath holding tasks can be attributed to higher bandwidth values during the 1 minute baseline task.

The comparison between the 1 minute baseline and tilting forward maneuvers is a clinally important question. A similar study has been done with the accelerometer signal [89], which showed that the tilt forward maneuvers contain low frequency components which contaminate signal information. The significant influence of head motion can be observed even by visual inspection of the accelerometer signals in time domain for this two tasks, and an algorithm was developed that removes low frequency components associated with head motions from the swallowing accelerometry signals [37]. In the case of swallowing sounds, statistical differences for most of the features between the 1 minute baseline and the tilting forward task are expected due to the clearly different behaviors. Of particular interest for this pairwise comparison is the peak frequency, which denotes the frequency component with the greatest energy. Statistically different peak frequency values would mean that the tilting forward maneuver contains dominant frequency components different from the dominant frequency component during the baseline signals, resulting in motion-based artifacts found in accelerometer signals. The presented result did not show statistical difference for the peak frequency for these two tasks. Visual inspection of the swallowing sounds also did not find any significant differences. Hence, we can conclude that there is no need for removing signal components associated with head movements.

We anticipate that the observed age effects are due to the behavior of the skin in older subjects. With the age, skin loses the collagen and elastin which are supportive connectivity for the tissue of the skin. These changes causes wrinkling, laxity and sagging of the skin [90]. The attached sensor on the subject's neck should record sounds at top of the cricoid cartilage through the skin. Due to the sagging skin on the neck, it is possible that the microphone does not directly sit at top of the cricoid cartilage in various head position. Consequently, some information is lost or artifacts are introduced (for example, a sound produced by touching the skin with cricoid cartilage when the head moves backward).

Males had significantly higher mean values for skewness during the 1 minute baseline task and for kurtosis during the tilting left task. We anticipate that these sex differences are not of any importance, as there is no theoretical reasons for these features to differ between genders during our passive recording tasks (e.g., [91] and references within).

6.2 DISCUSSION FORINFLUENCE OF VISCOSITY ON SWALLOWING CHARACTERISTICS OF THE SWALLOWING SOUND

6.2.1 Time Domain Features

Our results suggest that the time domain features for swallowing sounds are not different between nectar-thick and honey-thick fluids, while the water swallows had significantly different features from the other two fluids. These results imply that the difference in viscosity between nectar and honey have a limited effect on the extracted time domain features.

For the swallowing sounds, the negative value for skewness indicates that the probability distribution of amplitudes are mostly concentrated on the right side (i.e., stronger/louder amplitude values). Larger negative skewness values for swallows in chin-tuck position denote that swallows have larger (louder) amplitude values in the chin-tuck position than in the neutral position. Also, kurtosis tends to be higher when fluids viscosity increase. Since kurtosis is a measure of "peakness" of the amplitude probability distribution, the results imply that lower viscosity swallows would contain more variant amplitudes in the sound signal [92].

The entropy rate and the L-Z complexity for swallowing sounds were also influenced by fluid viscosity. As shown in Table 5.4, the mean value for the entropy rate is higher when viscosity increases, which implies that regularity of the signal is higher for more viscous fluids [78, 79]. Similarly, a higher value for the L-Z complexity means that swallowing sounds are more complex and more unpredictable [93, 94]. This is in agreement with previous studies of CA that have indicated large amounts of signal variability from subject to subject and swallow to swallow. From the Table 5.4, it is obvious that more viscous fluids have a lower mean value of the L-Z complexity, which implies that the signal complexity is lower for such fluids. The same results were provided by a previous study of the influence of viscosity on the accelerometer signal [30] in which is implied that higher viscosity fluids tends to behave by better defined patterns.

Swallowing accelerometry signals followed similar trends for the entropy rate and the L-Z complexity as shown in Table 5.5. These results confirm the findings from the previous study [30], which showed that regularity and predictability is higher for more viscous fluids. Also in the previous study, nectar-thick and honey-thick swallows had smaller negative values for skewness in the A-P direction. We confirmed the previous results for swallows in the chin-tuck position, but did not confirm this trend for swallows in the neutral position.

6.2.2 Frequency Domain Features

As shown in Table 5.6, thicker fluids yielded swallowing sounds with lower peak frequencies, which had already been proven by a previous study of the acoustic nature of normal swallows [95]. A similar trend was observed for swallowing accelerometry signals as well.

Comparing values for swallowing accelerometry signals from Table 5.7 with those values for swallowing sounds from Table 5.6, it can be concluded that swallowing sounds have much higher frequency content than the swallowing accelerometry signals. However, we observed similar trends for features extracted from these two types of signals. Bandwidth tends to be lower for higher viscosity fluids, which suggests that the more viscous fluids required more time for completion of the swallow [39]. The mean value of the centroid frequency for swallowing sounds is not dependent on viscosity, which implies that viscosity does not significantly affect spectral measure [71], which has also been observed for the accelerometer signal.

6.2.3 Time-Frequency Domain Features

The time-frequency decomposition of swallowing sounds showed that most of the signal energy is concentrated at lower frequencies, as was expected based on frequency analysis of swallowing sounds. Thicker fluids have more energy on the first, lowest frequency level, since higher viscosity liquids produce a lower swallowing frequency [39]. We consider the wavelet entropy to describe spread of energy. According to Table 5.8, the mean value of wavelet entropy tends to be lower for higher viscosity fluids, because the energy concentration is higher at the first frequency level for thicker fluids.

Similar to swallowing sounds, most of the energy from the accelerometry signals is concentrated at the lowest frequency level (a10) for all stimuli. Also, the mean value of relative energy in the a10 level tends to be higher for thicker fluids. These findings explain the mean value results of wavelet entropy which tends to be lower for thicker fluids.

6.2.4 Remarks

According to results, more differences are observed for features in the neutral than in the chin-tuck head position for both swallowing sound and swallowing accelerometry signals. Furthermore, this study showed more statistical difference for a greater number of features extracted from swallowing accelerometry signals than the previous study [30]. In the previous study, most of the statistical differences were based on time domain features [30]. It should be mentioned that the previous study only considered data from 17 participants.

6.2.5 Limitations and Strengths of the Present Study

In this study, swallowing conditions have been administered to the subjects in a specific order (water, nectar-thick, honey-thick) implying that we cannot rule out the possibility that the order of presentation can influence the results. Also, no inference regarding swallowing physiology can be made from the results of this study as simultaneous imaging was not performed. Future research in this area could compensate for these limitations by including simultaneously acquired images and randomizing the order of presentation. However, this study has contributed to the general knowledge regarding the usefulness of CA as a screening method, as we need to clearly understand if there is any more value to CA than was previously reported. Future research should also focus on combining CA and swallowing accelerometry in a concurrent design (with imaging). The goal would be to determine if the detection accuracy of swallowing physiological impairments increases by combining these two sensors, or a higher accuracy is achieved by considering sensors independently. Also, such studies would enables us to understand the detection accuracy of these sensors to other screening methods.

7.0 CONCLUSIONS AND FUTURE WORK

7.1 CONCLUSIONS

In this Thesis, we analyzed the baseline characteristic of high performance microphone and the effects of head movements on those characteristics, as well as the effects of fluid viscosity on swallowing sounds in the normal and chin-tuck head positions. Signal were collected from 56 participants and various features were considered.

Statistical differences between head movements which are of interest for analysis were examined. Any age and sex effects on a signal were also observed and discussed. We found that head tilting forward and tilting backward influences some features, but these head movements do not affect peak frequency, so it is not necessary to remove them from the signal. However, the study also showed that certain features exhibited age dependence. These findings may indicate that sex, head position and possibly other variables may influence swallowing acoustics. Further exploration of these findings may generate methods that increase the diagnostic value of CA. For CA to be eventually make its way into clinically usefulness as a valid and reliable screening or diagnostic method for dysphagia, abnormalities in swallow physiology need to be very reliably attached to specific acoustic signals that can be discerned either perceptually or with instrumentation.

Our analysis of different viscosity swallows yielded several important conclusions. First, swallowing sounds contained lower frequency components than previously reported. Second, fluid viscosity greatly influenced some of the observed features, especially in the frequency and time-frequency domains. Third, most of the time domain features exhibited differences between water and fluids with higher viscosity (i.e., nectar-thick and honey-thick fluids). The time domain differences were not dominant between nectar-thick and honey-thick fluids.

7.2 FUTURE WORKS

Since the physiological origin of the swallow sound has not been clearly identified, this investigation did not give us answers on all questions of interest to be totally familiar with swallowing sound. We concentrated here on the fluids with different viscosity, but we also need to investigate swallowing sound of different food.

During this study, both swallowing accelerometry signal and swallowing sound had some unwanted components which are produced one sensors coming in contact with other. In order to remove it we have to make few investigations. We have to examine how those components affect our original signal as well as if important information will be removed by removing these them. After these investigation we will be able to develop an algorithm for isolating swallowing sound from these components.

Our current project focuses on healthy subjects. However, since we want to develop technique for diagnostic dysphagia, our goal is to understand differences between healthy and swallow with diseases. In the future we will need to do the same research with the people with dysphagia and develop an algorithm to distinguish those two conditions. Also developing of the technique could involve combinations of cervical auscultation with some other techniques, like EEG (recording brain activity in certain brain regions), whch could improve accuracy of making decisions.

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