Investigating the Correlation between Swallow Accelerometry Signal Parameters and Anthropometric and Demographic Characteristics of Healthy Adults

by

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A thesis submitted in conformity with the requirements for the degree of Master of Health Science in Clinical Biomedical Engineering
Clinical Engineering Department-Institute of Biomaterials and Biomedical Engineering
University of Toronto

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Abstract

This thesis studied the correlation between swallowing accelerometry signal parameters and anthropometric variables, utilizing data from 50 healthy participants. Anthropometric data including age, gender, weight, height, body fat percent, neck circumference and mandibular length. Dual-axis swallowing signals, from a biaxial accelerometer (attachment: anterior to cricoid cartilage), were obtained for 5-saliva and 10-water (5-wet and 5-wet chin-tuck) swallows per participant.

Two patient-independent automatic segmentation algorithms using discrete wavelet transforms of swallowing sequences were developed to segment: 1) saliva and wet swallows and 2) wet chin-tuck swallows. Correct extraction of swallows hinged on dynamic thresholding based on signal statistics.

Canonical correlation analysis was performed on a set of both anthropometric and swallowing signal variables, which included: variance, skewness, kurtosis, autocorrelation decay time, energy, scale and peak-amplitude. For wet swallows, a significant linear relationship was found between selected signal and anthropometric variables. In the superior-inferior direction, a statistically significant correlation was detected linking weight, age and gender to skewness and signal memory. In the anterior-posterior direction, age was significantly correlated with kurtosis and signal memory. No significant linear relationship was observed for dry and wet chin-tuck swallowing.
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List of Acronyms

UES = Upper Esophageal Sphincter
LES = Lower Esophageal Sphincter
TBI = Traumatic Brain Injury
CBSA = Clinical Beside Swallowing Assessment
VFSS = Videofluoroscopic Swallowing Studies
MBS = Modified Barium Swallow
CA = Cervical Auscultation
SpO\textsubscript{2} = Arterial Oxygen Saturation Level by Pulse Oximetry
FEES\textsuperscript{®} = Fiberoptic Endoscopic Evaluation of Swallowing\textsuperscript{®}
SI = Superior-Inferior
AP = Anterior-Posterior
OSC = Ontario Science Centre
EMG = Electromyography
AR = autoregressive modeling
TFR = Time-Frequency Representation
GVF = Gradient Vector Flow
db = Daubechies
RMS = Root-Mean-Square
FP = False Positives
FN = False Negatives
SLP = Speech-Language Pathologist
BMI = Body Mass Index
BIA = Bioelectric Impedence Analysis
CV = Coefficient of Variation
Chapter 1
Thesis Roadmap

This thesis write-up has been organized into 6 individual chapters which outline the many aspects of this study.

This write-up begins with Chapter 2, which is an introductory chapter that delineates the necessary background information that is relevant to this thesis. Starting with section 2.1, a brief summary of the physiology of deglutition (swallowing) is given which includes a description of the four phases of swallowing described in subsections 2.1.1 to 2.1.4. This is followed by section 2.2 which is a description of the disorders of deglutition addressed in this study, namely, dysphagia and particularly aspiration. Section 2.3 describes the clinical protocols used to assess aspiration, while in section 2.4, a description of the instrumental aspiration detection techniques that are used to accurately assess aspiration for dysphagia management is given. A description of each technique along with their respective benefits and limitations are outlined in subsections 2.4.1 to 2.4.4. Section 2.5 describes the newest instrumental technique: accelerometry. This section describes how this new aspiration detection technique presents the most optimal benefits-to-limitations ratio in comparison with previously mentioned techniques. A summary of the previous work involving accelerometry in pediatric populations is given in section 2.6. Finally section 2.7 provides the scope of the problem addressed in this thesis namely the need for an accelerometry-based aspiration detection instrumental technique for an adult population.

This will lead into Chapter 3 where the objectives of this thesis are set. The rationale for this thesis is to assist in the ongoing research conducted by Toronto Rehabilitation Institute and Bloorview Kid’s Rehab in partnership with Panacis Medical to construct the first version of the adult version of the Aspirometer. The Aspirometer is a device currently under development that utilizes dual-axis accelerometry for the detection of aspiration in adult populations. Objectives for this thesis include the collection of healthy swallowing accelerometry signals, segmenting swallow signals to ascertain all correct swallows from background noise and finally to determine if a relationship exists between swallowing signal characteristics and anthropometric and demographic measures of participants. The methods for data collection are discussed in both subsequent chapters.
Following in Chapter 4 will be the details of the segmentation algorithm created to extract swallows from background noise. Section 4.2 will discuss the experimental methods used to obtain accelerometry signals. Sections 4.3 and 4.4 discuss the details of the two patient-independent automatic segmentation algorithms that were developed and section 4.5 discuss the evaluation of the algorithms.

Chapter 5 outlines the canonical correlation analysis used to determine if a relationship between anthropometrics and accelerometry signal characteristics exist. Section 5.2 will discuss the experimental methods used to obtain accelerometry signals along with anthropometrics. Finally, section 5.3 discusses the canonical correlation analysis performed and the results that were obtained relating to the presence of such a relationship.

A short conclusion is presented in Chapter 6. A synopsis of all contributions is provided in section 6.1. This specifically includes all methodological (6.1.1), algorithmic (6.1.2) and scientific contributions (6.1.3). Section 6.2 will delineate the future work that is required for the development of the Aspirometer. Figure 1.1 illustrates this roadmap for easier navigation through this thesis.
Figure 1.1 Illustration of Thesis Roadmap
Chapter 2
Introduction

2 Background

2.1 Normal Deglutition: Physiology and Phases

Deglutition (swallowing) is the process of transporting food or liquid from the mouth to the stomach. It is a well-defined, complex process that is essential for the transport of required nutrients for eventual digestion and absorption. It is also crucial for the effective rehydration of the body. This process in its entirety is vital for the continued existence of an individual.

Deglutition is performed by several structures found within the oral cavity (mouth), pharynx, larynx and esophagus within the head and neck. Figure 2.1 depicts (only) the areas wherein these structures lie within the head and neck.

Figure 2.1: Anatomy of sections where swallowing takes place, adapted from (Thomas & Keith, 2005)
The complexity of deglutition sequences is achieved by the control and coordination of the swallowing centre of the brain located in the medulla oblongata and pons (Ginsburg & Costoff, 1996). This centre receives afferent signals from oral, pharyngeal and esophageal receptors and initiates appropriate efferent motor responses. Afferent fibers travel via the trigeminal, facial, glossopharyngeal and vagus nerves to the nucleus of the solitary tract, which is associated with the swallowing centre. The swallowing center also has connections to the respiratory center of the brain, as respiration is temporarily inhibited while a swallow takes place. Efferent fibres then project from the swallowing centre down towards the motor nuclei of the trigeminal, facial, and hypoglossal nerves, and to the nucleus ambiguus (housing the motor nucleus of the vagus nerve) and dorsal motor nucleus of the vagus. Extravagal motor efferents also innervate the pharyngeal muscles involved in swallowing and lastly, somatic motor fibers from the nucleus ambiguus innervate the esophageal striated muscle, including the upper esophageal sphincter (Ginsburg & Costoff, 1996). Thus, coordinated movements of deglutition involve both skeletal and smooth muscles. These neural connections are summarized in figure 2.2.

![Diagram summarizing afferent and efferent connections involved in swallowing, adapted from (Ginsburg & Costoff, 1996)](image)

Deglutition is divided into four phases: oral preparatory, oral, pharyngeal, and esophageal (Logemann, 1998). Figure 2.3 illustrates three of the four phases of normal deglutition. While each of these four phases is discussed at length below, an image of the oral preparatory phase is excluded as it primarily involves mastication (chewing) of a bolus (a mass of chewed food mixed with salivary secretions).
2.1.1 Oral Preparatory Phase

On average, deglutition takes 10 seconds to complete for solids while on the contrary liquids take 2 seconds at most-1 second for the oral phase and 1 for the pharyngeal to complete. Deglutition may occur as many as 600 times per day (including saliva as well as bolus swallows). The first stage of this complex sequence is the Oral Preparatory Phase, which involves placement of food or liquid in the mouth and the resulting formation of a bolus using the teeth, mandible, and tongue (Logemann, 1998). A process model developed by Hiiemae and Palmer (1999) proposed that this initial phase contains two sub-stages: i) **Stage I Transport**, which involves the transport of the ingested food or liquid from the incisal teeth to the molars and ii) **Processing**, where food is reduced to a swallowable condition (mechanical breakdown). Both stages take place within the oral cavity (Hiiemae & Palmer, 1999).

This phase is entirely voluntary and primarily involves mastication. It can also be bypassed if the liquid or food is dropped into the back of the throat directly. In the first stage, anterior incisors are used to cut and/or tear food, and the food is transported to the posterior teeth; the molars, for grinding. Mastication is vital for the digestion of all foods and specifically of indigestible cellulose membranes which are found in fruits and vegetables. The objective of mastication is to reduce food to smaller particles that digestive enzymes can break down with greater ease. As the food within the oral cavity is chewed, it is also moistened by saliva and mixed with amylase and lingual lipase to commence digestion of carbohydrates and lipids.
respectively. The mixture of the food and saliva produces the desired bolus, which is rendered as “swallowable” at the end of the second stage. At this point Labial seal (sealing of lips) is maintained to prevent bolus leakage out of the mouth and Buccal (cheek) muscles are tensed in order to prevent the pocketing of the bolus (Cherney, Pannell, & Cantieri, 1994; Logemann, 1983, 1989, 1997). During this time, since the mouth is not available, nasal breathing is utilized (Logemann, 1998).

In the case of liquids, the second stage is absent for liquids according to Hiiemae and Palmer as the volume of liquid is held on the tongue with the posterior tongue elevated and is then delivered to the pharynx by “squeeze back” mechanism(moves the liquid through fauces (throat)), through contact between the anterior tongue surface and the hard palate, followed by the middle tongue, and then the posterior surface as the tongue surface traveled first forward and then upward (Hiiemae & Palmer, 1999).

### 2.1.2 Oral Phase

Once the ingested food has been rendered swallowable it is moved distally toward the fauces. Rather than a cohesive bolus being formed in the mouth and delivered in its entirety to the pharynx, aliquots of the bolus are transported through the fauces and into the vallecular space, with the total volume of the swallowable material gradually and progressively accumulating (via cycling on the tongue). This gradually but effectively triggers the pharyngeal phase, and accounts for the aforementioned average of 10 seconds required for swallowing. The force by which the bolus is propelled is proportional to its viscosity (Dantas & Dodds, 1990). As with the previous phase, labial seal is maintained, buccal musculature is tensed and nasal breathing is sustained (Logemann, 1998). This phase is once again done voluntarily and controlled by the cerebral cortex through the corticobulbar tracts.

### 2.1.3 Pharyngeal Phase

Once the bolus has been propelled posteriorly to the back of the mouth by the tongue, past the point where the lower edge of the mandible crosses the base of the tongue, receptors in the oropharynx and tongue are subsequently stimulated (Logemann, 1998), which initiates the
pharyngeal phase of swallowing. This phase is completely involuntary and can be considered to be the most critical stage of the swallow.

One of the primary characteristics of this phase is that here complete airway closure must occur to prevent the bolus from entering the respiratory system, and this results in a momentary cessation of respiration, and specifically of expiration (Miller, 1999). This phase is also marked by a number of events that must occur simultaneously for successful swallowing.

a) Sensory information from the aforementioned receptors in the back of the mouth and in the pharynx goes to the swallowing center in the medulla. The palatopharyngeal folds pull together medially to form a slit in the upper pharynx which allows the bolus to pass through.

b) The velopharyngeal port closure is achieved by components. First, the velum (soft palate) is raised and retracted, thereby closing off the nasal passages and preventing the entry of food into the nasopharynx. This is done primarily by the levator and tensor veli palatini muscles. Secondly, the upper pharynx is constricting along an approximately horizontal plane, thereby encasing the free edges of the velum (Logemann, 1998).

c) The tongue is ramped and retracted to prevent the bolus from re-entering the mouth but rather directing it into the pharynx (Logemann, 1998)

Other events also take place to protect the airway:

da) Both the larynx and hyoid bone are elevated and moved anteriorly to enlarge the pharynx and to remove the airway from the path of the bolus (Spiro, Rendell, & Gay, 1994). Furthermore the anterior movement aids in the opening of the upper esophageal sphincter (Logemann, 1998).

e) The true and false vocal folds adduct (move towards a midline from an extremity).

f) The laryngeal sphincter is closed (Spiro et al., 1994).

g) The epiglottis covers the laryngeal opening (Spiro et al., 1994) by dropping down over the top of the larynx and causing the bolus to pass down on both its sides. If the bolus is liquid, the epiglottis acts as a ledge to slow its movement through the pharynx, giving the vocal folds time to adduct and the larynx time to elevate.

h) Several components take place to aid in the movement of the bolus down the pharynx. This primarily includes: the retraction of the tongue base and the contraction of the pharyngeal
wall (until it makes contact with tongue base) (Logemann, 1998). Secondarily this includes: induced negative pressure in the laryngopharynx caused by the closure of the larynx as well as gravity. All these components cause an increased differential pressure within the pharynx and allow the bolus to move steadily down the pharynx to the upper esophagus.

As the bolus moves down the pharynx, the cricopharyngeus muscle relaxes, which allows the opening of the upper esophageal sphincter (UES) thereby allowing the bolus to successfully enter the esophagus. This action concludes the pharyngeal phase (Logemann, 1998).

### 2.1.4 Esophageal Phase

This stage is also involuntary. Once the bolus has entered the esophagus, it is transported downward into the stomach by peristalsis (a rippling or wave-like muscular contraction performed by the inner wall of the esophagus) (Logemann, 1998). Gravity also aids in the movement of the bolus towards the stomach. Also, in this stage, the larynx is lowered back to its neutral position, respiration is resumed and the cricopharyngeus muscle contracts to prevent reflux of the bolus. The esophageal phase continues until the bolus enters the stomach at the lower esophageal sphincter (LES) (Logemann, 1998).

### 2.2 Disorders of Deglutition: Dysphagia and Aspiration

Dysphagia is a term that refers to any disorder that produces difficulties with swallowing (Logemann, 1998). This is a common occurrence in patients following a stroke or traumatic brain injury (TBI) and can be found in patients suffering from cerebral palsy, Parkinson’s disease, multiple sclerosis and/or any other illness that results in a change in the neural structures or muscles associated with the swallowing reflex described in the previous section (Miller, 1999; Morrell, 1992). Dysphagia can also be found in patients who suffer from mechanical changes in the physiological structures related to deglutition following surgery, cancer and inflammation (Groher & Gonzalez, 1992). Inherent abnormalities in the oral or nasal cavity, pharynx, larynx, trachea, or esophagus that one is born with can also lead to dysphagia (Sheppard, 1997).
One of the typical symptoms associated with dysphagia is a difficulty protecting the airway during deglutition. As seen in figure 2.4, this can lead to aspiration which is the invasion of foreign material (food or liquid) into the lungs, below the true vocal folds (Logemann, 1998).

![Figure 2.4: Depiction of aspiration of barium into the larynx and trachea: A large amount of the bolus entering the airway rather then esophagus because of a failure of the epiglottis to fully cover the larynx; adapted from (Massey & Shaker, 2006)](image)

Normally, a person who aspirates triggers a protective mechanism (coughing) to expectorate the foreign material from the air passages. Those who do not produce a cough mechanism, while alert, suffer from silent aspiration. A recent study by Smith, Logemann, Colangelo, Rademaker, & Pauloski, (1999) analyzed the frequency of the cough response in patients identified as aspirators in two acute care hospitals for two years and found that up to 59% of aspirators have silent aspiration (Smith, Logemann, Colangelo, Rademaker, & Pauloski, 1999).

Stroke patients comprise the largest group that suffers from the life-threatening complications of dysphagia. Studies report prevalence of dysphagia in up to 70% (Nishiwaki et al., 2005) and aspiration in 38% (67% of which are silent aspirators) (Daniels et al., 1998) of all stroke patients. Dysphagic stroke patients have mortality rates ranging from 20% to 65% due to aspiration pneumonia. The 30-day mortality rate of stroke patients with dysphagia has been found to be six-times higher than those without dysphagia. Furthermore, greater than 1/3 of post-stroke aspirators develop pneumonia of which 3.8% will die as a result of this complication, making aspiration pneumonia the second most common cause of death of stroke patients (Hammond, 2008). Dysphagia can persist for a long period following stroke without being complained of by patients. While some stroke patients may recover swallowing function, 10-
30% of these individuals will continue to have dysphagia with aspiration (Mari, Matei, Ceravolo, Pisani, & Provinciali, 1998).

Aspiration can lead to acute aspiration pneumonia (Miller, 1992), chronic lung disease and even death (Ding & Logemann, 2000). About 15 million people in the United States are affected by dysphagia due to a range of causes, and upwards of 600,000 individuals each year will be affected by aspiration pneumonia, of which 50,000 will die of related complications (Dray, Hillel, & Miller, 1998). Aspiration pneumonia is also the most common form of hospital-acquired pneumonia among adults and occurs in 4-8 of every 1000 patients who are admitted to hospitals in the United States (Hammond, 2008). Aspiration and more generally dysphagia also has an impact on a person’s psychological and psychosocial health as those who suffer from these disorders fear mealtimes and may even refuse social eating (Riensche & Lang, 1992).

2.3 Aspiration Assessment: Clinical Examinations

When a patient exhibits symptoms of dysphagia, a clinician, who is often a nurse or an attending physician, must make timely determinations regarding swallowing ability and the related risk of aspiration. Results will direct the need for further assessment, as well as feeding protocols. Commonly, patients are required to take nothing by mouth (NPO) until a swallowing assessment is conducted by a specialist (normally, a speech-language pathologist).

In many cases, an initial dysphagia swallow screening is performed. Dysphagia screening is a quick procedure often conducted by nurses upon admission of certain patients (such as stroke and TBI) to the hospital. Small sips of water are administered, and the nurse looks for indications of coughing or choking. Coughing has widely been considered the most important potential indicator of aspiration, as coughing in adult patients with an abnormal swallow suggests aspiration has occurred (Hammond, 2008). Referral of the patient to the specialist, who will then perform a clinical bedside swallowing assessment (CBSA) follows.

A CBSA is a more in-depth evaluation than a dysphagia screening, involving assessment of the physical capabilities of the swallowing anatomy and the swallowing of other foods in addition to water. The specialist uses a number of subjective clinical signs to assess the risk of aspiration. The increased comprehensiveness of the CBSA combined with the experience of the
specialist (in comparison to a nurse) leads to more accurate results with CBSA than with dysphagia screening. Based on the CBSA, the specialists may employ several methods for dysphagia management, which include: postural adjustment during feeding, altering food consistency or modifying the volume of food consumption (Logemann, 1998).

Studies however, question the effectiveness of dysphagia screening and CBSA in accurately assessing aspiration, particularly in the assessment of silent aspiration. As previously mentioned, these examinations involve the subjective assessment of clinical signs, and in the presence of silent aspiration, have limited effectiveness in diagnosis. Therefore silent aspiration can not be accurately detected without an instrument assisted evaluation.

2.4 Instrumental Aspiration Detection Techniques: Benefits and Limitations

In an attempt to accurately assess aspiration and particularly silent aspiration, as well as generally manage dysphagia, several techniques using various instruments and methodologies are employed in addition to the CBSA. Furthermore, once there is an initial determination that a patient does aspirate, instrumental assessment techniques are used to determine the efficacy of the therapeutic or rehabilitative interventions prescribed in reducing the occurrence of aspiration. Such interventions include: food texture modifications, airway maneuvering and/or postural adjustments.

Four of the most widely used instrumental techniques are introduced in this section along with their respective benefits and limitations.

2.4.1 Videofluoroscopic Swallowing Study (VFSS)

Videofluoroscopic swallowing studies (VFSS), also known as the modified barium swallow (MBS) procedure, are currently considered to be the “gold standard” in dysphagia assessment (Tabaee et al., 2006). The patient being evaluated using VFSS is asked to swallow barium coated materials while an X-ray video of the upper aerodigestive anatomy (see figure 2.1) is recorded. Although aspiration, and particularly silent aspiration is easily detected using this technique, it is quite effective in displaying all components of a swallow sequence in real-time which allows specialists viewing the video to ascertain the reason behind the swallowing impairments
Furthermore, if aspiration is observed, clinicians can immediately attempt to mitigate this problem by asking the patient to try various postures or maneuvers that can help decrease aspiration while the tasks continue as well as determine the appropriate course of therapy accordingly (Martin-Harris, Logemann, McMahon, Schleicher, & Sandidge, 2000).

A VFSS is performed in specialized radiology suites which may not be available in all health care institutions. A VFSS also requires the expertise of an entire health care team usually comprised of a speech-language pathologist, a radiologist and a radiology technician to obtain and analyze the recorded swallow for possible aspiration and other physiological abnormalities. The consensus from the team is very accurate (Scott, Perry, & Bench, 1998).

Figure 2.5 illustrates the difference between a patient who has a healthy swallowing pattern and one where aspiration has occurred. Both images are obtained from VFSS.

![Figure 2.5: Two VFSS images depicting a normal healthy swallow (left) and a swallow where aspiration was observed (right) (Massey & Shaker, 2006)](image)

**Benefits:**

1. **Very high validity:** serves as gold-standard against all other instrumental techniques. All swallow sequence events are captured, aspiration is easily detected and therapeutic positions and/or maneuvers can be employed in real-time.

2. **Repeatable:** highly accurate as it relies on the consensus of a team of professionals.

3. **High physiological basis:** can easily determine origin of swallowing impairment.
Limitations:

1. **Limited access**: VFSS is not available in small institutions and it is associated with large wait-times in certain centers.

2. **High complexity**: Requires the expertise of several trained health care professionals to obtain an image and moreover, an accurate result.

3. **Expensive**: Radiology equipment is expensive and the cost of one VFSS not only includes the operating cost, but also fee costs for the various professionals involved as well material costs (e.g. barium).

4. **Exposure to radiation**: Although VFSS radiation doses are lower than other common radiological procedures, exposure to any radiation limits the number of times that a patient can undergo this technique (Wright, Boyd, & Workman, 1998)

5. **Patient must be fully alert**: patients have to transported to radiology suite and be able sit upright during the study and follow instructions (Tabaee et al., 2006)

2.4.2 Cervical Auscultation

Cervical auscultation (CA) is a noninvasive instrumental assessment technique that involves placing a stethoscope, a microphone, or an accelerometer on a patient’s neck (near the larynx) and listening to the sounds that are generated during swallowing (Logemann, 1998; Zenner, Losinski, & Mills, 1995). CA is based on the principle that patients with dysphagia and particularly aspiration produce swallowing-sounds which deviate from known, normal swallowing-sound characteristics (Hamlet, Nelson, & Patterson, 1990). Typically, patients with aspiration will exhibit the following swallow-sound characteristics: noisy/breathy swallows, gurgled (wet) and rough vocal or respiratory quality, rapid and non-rhythmic swallows, excessive coughing, and excessive throat clearing. This is clearly distinguished from normal swallow sounds which are: crisp, rhythmic and dry (Vice, Bamford, Heinz, & Bosma, 1995).

**Benefits:**

1. **Economical**: The listening devices used (mainly stethoscopes) are relatively low in cost and can be reused across patients.
2. **High portability**: The listening devices are easily moved and carried between health care institutional departments. The noninvasiveness of this technique allows for it to be easily transferred between patients and makes it ideal for the bedside setting.

3. **Low Complexity**: Requires no knowledge or use of any instrumentation other than a stethoscope

**Limitations:**

1. **Low validity**: In comparison with videofluoroscopy, this technique yields an accuracy of 40%-60%; specificity (proportion of actual safe swallows that are correctly classified as safe swallows (Lee et al., 2006)) is determined to be 66% (Leslie, Drinnan, Finn, Ford, & Wilson, 2004; Zenner et al., 1995) and sensitivity (proportion of actual aspirations that are correctly classified as aspirations (Lee et al., 2006)) was only found to be 62% (Leslie et al., 2004; Zenner et al., 1995).

2. **Low physiological basis**: the physiological origin(s) of the detected swallow sounds is still not clearly identified (Logemann, 1998).

3. **Repeatable**: While there are obvious benefits including the ability to quickly monitor progress in therapy, reaching the same diagnosis by different clinicians is quite difficult. This technique heavily relies on the experience of the clinicians and since results are qualitative, they can be quite subjective as well.

### 2.4.3 Pulse Oximetry

Pulse Oximetry is also a non-invasive technique that refers to the ability to measure the arterial oxygen saturation level ($\text{SpO}_2$) or the percentage oxygenation of a patient’s hemoglobin. A probe containing a red and infrared light emitter and a photo-detector is attached to the finger, toe, or pinna (top) or lobe of the ear of a patient and the absorption characteristics of oxygenated hemoglobin are monitored. Oxygenated hemoglobin absorbs more infrared light (850-1000 nm) and allows more red light (600-750 nm) to pass through. The pulse oximeter converts the measure of light absorption into a percentage of oxygen saturation (Johnson & Jacobson, 1998).

The principle behind how this relates to swallowing is that in the case of patients who aspirate, their respective airways should be obstructed in comparison with healthy individuals. This obstruction would hypothetically result in hypoxemia, which could be measured as a
decrease in SpO₂. Therefore, SpO₂ is measured before, during, and after swallowing, and if the patient has aspirated, it is expected that the percentage of SpO₂ will decrease (Johnson & Jacobson, 1998).

Benefits:

1. **High portability:** the noninvasiveness of this technique allows for it to be easily transferred between patients and makes it ideal for the bedside setting.

2. **Low complexity:** functionally pulse oximeters are easily used and output one number that needs to be tracked during assessments and over time.

3. **Repeatable:** an objective percentage is produced that is independent of the clinician’s expertise. Thus, progress can be tracked objectively over time, although it should be noted that while this method provides detection of swallowing difficulty, it does not specifically detect aspiration or silent aspiration.

4. **Economical:** Pulse Oximetry equipment is not expensive if purchased in large amounts.

Limitations:

1. **Low validity:** while some studies (Sherman, Nisenboum, Jesberger, Morrow, & Jesberger, 1999) showed that arterial oxygenation significantly decreased in cases of aspiration, other studies could not validate that changes in SpO₂ related to aspiration when measured against VFSS (Sellars, Dunnet, & Carter, 1998) or Fiberoptic Endoscopic Evaluation of Swallowing® (Colodny, 2000; Leder, Sasaki, & Burrell, 1998). In addition, it was speculated that oxygen desaturation is probably caused by dysphagia rather than specific incidents of aspiration (Colodny, 2000).

2. **Low Physiological Basis:** the physiological basis between SpO₂ and aspiration is not well established. While reliability detecting aspiration, Pulse Oximetry does not provide a direct link to the physiological mechanism associated with swallowing.

2.4.4 Fiberoptic Endoscopic Evaluation of Swallowing (FEES®)

FEES® is a technique that involves the insertion of a small, flexible, custom-designed scope, attached to a camera, through the nose and into the middle of the throat (at the level of the soft palate (Logemann, 1998)). The clinician records a video of the throat and larynx as patients swallow liquid and foods and imaging of some physiological changes during the pharyngeal
phase is possible, including velopharyngeal closure, movement of the pharyngeal walls and the elevation and retraction of the soft palate (Logemann, 1998).

In the evaluation, clinicians can use the produced images to determine if the patient has aspirated as well as observe the efficacy of certain therapeutic techniques since the clinician may ask the patient to try various postures to decrease aspiration rates.

Benefits:

1. **High portability:** although invasive it can be transported to bedside and performed quickly.
2. **Repeatable:** an objective image is displayed. Allows clinician to easily observe aspiration before and after the swallow, and to infer its occurrence during the swallow, as well as to determine whether or not the event has been silent. Patients are allowed to swallow liquid and regular food without the use of barium (which is desired by patients) and there is no harmful radiation associated with procedure, making it highly repeatable.
3. **High validity:** comparable to VFSS in accuracy, specificity and sensitivity. Studies show a strong agreement between FEES® and MBS (Leder et al., 1998) with only minor between them (Tabaee et al., 2006)

Limitations:

1. **Limited Observability:** the view of the pharynx during the pharyngeal phase is unavailable because of the contraction of pharyngeal muscles (Logemann, 1998). Since most events relating to a swallow as well as aspiration occur in this phase, detection of aspiration can be hampered and information about the efficacy of treatment is limited.
2. **Uncomfortable:** Some patients may have a difficult time performing swallowing tasks properly with the endoscope inserted and can find the scope uncomfortable.
3. **Expensive:** specialized imaging equipment and software is expensive.
4. **High Complexity:** FEES® must be performed by trained specialists (and may require supervision by a physician under certain jurisdictional regulations).
2.5 Accelerometry: A New Aspiration Detection Methodology

Accelerometry is a new aspiration detection technique that, as previously mentioned, has been used in CA. This noninvasive technique involves placing an accelerometer on the surface of the neck (below the thyroid cartilage) which gathers vibrations from the surface of the neck during swallowing tasks and an automatic signal processing algorithm interprets the acquired signal as being normal or abnormal. The main differences between CA and Accelerometry are that the acquired signals are not audible (and are therefore not evaluated through perceptual judgment), and that no trained specialists are required for the interpretation of the signals (Lee et al., 2006). With respect to the latter difference, accelerometry is rendered much more objective in that signal processing algorithms extract and use mathematical and statistical features of the accelerometry signal which allow a classifier to distinguish between healthy and abnormal swallowing.

Although the origin of the vibratory physiological signals has not been confirmed, studies point to laryngeal elevation as a possible source (Reddy et al., 2000). Moreover, since the larynx elevates and moves anteriorly during the healthy swallowing phases previously described, a dual-axis accelerometer oriented in the anterior-posterior (AP) and superior-inferior (SI) directions, is anticipated to capture all relevant abnormalities that could potentially cause aspiration (Das, Reddy, & Narayanan, 2001).

Previous studies have shown that accelerometry signals acquired from non-dysphagic patients share common characteristics with each other, while differing in some characteristics (e.g. amplitude) with those accelerometry signals obtained from known dysphagic patients (Reddy et al., 1991; Reddy, Thomas, Canilang, & Casterline, 1994).

Benefits:

1. High portability and accessibility: the noninvasiveness of this technique (as with CA) allows for it to be easily transferred between patients and makes it ideal for the bedside setting.

2. Repeatable: an objective result is given based on extracted signal features and classification. This should easily detect abnormal signals, including silent aspiration.
3. **High validity:** is comparable to VFSS for detecting abnormality in accuracy, specificity and sensitivity without the radiation exposure; however it must be stressed that the richness of information provided by VFSS cannot possibly be matched by accelerometry since VFSS provides full-view of the act of swallowing. One should also note that validity can be comprised if precise methods associated with accelerometry signal acquisition are not employed and/or if additional noise is introduced by a variety of methods including sensor attachment in an incorrect location, poor sensor contact or excessive talking or moving during signal acquisition.

4. **Economical:** accelerometer and electronic devices with additional embedded systems are low in cost.

5. **Low Complexity:** accelerometry signal processing is entirely automatic and thereby entirely objective as classification of the signal depends on extracted signal features.

**Limitations:**

1. **Low Physiological basis:** The origin of the vibratory signal is yet to be confirmed.

   Given that accelerometry has the largest benefits to limitations ratio, it is assumed that this instrumental swallow assessment technique will be used quite readily in the future.

2.6 **Pediatric Aspirometer: Aspiration Detection Using Dual-Axis Accelerometry in Pediatric Populations**

The Aspirometer is a small, portable electronic device that attempts to develop and implement the principle of automatic aspiration detection using accelerometry that was described in the previous section (Lee et al., 2006). Initial development of this device involved the assessment of a pediatric population with cerebral palsy (Chau, Chau, Casas, Berall, & Kenny, 2005; Lee et al., 2006). Vibration signals associated with healthy swallows as well as aspirations were gathered using a single-axis accelerometer and the respective swallows were also identified by videofluoroscopy. A single axis accelerometer was used to initially determine if accelerometry could be used to detect aspiratory events in children with cerebral palsy. Signals were acquired from a total of approximately 100 children and five potentially discriminatory mathematical features were extracted from the accelerometry signals. These five signal features included: Stationarity, Normality, Dispersion ratio, Zero-crossings and Energy.
Furthermore, several classifiers were chosen and the performance of different classifiers were compared and the best feature sets were identified (Lee et al., 2006). A radial basis function classifier was chosen.

This initial version of the Aspirometer produced an accuracy rate of 79.8 ± 7.3%, a sensitivity of 79.4 ± 11.7% and specificity of 80.3 ± 12.8% for aspiration detection which achieves up to a 30% improvement in accuracy over the worst reported accuracy for CA (Lee et al., 2006).

While the initial single axis version of the Aspirometer provided promising accuracy for aspiration detection in children, this level of accuracy required further enhancement for it to be used in a clinical setting. Also, while this initial version of the Aspirometer was an important first step towards the eventual development of wearable intelligent intervention system to aid with the management of aspiration in children, the majority of patients who aspirate are in the adult population. Preliminary work involving the use of the Pediatric Aspirometer on adults proved to be not feasible; this may be due to the large variance of body types (anthropometrics) found in adults. Therefore, further research was required to construct an adult version of the Aspirometer.

2.7 Adult Aspirometer: Need for Aspiration Detection using Accelerometry in Adult Populations

While the Adult Aspirometer involves essentially the same detection methodology as the Pediatric Aspirometer, the vision for the Adult Aspirometer is to aid in the management of dysphagia and particularly the detection of aspiration and other swallowing abnormalities within varying age groups, regardless of the different etiologies of dysphagia. Also, unlike the pediatric version, dual-axis accelerometry will be used since it corresponds better with laryngeal movement: elevation and anterior movement.

There is a critical need in health care institutions, where the management of dysphagia takes place in adult populations, for an instrumental method to be used that is comparable to the gold-standard of videofluoroscopy especially in the detection of silent aspiration but that is much
more economical, not complex, more objective and does not expose the patient to doses of radiation.

To construct the Adult Aspirometer, several factors need to be determined:

- Exhaustively determine all intrinsic characteristics found in healthy adult accelerometry signals as well as those found in abnormal accelerometry signals;
- Determine any distinguishing signal characteristics between healthy vs. abnormal adult accelerometry signals;
- Develop segmentation algorithms for each category of accelerometry signals so as to allow separation of true swallowing signals from background noise gathered during signal acquisition;
- Determine if a relationship exists between adult swallowing signal features and body measurements (anthropometrics);
- Characterize baseline accelerometry noise so as to filter out such noise from signal processing.
3 Rationale and Objectives

The main intention of this thesis is to assist in the ongoing research that is being conducted by Toronto Rehabilitation Institute and Bloorview Kid’s Rehab (Chau et al., 2005; Lee et al., 2006) in partnership with Panacis Medical to construct the first version of the adult version of the Aspirometer.

There is a considerable need in acute health care settings for accelerometry-based instrumental detection of aspiration in adult populations. Given the limitations of current screening methods, as well as those associated with instrumental detection of aspiration, a portable, economical, objective real-time aspiration detection system, that has high validity (comparable to videofluoroscopy), low complexity and high physiological basis is greatly desired. Such a device would enhance bedside screenings (swallow screenings and CBSA) by allowing clinicians to quickly verify the presence of aspiration and effectively aid in the determination of the method of feeding and medication of patients. Also, the Aspirometer can be used in the rehabilitative setting to observe the efficacy of prescribed therapies.

The specific objectives of this thesis involve the investigation of accelerometry signals of swallows from healthy adult populations. Three objectives are given for this thesis:

1) Gather a large dataset of healthy adult swallowing accelerometry signals from visitors to the Ontario Science Centre (OSC). Participants were to vary in age, gender and anthropometrics. In this dataset, swallowing accelerometry signals are to be gathered for three swallowing tasks: dry (saliva), wet (water) and wet chin-tuck swallows.

2) Construct a patient-independent automatic segmentation algorithm suitable for dual-axis swallowing accelerometry signals. Given the voluminous amount of accelerometry recordings that are accumulated, and the need for the device to analyze signals in real-time, this segmentation algorithm attempts to extract swallows from background noise obtained during accelerometry signal acquisition to facilitate feature extraction of the swallow signal.
3) Determine if anthropometric variables such as height, weight, age and gender have a relationship with swallowing accelerometry signal characteristics in adult populations.

By gathering and analyzing healthy swallowing accelerometry signals, a basis for healthy adult swallowing signals can be established by which future studies involving abnormal swallowing accelerometry signals can be compared against for classifier development. Also, determining whether a linear relationship exists between anthropometrics and accelerometry signals can further enhance aspiration detection accuracy as different demographic bases for swallowing accelerometry signals can be established.
Preface for Chapter 4

This chapter entitled “Automatic segmentation of dry, wet and wet chin-tuck swallows in dual-axis cervical accelerometry signals” is based on a technical note, which outlines the methods employed to automatically isolate and extract swallowing segments from large dual-axis accelerometry signal sequences. The created techniques, described in this chapter, were developed to produce the desired automatic segmentation in the face of voluminous accelerometry recordings acquired from several swallowing tasks and also for potential use involving real-time swallow-segment extraction for an accelerometry-based aspiration detection device.

The first section (4.1) of this chapter describes: introductory information relating to deglutition, dysphagia and aspiration (4.1.1), the need for the development of the swallowing segmentation algorithms (4.1.2), a review of existing automatic segmentation algorithms currently used (4.1.3) and an overview of the organization of the chapter (4.1.4). Subsections 4.1.1 and 4.1.4 can be passed over if introductory background information has already been acquired from the preceding chapters and if this preface is read.

Section 4.2 provides a description of the experimental methodology used to acquire the swallowing signal sequences. This includes a description of the specific swallowing tasks employed for accelerometry signal acquisition that took place at the OSC. While large data set was collected, data for ten participants were used, which included signals from three distinct swallowing tasks. Only ten participants were used to perform a preliminary evaluation on the algorithms. The reader may choose to skip this section if they are familiar with the details of the OSC study however, it is strongly suggested that this section be reviewed nonetheless as it is pertinent to subsequent sections.

Two patient-independent automatic segmentation algorithms are presented in section 4.3, which describes an algorithm for segmenting dry and wet swallows and section 4.4 which details an alternative algorithm for obtaining wet chin-tuck swallows. The validation of the segmentation algorithms against manual extraction by trained experts is reported in sections 4.5 and 4.6. Section 4.7 then closes a brief discussion on the limitations of the proposed segmentation methods.
Chapter 4
Automatic Segmentation of Dry, Wet and Wet Chin-Tuck Swallows in Dual-axis Cervical Accelerometry Signals

Abstract

The purpose of this note is to demonstrate the methods employed to automatically isolate and extract swallowing segments from large dual-axis accelerometry signal sequences obtained from various swallowing tasks.

Data for 10 healthy participants (6 women and 4 men), ranging in age from 18-80 were sampled from the larger dataset for this project. Each participant was involved in a 15 minute data collection session. Swallowing signals were obtained for 5-saliva and 10-water (5-wet and 5-wet chin-tuck) swallowing tasks for each participant using a dual-axis accelerometer placed anterior to the cricoid cartilage.

Accelerometry signals were automatically segmented to extract individual swallows from background noise. Two patient-independent automatic segmentation algorithms using discrete wavelet transforms of swallowing sequences were developed: one to segment saliva and wet swallows and another to segment wet chin-tuck swallows. The methods hinged on a dynamic threshold based on the signal statistics to correctly extract swallows within the sequence from background noise.

The techniques employed to produce the desired automatic segmentation are necessary in the face of voluminous accelerometry recordings.

4 Introduction

4.1 Background on Dysphagia and Aspiration

4.1.1 Aspiration and Accelerometry

Deglutition (swallowing) is the process of transferring food or liquid from the mouth to the stomach and includes four distinct phases: preparatory, oral, pharyngeal, and esophageal (Logemann, 1998) Dysphagia (swallowing difficulty) refers to deglutition disorders which digress from the pattern of healthy swallowing (Perry & Love, 2001) and is common among
individuals with neurological impairments such as cerebral palsy, traumatic brain injury (TBI),
cerebrovascular accidents, stroke, Parkinson’s disease and multiple sclerosis (Daniels et al.,
1998; Mari et al., 1998; Wright et al., 1998). Patients with dysphagia have a high probability of
aspiration. Aspiration is the entry of material into the airway below the true vocal folds (Miller,
1992). Aspiration may have severe consequences including: acute aspiration pneumonia, chronic
lung disease and even death (Ding & Logemann, 2000; Prontnicki, 1995; Sheppard, 1997). Silent
aspiration is a form of aspiration which is not associated with a cough response in alert
individuals.

Accelerometry signals have been used to assess swallowing and to detect aspiration in
several studies (Das et al., 2001; Reddy et al., 1991; Reddy et al., 2000; Reddy et al., 1994).
Here, accelerometry refers to the placement of an accelerometer on the neck (near thyroid
cartilage) and the subsequent recording of vibrations from the surface of the neck during
swallowing. For this study, a dual-axis accelerometer is used to simultaneously acquire
vibrations in both the superior-inferior (SI) and anterior-posterior (AP) directions.

4.1.2 Need for Swallowing Segmentation

Figure 4.1 portrays two examples of typical cervical vibration signals, each containing a
sequence of 5 swallows. Clearly, to study the vibrations associated with swallowing activity, it is
necessary to isolate the actual segments where swallowing occurs. Although automatic
segmentation would be preferable in the face of voluminous accelerometry recordings, Figure
4.1 suggests that this may be a non-trivial task given the waveform variations between
participants and tasks.

Past studies involving swallowing accelerometry (Lee et al., 2006; Reddy et al., 1991;
Reddy et al., 2000) have reported the segmentation of small samples of swallows exclusively by
visual inspection, or with the aid of simple threshold functions. Manual segmentation was
possible for previous studies as the sample sizes were typically small and involved only one or
two swallowing tasks, usually with discrete swallows. The present study required a segmentation
algorithm for three types of sequential swallowing tasks per participant, with approximately five
swallows per task. It is known that swallowing duration is influenced by postural variations
(Inagaki, Miyaoka, Ashida, Ueda, & Yamada, 2007), age, gender and bolus volume (Hiss,
Treole, & Stuart, 2001). In past studies, manual segmentation was validated against videofluoroscopy. However, as we sampled a healthy population, videofluoroscopy was not feasible. In light of the aforementioned challenges, an automatic, signal-based segmentation method was developed.

### 4.1.3 Existing Segmentation Algorithms

While no automatic segmentation method has been reported for swallowing accelerometry, segmentation algorithms have been developed for other biomechanical or biopotential signals. Specifically, EMG segmentation methods are discussed in this section in order to see if similar methods can be applied for accelerometry segmentation. EMG segmentation methods can appropriately be chosen as a main comparator to accelerometry since swallowing accelerometry signals have similar characteristic signal-to-baseline noise discrimination as EMG signals.

One type of EMG segmentation extracted the required EMG signals by analyzing the respective durations of muscular contractions. This method requires initial filtering based on segment duration and the average power ratio between two successive segments; information that is not known a priori. Previous algorithms were unable to detect segments of very small duration (less than 0.24 s) (Duchene & Lamotte, 2001; El Falou et al., 2005). This extraction of swallows based on duration detection would not be feasible as true swallows can vary in duration and partial swallows, wherein an individual initiates, stops and then completes the swallow, occur quite frequently.

A second, more traditionally used method for EMG segmentation uniformly relied on the assumption that large amplitude differences existed between initiated muscle contractions and baseline noise (1-3 SDs) (Micera, Vannozzi, Sabatini, & Dario, 2001). A threshold can be determined by either: using the inherent statistics of the signal to produce a dynamic threshold (Micera et al., 2001; Staude & Wolf, 1999) or to arbitrarily set a static threshold if the signals to be extracted are significantly larger than baseline noise (Hudgins, Parker, & Scott, 1993; Micera et al., 2001). The latter method has been used in the past with respect to swallowing accelerometry signals (Das et al., 2001). To further eliminate the possibility of false-positive extraction, an extension of the threshold determination technique (The Double-Threshold Detector) has also been developed wherein a relationship between the probability of true EMG
contraction detection and the probability that a noise sample (the envelope of the EMG signal being at rest) is above the threshold is determined (Bonato, D'Alessio, & Knaflitz, 1998). The former is maximized, while the latter is minimized to produce the optimal threshold. While there is a necessity of false-positive removal within swallowing sequences, a lack of knowledge of baseline noise with respect to swallowing accelerometry signals would make the determination of the probability of noise quite difficult.

Another method used for EMG segmentation involves the use of autoregressive (AR) modeling to differentiate between biomechanical muscular contractions and background noise (Khalil & Duchene, 1999; Staude & Wolf, 1999). For the case of swallow segment detection however, AR modeling could not be used due to the nonstationarity of the swallow sequences (Chau et al., 2005).

A fourth method utilized for EMG segmentation is that of the extraction of ridges from Time-Frequency Representations (TFRs) of signal data. This is based on the image processing technique of active contours (method for geometric and probabilistic modeling of shapes and their dynamics) using a gradient vector flow (GVF) formulation that assess signal energy and frequency variation. This method however is quite computationally intensive for the segmentation of long accelerometry signals (Terrien, Marque, & Germain, 2008).

Given the observation that an amplitude discrepancy exists, albeit small at times, between baseline noise and accelerometry swallowing segments, a threshold using varying statistical parameters based on the given EMG sequence could be adapted for segmentation of accelerometry signals. Other postural EMG segmentation algorithms could not be directly applied for the segmentation of accelerometry swallow sequences.

4.1.4 Overview of Note

The goal of this technical note is to propose a signal-based automatic segmentation algorithm suitable for dual-axis swallowing accelerometry signals. Section 4.2 provides a description of the experimental methodology used to acquire the swallowing signals. Section 4.3 describes an algorithm for segmenting dry and wet swallows while section 4.4 details an alternative algorithm for obtaining wet chin-tuck swallows. The validation of the segmentation algorithms against
manual extraction by trained experts is reported in sections 4.5 and 4.6. This note closes with a brief discussion of the limitations of the proposed segmentation methods in section 4.7.

Figure 4.1: Sample SI dry swallowing signal (top) and SI wet chin-tuck swallow signal (bottom) prior to segmentation. Each contains five distinct swallows obtained from dual-axis accelerometer.

4.2 Experimental Methods to Obtain Accelerometry Signals: Data Collection

Ten healthy adult participants (average age 40.7 ± 13.1 years, 4 males) were recruited to participate in this study. Participants were sampled from a larger dataset of 408 participants gathered from a public science centre. All participants provided written consent. The protocol was approved by the research ethics boards of the Toronto Rehabilitation Institute and Bloorview Kids Rehab, both academic health science centres of the University of Toronto. An accelerometer was placed on the participant’s neck (anterior to the cricoid cartilage) using double-sided tape. The accelerometer was carefully aligned to capture vibrations in the anterior-posterior and superior-inferior directions. Dual-axis swallowing signals were acquired at 10kHz
using a custom LabView program, low-pass filtered in hardware with a 3kHz cutoff and stored on a laptop for subsequent off-line analysis.

With the sensor attached, the participant performed 5 saliva swallows with 20-second pauses between each swallow to allow for saliva production. The participant was then asked to complete 5 water swallows by cup, with their chin in a neutral position (head upright) and pausing for 5-seconds after each swallow. Finally, the participant performed 5 water swallows by cup in the chin-tuck position, again punctuating each swallow with a 5-second pause. Water was chilled to 4°C and sip size was not regulated.

4.3 Segmentation of Dry and Wet Swallows

Figure 4.2 illustrates the seven components which make up this algorithm. The objective is to automatically segment swallows from noise using the respective characteristics of the raw signal produced by each participant during dry and wet swallowing. Each of the seven components is described in greater detail in the subsequent sections.

![Diagram](image.png)
4.3.1 Automatic Determination of Dry/Wet Swallow Threshold

The raw accelerometry signal was decomposed using a Daubechies-10 (db10) wavelet with eight (8) decomposition levels (Berkner & Wells, 2002; Ovanesova & Suarez, 2004). For the majority of the decomposition levels, we observed that the wavelet detail coefficients provided the clearest visual distinction between swallows and noise at the precise temporal locations where swallows were expected.

To establish a threshold to distinguish between potential swallow segments and noise, we first determined the decomposition level that provided the maximum differentiation between swallow and background noise. As the noise floor was fairly uniform across levels, we simply selected the level with the highest root-mean-square (RMS) peak over the length of the detail signal. The RMS value was estimated using a sliding window, 5% the length of the detail signal. To accommodate large magnitude swallows, we performed selective amplitude scaling, whereby any detail coefficient that was eight times larger than the median coefficient value was scaled down by taking its $9^{th}$ root. The $9^{th}$ root was empirically selected as it produced a nonlinear suppression of detail coefficient magnitude such that the resulting swallow was still distinguishable from baseline noise. Next, a threshold, $T$, was determined for each sequence of swallows as follows,

$$T = d_{\text{mean}} + 0.35 \times (d_{\text{max}} - d_{\text{mean}})$$  \hspace{1cm} (1)$$

where 0.35 is an empirically determined constant and $d_{\text{mean}}$ and $d_{\text{max}}$ are the mean and maximum detail coefficient values after selective amplitude scaling. This equation has been adapted from the amplitude threshold proposed by Micera et al. (2001) to detect EMG signals from noise (Micera et al., 2001).

4.3.2 Estimating Dry/Wet Swallow Times

For each swallow sequence, we created an indicator vector of length equal to that of the detail signal under study. For each data point exceeding the threshold, $T$, defined by (1), the corresponding indicator vector entry was set to 1. All other entries were set to zero.
The first 0 to 1 transition in the indicator vector was identified as the start of the first candidate swallow. From this transition, we imposed a 2 second window in which no other swallow initiations are allowed. This criterion ensured that the detail signal fluctuations due to swallowing are not flagged as new swallow onsets. In similar fashion, the remaining start times are extracted from the indicator vector. To obtain the candidate swallow end times, all the 1 to 0 transitions in the indicator vector are obtained. Given a candidate swallow start time, the corresponding end time is selected as the time of the last 1 to 0 transition in the indicator vector prior to the start of the next candidate swallow.

To ensure that the start and end times encompass the entire candidate swallow, we made an additional adjustment to the extracted onset and offset times. In particular, if the duration of a candidate swallow (end time minus start time) was less than 3 seconds, the start time was decremented by 1.5 seconds while the end time was incremented by 1.5 seconds. While this adjustment may introduce additional noise to the candidate swallow, it ensured that no components of a swallow were missed. Subsequent post-processing described below mitigated the noise within the extracted segments.

4.3.3 Elimination of Non-swallow Segments from Dry/Wet Sequences

With the threshold (T) proposed above, the algorithm may incorrectly identify certain noise segments as candidate swallows. These noise segments are false positives (FP). The initial threshold was intentionally non-stringent to mitigate the possibility of disregarding any true swallowing segments within the sequence. To remove FPs from the set of extracted segments, we assume that the RMS of FP segments should be much closer to that of baseline noise than to the amplitude of the identified swallows. Conversely, the RMS of genuine swallow segments should be much closer to that of the identified swallow segments than to baseline noise.

We calculated the overall RMS value for each candidate segment. These RMS values were sorted in descending order. Let us denote the set of sorted RMS values as \( \{r_1, r_2, ..., r_N\} \), where \( r_1 > r_2 > ... > r_N \) and \( N \) is the total number of candidate segments. The three segments with the largest RMS values were assumed to be true swallows. Some of the remaining segments were genuine swallows while others were non-swallowing activities. Therefore, the next step was to identify the authentic swallows among the remaining candidate segments.
We computed the median RMS value of the 3 largest segments, i.e., \( M_3 = \text{median} \{ r_1, r_2, r_3 \} \), and the median RMS value of the first 0.5% of the signal, \( M_{\text{noise}} \), which was assumed to be noise. For a segment to qualify as a swallow, the amplitude of the segment (\( r_n \)) should be closer to that of the identified swallows (\( M_n \)) than to the noise floor (\( M_{\text{noise}} \)). In other words,

\[
S_n \times |r_n - M_n| < |r_n - M_{\text{noise}}|
\]

where \( M_n = \text{median} \{ r_1, \ldots, r_n \} \) a scaling function given by

\[
S_n = 1 - 0.6 \times e^{-0.5(n-4)}
\]

and \( n \geq 4 \) indexes the candidate segments. The scaling function \( S_n \) starts at 0.4 when \( n = 4 \) and approaches unity as \( n \) grows. In this way, large amplitude swallows are scaled down while smaller amplitude swallows are preserved, facilitating a uniform comparison to the already derived swallows. The constants in (3) were empirically determined. Specifically the value 0.6 was selected from a set of numbers ranging from 0.4-0.9, while 0.5 was selected from a set of ranging from 0.4-0.7 in order to provide adequate scaling as \( n \) grows. Since the segments are rank ordered in terms of RMS values, it is assumed that once a false positive is detected, subsequent segments are deemed as FPs.

Every time a segment is identified as a valid swallow, i.e., inequality (2) is satisfied, \( n \) is incremented and the quantity \( M_n \) is recalculated to include the new swallow. This is repeated for each subsequent segment until a violation of (2) occurs. At that time, all segments thereafter are deemed as FPs and discarded.

### 4.3.4 Trimming the Dry/Wet Swallows

The identified swallow segments may contain a small amount of noise at the ends of the swallow (see Section 4.3.2). To remove the unwanted noise, the RMS value of each identified swallow is iteratively re-estimated, each time omitting a small window (4% of size of segment) of data. This window of omitted data progresses along the length of the signal in a non-overlapping fashion. Let \( \{ X \} \) represent the swallow signal under consideration and let \( \{ W_1, \ldots, W_N \} \) represent the non-overlapping, windowed subsets of \( \{ X \} \). Data within the \( i^{th} \) window is classified as noise only if
\[ \text{RMS}([X]/W_i] - \text{RMS} ([X]) > 0 \]

where \([X]/W_i\) is the set difference between \([X]\) and \(W_i\). In other words, if the RMS estimate actually increases when \(W_i\) is omitted, then likely \(W_i\) contained baseline noise and thus should be trimmed from the signal. If the RMS difference decreases or stays the same, the window of data is retained. In this way, noise is eliminated on either side of the swallow. The difference between the location of the swallow before and after noise removal is seen in figure 4.3.

![Sample segmentation results for a sequence of wet swallows](image)

**Figure 4.3:** Sample segmentation results for a sequence of wet swallows

### 4.4 Segmentation of Wet Chin-Tuck Swallows

Unlike dry and wet swallowing tasks, the wet chin-tuck involves more physical movement but the point where the swallow takes place is usually well-defined. As seen in figure 4.1, the chin-tuck action, if performed properly, will produce a large maximum when the participant’s chin is lowered and a steep minimum when the participant’s neck returns to the neutral position. The participant was cued to swallow while the chin was in the tucked position, and thus a swallow should be found between a maximum (chin lowering) and the subsequent minimum (return to
neutral position). Figure 4.4 summarizes the wet-chin tuck segmentation algorithm. Each component will be discussed in the subsequent sections.

4.4.1 Wet Chin-Tuck Maximum-Minimum Locator

To obtain the maxima and minima, the original signal was first subjected to wavelet denoising using a Daubechies-8 wavelet, at ten decomposition levels. This wavelet has been previously used to filter swallowing acceleration signals. This denoising did not remove a significant amount of signal information as more than 80% of the signal energy was retained.

Next, all the local extrema in the signal were obtained and stored in two vectors, one for the maxima and another for the minima. From these vectors, we wanted to extract the maximum-minimum pairs that encapsulated a swallow in the sequence. In other words, we required the local extrema of the maxima and minima vectors. This was practically achieved by the following procedure. Let $Y = \{Y_1, \ldots, Y_P\}$ denote vector containing the $P$ maxima extracted from the raw swallowing signal.

1. Compute the sign of the first difference of the maxima vector, $S$, where $S_i = \text{sign}(Y_i - Y_{i+1})$, $i=1, \ldots, P-1$

2. Compute the first difference of the sign data, $D$, where $D_i = S_i - S_{i+1}$, $i=1, \ldots, P-2$
3. The local maxima were taken to be the points where $D_i = -2$.

The same process was repeated for the minima vector and local minima were identified as points where $D_i = +2$.

**4.4.2 Wet Chin-Tuck Zero-Crossing Locator**

Once we obtained the maximum-minimum pair encapsulating each swallow, we used the zero-crossing between a given maximum (chin lowering) and corresponding minimum (return to neutral position) to locate the swallowing event. To obtain the zero-crossings where the swallows were located, the sign of the original signal was obtained. All sign transitions identified candidate zero crossings. In particular, the zero-crossing between each maximum-minimum pair identified above was used to locate the swallowing event. In instances where more than one zero-crossing occurred between a maximum-minimum pair, the average location of the zero-crossings was selected.

**4.4.3 Wet Chin-Tuck Swallowing Onset and Offset**

To isolate all the relevant signal activity associated with each wet chin-tuck swallow, we extracted a 2.5 second window of data: 1.25 seconds preceding and 1.25 seconds after the zero-crossing identified above. Next we detrended the 2.5 seconds of data by decomposing the segment (with a wavelet), setting the approximation coefficients to zero and then reconstructing the signal. Finally, we applied the same trimming algorithm as for the dry and wet swallows to hone in on the precise boundaries of the swallowing activity. The action of this algorithm is exemplified in Figure 4.5.
Figure 4.5: Sample segmentation results for a wet chin-tuck swallowing sequence. The circles denote the locations of the identified zero-crossings.

4.5 Algorithm Evaluation

To evaluate the algorithms, two experienced speech-language pathologists (SLPs) from the Toronto Rehabilitation Institute manually segmented swallows from 10 participants. Each SLP was presented with graphs of swallow sequences using a custom program. They indicated their choices of start and end times for each suspected swallow segment by clicking directly on the graph. The program automatically logged the identified locations. This expert identification of swallow locations for each swallowing task in both the SI and AP directions served as the gold-standard.

The evaluation measures included: accuracy which is a ratio between the swallows which are correctly identified by the algorithms to the total number of swallows in the task signal;
sensitivity which measures the ability of the algorithm to detect true swallows within the signal and specificity which measures the ability of the algorithm to reject noise.

Due to task differences in dry/wet and chin-tuck swallowing, two separate definitions of correct segmentation were adopted. In both cases, the gold standard segment for each swallow was the region of intersection between the corresponding swallows extracted by each SLP. The inter-rater intersection for both AP and SI axes was respectively, 75±1.7% and 73±0.9% across all swallowing tasks.

For dry and wet swallows, a segment was considered correctly extracted if it temporally overlapped with the gold standard by at least 70% in both the SI and AP directions. Percentage overlap is defined as the number of samples in the algorithm-extracted swallow which intersect with the gold standard, divided by the total number of points in the gold standard swallow. As a result of the increased movement associated with the chin-tuck swallowing task, the requisite overlap for a correct segmentation was relaxed to 60%.

4.6 Results

The sensitivity and specificity of the segmentation algorithms are summarized in Table 4.1. There was no difference between sensitivity in the SI and AP directions. The same observation was noted for specificity. In other words, the algorithm seemed to perform equivalently well in either direction. However, segmentation performance did vary significantly among tasks. In the SI direction, sensitivity was lowest for wet swallows (p=0.05) while specificity was highest (p<0.035) for wet chin-tuck swallows. In the AP direction, specificity was significantly lower for dry swallows than for chin-tuck swallows (p=0.008).
Table 4.1: Sensitivity and specificity of the proposed segmentation algorithms (154 swallows) averaged over 10 participants for each swallowing task

<table>
<thead>
<tr>
<th>Swallowing task</th>
<th>Superior-inferior (SI) direction</th>
<th>Anterior-posterior (AP) direction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sensitivity*</td>
<td>Specificity*</td>
</tr>
<tr>
<td>Dry</td>
<td>98.1±5.3</td>
<td>91.5±9.1</td>
</tr>
<tr>
<td>Wet</td>
<td>90.6±9.6</td>
<td>91.3±10.6</td>
</tr>
<tr>
<td>Wet chin-tuck</td>
<td>97.8±5.3</td>
<td>100</td>
</tr>
</tbody>
</table>

* statistically significant difference among swallowing tasks (p≤0.047)

The durations of the swallows extracted by SLP and by the algorithms are tallied in Table 4.2. In general, the durations of the algorithm-extracted swallows agree closely with those of segmented by the SLP. The only exceptions are the durations of wet and wet chin-tuck swallows in the SI direction.

Table 4.2 Durations of swallows (in seconds) extracted by SLP and segmentation algorithms

<table>
<thead>
<tr>
<th>Swallowing task</th>
<th>SI</th>
<th>AP</th>
<th>SI</th>
<th>AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>1.88±1.11</td>
<td>1.9±1.1</td>
<td>1.63±0.83</td>
<td>1.65±0.94</td>
</tr>
<tr>
<td>Wet</td>
<td>1.16±0.49</td>
<td>1.35±0.54</td>
<td>1.58±0.72*</td>
<td>1.4±0.68</td>
</tr>
<tr>
<td>Wet chin-tuck</td>
<td>1.12±0.42</td>
<td>1.58±0.63</td>
<td>2.47±0.09*</td>
<td>1.79±0.96</td>
</tr>
</tbody>
</table>

* duration significantly different from SLP-extracted segment (p≤0.003)

4.7 Discussion

The proposed algorithms were able to detect the vast majority of swallows identified by the SLPs. Negligible amounts of false negative (missing swallows) were observed and the number of false positive readings was also low.
The generally high sensitivity and specificity of segmentation implies that the proposed algorithms are comparable to manual segmentation and hence may be viable for processing large volumes of dry and wet swallow signals. The results in Table 4.1 suggest that the proposed algorithms are particularly suited for the extraction of wet chin-tuck swallows in the SI direction. In part, this is due to the explicit consideration of task characteristics (i.e., large vibrations occur with chin lowering and lifting). Although performance in AP and SI directions were statistically similar overall, the worst segmentation occurred in the AP direction for dry swallows. This may be attributed to a reduced signal amplitude in the AP direction during dry swallows.

The noted discrepancy in durations for wet and chin-tuck swallows extracted in the SI direction may be due to motion artifact associated with the task. Vibrations due to gross body motions tended to limit the effect of noise trimming, resulting in longer segments.

A limitation assumption of the wet/dry algorithm is that the participant does not move his/her neck or head excessively during the swallowing tasks. These movements would be manifested as additive noise throughout the signal and encumber segmentation. However, as with wet chin-tuck swallows, we know that the effect of motion artifact could be mitigated via an extra detrending step. In addition, the wet/dry algorithm assumes the participant does not cough or vocalize during the swallowing tasks. In the presence of coughing or vocalizations, the algorithm may wrongly segment non-swallowing activities. To address these limitations, one would need to conduct a closer examination of specific noise components in the accelerometry signals and develop additional filters.

The wet chin-tuck segmentation algorithm exploits the task characteristics (i.e., chin lowering) to automatically locate the swallow. This is done with at least 90% accuracy, sensitivity and specificity in both AP and SI directions.

As in the dry/wet swallow algorithm, the wet chin-tuck algorithm is presently not equipped to reject signal activity due to coughing, vocalizations, and excessive body movements.

4.8 Conclusion
We have proposed a segmentation algorithm to automatically extract swallowing activity from dual-axes cervical vibration signals recorded from healthy adults during a continuous sequence
of swallows. The algorithm exploits inherent signal characteristics to differentiate activity from noise and was validated against manual segmentation by two speech-language pathologists with signals from three types of swallowing tasks, namely, dry, wet and wet chin-tuck swallowing. For all tasks and both vibration directions (anterior-posterior and superior-inferior), the proposed algorithm achieved a minimum average accuracy of 90%, sensitivity of 90% and specificity of 84%. To achieve clinical significance, accuracy is required to be at least 90%. Both algorithms were found not to perform well with excessive movements, coughing and/or vocalization. Future work should focus on enhancing the segmentation specificity, and in particular, the rejection of non-swallowing activities, such as body motion, vocalizations and coughing.
Preface for Chapter 5

This chapter entitled “Anthropometric and demographic correlates of dual-axis accelerometry signal characteristics: a canonical correlation analysis” outlines the canonical correlation analysis performed to determine the correlation between a set of swallowing accelerometry signal parameters and a set of anthropometric variables. The first independent multidimensional set comprised of anthropometric variables including: age, gender, weight, height, body fat percent, neck circumference, mandibular length, activity level, alcohol consumption and smoking habits were recorded. The methods involving the collection and recording of the data included in this set are described in this chapter. The second dependent multidimensional set comprised of accelerometry signal characteristics including: variance, skewness, kurtosis, autocorrelation decay time, energy, scale and peak-amplitude. These signal characteristics were obtained from manual segmentation and extraction of swallowing segments from background noise. Any linear relationships should be taken into consideration for any potential accelerometry-based aspiration detection device.

Section 5.1 of this chapter describes: introductory information relating to deglutition, dysphagia and aspiration, the need for the development of a novel device to assist in aspiration-detection using accelerometry signals and finally how research is required to assess whether accelerometry signals vary according to anthropometric variables. Section 5.2 provides a description of the experimental methodology used to acquire the accelerometry swallowing signals as well as anthropometric data. These sections can be passed over if introductory background information has already been acquired from the preceding chapters and if the reader is familiar with the details of the OSC study.

Sections 5.3-5.5 provide details of the analysis required for canonical correlation, the results of the canonical correlation analysis for both sets and with respect to all swallowing tasks and finally a discussion providing possible explanations regarding the results of the analysis is given.
Chapter 5
Anthropometric and Demographic Correlates of Dual-Axis Accelerometry Signal Characteristics: A Canonical Correlation Analysis

Abstract

This study examined the correlation between swallowing accelerometry signal parameters and anthropometric and demographic variables. A total of 50 healthy participants (25 women and 25 men), ranging in age from 18-80 and with approximately equal distribution across four age groups (18-35, 36-50, 51-65, 66 and older) participated in the study. Each participant was involved in a 15 minute data collection session. The age, gender, weight, height, body fat percent, neck circumference and mandibular length of each participant was recorded. Swallowing signals were obtained for 5-saliva and 10-water (5-wet and 5-wet chin-tuck) swallows for each participant using a dual-axis accelerometer placed anterior to the cricoid cartilage. Upon manual segmentation and extraction of swallowing segments from background noise, several swallowing signal characteristics per swallowing task were estimated for each participant. These characteristics included variance, amplitude distribution skewness, amplitude distribution kurtosis, signal memory, energy, scale and peak-amplitude.

Canonical correlation analysis was performed on a set of anthropometric and demographic variables and a set of swallowing signal variables. Two significant linear relationships were identified for wet swallowing tasks. In the SI direction, weight, age and gender were linearly correlated (R=0.76, p=0.00063) with amplitude distribution skewness and signal memory. In the AP direction, age was correlated (R=0.52, p=0.0473) with amplitude distribution kurtosis and signal memory. No significant linear relationship was observed for dry and wet chin-tuck swallowing tasks. Our findings suggest that swallowing accelerometry signals have task-specific associations with demographic and anthropometric factors. The uncovered correlations generally resonate with previously documented relationships between quantitative swallowing parameters and participant characteristics.
5 Introduction

5.1 Background on Dysphagia and Aspiration

Deglutition (swallowing) is the process of transferring food or liquid from the mouth to the stomach and includes four distinct phases: preparatory, oral, pharyngeal, and esophageal (Logemann, 1998). Dysphagia refers to deglutition disorders which digress from the pattern of healthy swallowing (Smith et al., 1999) and is common among individuals with cerebral palsy, traumatic brain injury (TBI), cerebrovascular accidents, stroke, Parkinson’s disease and multiple sclerosis (Daniels et al., 1998; Ding & Logemann, 2000; Mari et al., 1998; Perry & Love, 2001). A common issue with dysphagia is difficulty in protecting the airway during swallowing. For this reason, patients with dysphagia have a high risk of aspiration, that is, the entry of foreign material into the airway below the true vocal folds (Prontnicki, 1995). Aspiration may have severe consequences including: acute aspiration pneumonia, chronic lung disease and even death (Miller, 1992; Reddy et al., 1994; Sheppard, 1997). Current methods of dysphagia management include: postural adjustment during feeding, altering food consistency, or modifying the volume of food consumption (Logemann, 1998).

Current dysphagia diagnosis relies heavily on videofluoroscopic swallowing studies (VFSS) (Tabae et al., 2006; Wright et al., 1998). Although this is a very effective method for aspiration detection, VFSS requires expensive x-ray equipment as well as the expertise of speech-language pathologists and radiologists. Consequently, only a limited number of specialized institutions can offer VFSS and access to the available radiology suites is often limited, leading to significant wait times for VFSS in certain communities (Scott et al., 1998). Also, while long-term monitoring of swallowing function is critical to the management of a dynamic condition such as dysphagia, VFSS is not a suitable tool for this purpose, given the amount of ionizing radiation to which patients are exposed. Therefore, a speedy, accessible, reliable, non-radiographic and non-invasive screening process is desired for aspiration-detection and rehabilitation.

To achieve this desired screening process a new, non-invasive accelerometry device (the “Aspirometer”) is being developed and designed to detect aspiration based on the analysis of vibratory signals measured through the neck (near the thyroid cartilage; anterior to the cricoid
Accelerometry signals have been used to assess swallowing and to detect aspiration in several studies (Das et al., 2001; Reddy et al., 1991; Reddy, Costarella, Grotz, & Canilang, 1990; Reddy et al., 2000; Smith et al., 1999). While preliminary aspiration-detection algorithms were developed in the past for the Aspirometer (using accelerometry signals) in pediatric populations (Chau et al., 2005), algorithms for adult populations have yet to be established. For this study, dual-axis accelerometry is used to acquire (simultaneously) mechanical vibrations of swallowing signals in both the superior-inferior (SI) and anterior-posterior (AP) directions from healthy adults. Before the Aspirometer can be used to detect aspiration, an understanding of accelerometric signal characteristics in healthy populations is required (Lee et al., 2006). No previous research has reported such normative data. The intent of this study is to acquire knowledge regarding the characteristics of swallowing in healthy adults in order to compare such swallows with aspirations.

In particular, previous research has not explored whether swallowing accelerometry signals vary according to differences in anthropometric or demographic variables. The purpose of this paper is to consider this one facet of healthy swallowing: to determine if anthropometric variables such as height and weight and demographic variables such as age and gender have an effect on swallowing accelerometry signal characteristics in adult populations.

This paper is organized as follows. A description of the study methods used to obtain healthy adult swallow signals using dual-axis accelerometry as well as anthropometric variables is given in Section 5.2. In Section 5.3, the details of the canonical correlation analysis are depicted including the identification of the two multidimensional variable sets used along with the respective methods used to obtain the variable sets. The results and discussion surrounding the analysis section as well as its implications on the future development of automatic aspiration detection algorithms are discussed in Section 5.4.

5.2 Experimental Methods

Each participant completed a two-part protocol. The first part of the protocol involved the collection of anthropometric and demographic data, while the second involved the acquisition of swallowing signals using dual-axis accelerometry for three swallowing tasks. A total of 408 healthy individuals (age ranging from 18-80) participated in this study. Participants were
recruited from a public science centre and provided written consent. The protocol was approved by the research ethics board of the collaborating hospitals.

Participants were asked a series of questions regarding their health history. Participants with any previous record of stroke or other neurological conditions, swallowing difficulties, head or neck cancer, tracheotomy or an inability to stand on their own (as this is necessary for the proposed anthropometric measures) were excluded.

In the first part of the protocol, the participant’s height, weight, body fat percent, neck circumference, and mandibular length were recorded. The participant’s age, gender and activity level (Level 1: no little or no activity; Level 2: 3 or 4 hours of exercise per week; Level 3: >10 hours of exercise per week) were also documented. Participants were asked to report their habitual smoking habits, alcohol consumption and whether they exercised 24 hours prior to the study, because these variables can affect the validity of body composition measures. From the height and weight measurements the participant’s body mass index (BMI) was calculated. Body fat percent was determined using bioelectrical impedance analysis (BIA Meter, BC-550, Tanita). Information about alcohol consumption was acquired exclusively to ensure accuracy of the BIA readings.

After anthropometric and demographic data collection, participants were assessed by a registered speech language pathologist (SLP) to ensure overall swallowing health. The SLP performed an oral mechanism examination, which included the appraisal of voice quality, tongue range of motion, maximum phonation time and voluntary cough. Participants were also asked whether or not they regularly choked on water. Those who reported of exhibited swallowing-related difficulties were excluded from the study.

The second part of the protocol involved accelerometric signal data collection (see figure 5.1). Here, the participant was asked to sit in a chair and an accelerometer (Analog Devices, ADXL322) was placed on the participant’s neck (anterior to the cricoid cartilage) using double-sided tape. The accelerometer was oriented to record vibrations in the superior-inferior (SI) and anterior-posterior (AP) directions. Swallowing signals were amplified 10 times by a GRASS P55 amplifier, band passed between 0.1 Hz and 3 kHz, sampled at 10 kHz using a USB data
acquisition card (National Instruments, NI-USB 9215A) and a custom LabView program. Data were saved onto the hard drive of the attached computer for subsequent off-line analysis.

With the sensor attached, the participant was cued to perform 5 saliva swallows (dry swallows) with brief rests between each swallow to allow for saliva production. The participant was then asked to complete 5 water swallows (wet swallows) with the chin in a neutral position (perpendicular to the floor) with brief rests between each swallow. Finally, the participant was cued to perform 5 water swallows in the chin-tucked position (wet chin-tuck swallows) also with brief rests between each swallow.

5.3 Analysis

From the larger dataset of 408 individuals, the signals of 50 randomly sampled participants (25 women and 25 men), ranging in age from 18-80 and with approximately equal distribution across four age groups (18-35, 36-50, 51-65, 66 and older) were used to perform a canonical correlation analysis. Canonical correlation analysis is a multivariate method of measuring the linear relationship between two multidimensional variable sets. The analysis uncovers canonical variate pairs (linear combinations of the original variables) that are maximally correlated (Abdelmonem, Clark, & May, 2004; Hardoon, Szedmak, & Shawe-Taylor, 2004; Kelly & Manly, 2004). In the present study, the first multidimensional variable set consisted of the
anthropometric and demographic variables mentioned in Section 2. These included height, weight, age, gender, body fat percent, neck circumference, mandibular length, BMI, and activity level. Discrete variables such as gender were coded as continuous variables to facilitate canonical analysis. For example, gender variable values for male were drawn from a uniform random distribution between 0.75 and 1.0 while values for female were drawn from a uniform distribution between 0 and 0.25. Collinearity of variables was checked using the correlation coefficient. When collinearity was detected, the variable set was reduced accordingly. The second multidimensional variable set was comprised of signal characteristics described below.

From the 5-saliva and 10-water swallows from each participant, a total database of 750 swallows was obtained. Time-linked accelerometry signals were captured both in the superior-inferior (SI) and anterior-posterior (AP) directions during all swallowing tasks. The accelerometry signals were segmented manually in order to extract individual swallows from the background noise. The second multidimensional variable set for canonical correlation consisted of a collection of within-participant average swallowing signal characteristics. In other words, each participant produced a sequence of swallows for each swallowing task. For each participant, signal characteristics were initially estimated for each swallow and subsequently averaged over all the swallows within a given task. These averaged signal characteristic included variance, amplitude distribution skewness, amplitude distribution kurtosis, signal memory (when the autocorrelation of the signal decays to 1/e of its maximum), energy of the swallowing signal, scale (the level of the discrete wavelet transform of the signal bearing the highest fraction of the signal energy), peak amplitude, and duration. These variables were used in previous studies relating to dual-axis accelerometry signals by Lee et al (2006) and represent fundamental summary statistics and spectral features of the signal. This set was reproduced for every swallowing task and for both SI and AP directions. Again, collinearity was checked with the correlation coefficient and the variable set was reduced as necessary.

Canonical correlation analysis was carried out with the reduced sets of variables, for each swallowing task, for each axis. In other words, six (3 tasks x 2 axes each) separate analyses were performed. When no significant correlations were found between canonical variates, we performed several post-hoc analyses to confirm the lack of correlation. First, we removed variables with a high coefficient of variation (CV) and repeated the canonical correlation
analysis. The CV represents the ratio of the standard deviation to the mean, and it is a useful statistic for comparing the degree of variation from one data set to another. Typically when CV < 1, such a set is considered low variance, while those with CV > 1 are considered high variance. This analysis was intended to mitigate the possibility that genuine correlations were masked by high variance in certain variables. Secondly, all outliers within the data set were removed and canonical correlation was repeated. By definition, outliers were identified as values outside 2.5 standard deviations of the mean of a given variable. Finally, canonical correlation was repeated after the variable lists for both sets were reordered randomly. These three post-hoc analyses were done independently of one another, each starting with the original variable set subjected to canonical correlation.

5.4 Results and Discussion

Our check for collinearity indicated strong correlations (R ≥ 0.6) between: weight and BMI (R=0.88294), neck circumference and mandibular length (R=0.845604), body fat percentage and BMI (R=0.722978) and weight and neck circumference (R=0.685867). Therefore, to perform canonical correlation analysis, the list of anthropometric and demographic variables was collapsed to include only height, weight, age, gender and activity level. Also, it was observed that among the accelerometry swallowing signal characteristic variables, a strong inverse relationship (R=-1) was observed between memory and duration. Therefore, the list of average signal characteristics was reduced to include only variance, skewness, kurtosis, signal memory, energy, scale and peak amplitude.

5.4.1 Results for Dry Swallowing Task

For dry swallows, in both directions (SI and AP), there was no significant relationship between signal characteristics and anthropometric/demographic variables. The CV for both the anthropometric variables and the accelerometry signal characteristics for dry swallows can be observed in tables 5.1 and 5.2 respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Height</th>
<th>Weight</th>
<th>Age</th>
<th>Alevel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coefficient of Variation (σ/µ)</td>
<td>0.06</td>
<td>0.23</td>
<td>0.35</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 5.1: Coefficient of variation (CV) for non-discrete anthropometric/demographic variables
Table 5.2: Coefficient of variation (CV) for dry swallow accelerometry signal characteristics (SI (top); and AP (bottom))

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Memory</th>
<th>Energy</th>
<th>Scale</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-Coefficient of Variation</td>
<td>0.53</td>
<td>2.32</td>
<td>0.62</td>
<td>0.36</td>
<td>0.70</td>
<td>0.20</td>
<td>1.23</td>
</tr>
<tr>
<td>AP-Coefficient of Variation</td>
<td>1.35</td>
<td>3.98</td>
<td>0.69</td>
<td>0.35</td>
<td>1.33</td>
<td>0.12</td>
<td>2.72</td>
</tr>
</tbody>
</table>

Variables with a CV ≥ 1 (high variability) were identified and removed from the respective variable list. Accelerometry signals for dry SI swallows with high variability included: skewness and peak amplitude, whereas for AP swallows high variability variables were variance, skewness, energy and peak amplitude. No high CV variables were identified for the anthropometric and demographic set. With the reduced list, canonical correlation analysis confirmed a lack of correlation. Furthermore, canonical correlation analysis upon the removal of outliers as well as the reordering of variables in both sets also yielded no significant relationships between dry swallowing signal characteristics in both SI and AP direction and anthropometric/demographic variables.

5.4.2 Results for Wet Swallowing Task

The CV for the accelerometry signal characteristics for wet swallows are observed in table 5.3.

Table 5.3: Coefficient of variation (CV) for wet swallow accelerometry signal characteristics (SI (top); and AP (bottom))

<table>
<thead>
<tr>
<th>Variable</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Memory</th>
<th>Energy</th>
<th>Scale</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-Coefficient of Variation</td>
<td>0.68</td>
<td>1.16</td>
<td>0.63</td>
<td>0.35</td>
<td>0.62</td>
<td>0.22</td>
<td>1.26</td>
</tr>
<tr>
<td>AP-Coefficient of Variation</td>
<td>1.12</td>
<td>56.54</td>
<td>0.75</td>
<td>0.40</td>
<td>1.04</td>
<td>0.16</td>
<td>11.98</td>
</tr>
</tbody>
</table>
Canonical correlation analysis revealed that significant relationships existed between accelerometry signal characteristics and anthropometric/demographic variables in both SI (p=0.00063) and AP directions (p=0.0473). Figure 5.2 depicts the canonical weights (extensions), correlations and p-value for wet swallows in the SI direction. Relationships were observed between weight, age and gender and amplitude distribution skewness and signal memory. Specifically, weight, age and gender are inversely related to the signal characteristics.

Figure 5.2: Path-diagram for wet swallowing task in SI direction

Figure 5.3 depicts the canonical weights (extensions), correlations and significance (p-value) for wet swallows in the AP direction. Initially, no significant correlation was found. Upon removal of high CV variables relationships were observed between age and kurtosis and memory. Results of this secondary canonical correlation analysis are depicted in figure 3. Canonical correlation analysis involving the removal of outliers as well as the reordering of variables yielded no further significant relationships between wet swallowing signal characteristics and anthropometric/demographic variables.
5.4.3 Results for Wet Chin-Tuck Swallowing Task

The CV for the accelerometry signal characteristics for wet chin-tuck swallows is observed in table 5.4.

Table 5.4: Coefficient of variation (CV) for wet chin-tuck swallow accelerometry signal characteristics; SI (top); and AP (bottom)

<table>
<thead>
<tr>
<th>Accelerometry Signal Multidimensional Set-WET CHIN-TUCK</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>Memory</th>
<th>Energy</th>
<th>Scale</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>SI-Coefficient of Variation [[σ/µ]]</td>
<td>0.99</td>
<td>9.43</td>
<td>0.65</td>
<td>0.29</td>
<td>1.01</td>
<td>0.24</td>
<td>2.64</td>
</tr>
<tr>
<td>AP-Coefficient of Variation [[σ/µ]]</td>
<td>0.99</td>
<td>8.79</td>
<td>0.85</td>
<td>-0.36</td>
<td>1.39</td>
<td>0.26</td>
<td>-7.36</td>
</tr>
</tbody>
</table>

As with dry swallows, in both swallowing directions (SI and AP), no significant relationship was found between wet chin-tuck swallowing signal characteristics and anthropometric/demographic variables.

Amplitude distribution skewness, energy and peak amplitude were subsequently identified as having high CV and were removed from the variable lists. With the reduced list, canonical correlation analysis confirmed a lack of correlation. Furthermore, canonical correlation analysis upon the removal of outliers as well as the reordering of variables in both sets also
yielded no significant relationships between wet chin-tuck swallowing signal characteristics in both SI and AP direction and anthropometric/demographic variables.

5.4.4 Discussion

We formulate some possible explanations for the significant correlations uncovered in our analyses. For wet swallows, in the SI direction, the inverse relationship between weight and signal characteristics implies that as a person’s weight increases, the signal memory and skewness will decrease. This may be due to the increase in adipose tissue around the neck that is associated with elevated BMI (weight was correlated with BMI). Skewness was generally negative implying an overwhelming acceleration in the superior direction during swallowing. The additional tissue may have differentially affected the vibration signals, favouring the superior vibration while diminishing the inferior vibration (Kuiken, Lowery, & Stoykov, 2003). The superior vibration may have been sustained by slight head movements and laryngeal elevation (Reddy et al., 2000) while the inferior vibration may have been weakened by additional adipose tissue. The mechanical attenuation of the superficial measurement of muscle activity as a result of subcutaneous adipose tissue has been previously reported in mechanomyographic studies (Evetovich et al., 1998; Nonaka, Mita, Akataki, Watakabe, & Itoh, 2006). While we are not concerned with muscle activity, it is conceivable that adipose tissue exerted a similar mechanical damping in our measurements.

The inverse relationship between weight and memory, suggests that as weight increases, the autocorrelation of the swallowing signal decays more rapidly. Since memory (decay time of the autocorrelation) was inversely related to swallow duration, this finding also implies that an increase in weight will lengthen the duration of the swallow. A possible explanation may be that heavier individuals took larger sip volumes and hence required a longer time to swallow. Previous studies have suggested that males, who on average have a larger BMI than females, tend to take larger sip volumes of liquid in comparison with females and accordingly have swallow durations which are longer than females (Chi-Fishman & Sonies, 2002; Lawless, Bender, Oman, & Pelletier, 2003). Since the larynx sits lower in the neck in males, a bolus has further to travel, which may produce extended swallowing vibrations.
The second significant correlation observed in the SI direction was the inverse relationship between age and signal characteristics (skewness and memory). Our SI findings suggest that as age increases, memory diminishes (duration increases) as does superior vibrations (positive skewness). Acoustic sounds relating to swallowing have been found to be longer in duration as age increases (Tracy et al., 1989; Youmans & Stierwalt, 2005). Studies suggest that as age increases, the relative tone of the muscles producing the desired actions are decreased and consequently the associated biological signals corresponding to the muscular actions also decrease (Basta, Todt, & Ernst, 2007). Past studies have also suggested that the accelerometry signals associated with swallows are due to the muscles responsible for laryngeal elevation (Reddy et al., 2000). Hence, weakened muscle tone and/or deteriorated neuromuscular coordination during swallowing secondary to advanced aging, may prolong the action of swallowing. Further, as age increases the duration of swallowing apnea (airway closure during swallowing) tends to increase (Hiss et al., 2001). Increased apnea may contribute to longer overall swallowing duration, since the majority of swallowing components occur during airway closure (pharyngeal phase of swallowing). With respect to positive skewness in the SI vibration amplitude distribution (reduced superior vibration), it has been noted that sip volumes decrease with age. Consequently, acceleration of the head and neck may decrease, producing less superior acceleration during the swallowing task.

The third relationship in the SI direction was the inverse relationship between gender and signal characteristics (skewness and memory). Recall that higher numerical values for gender imply males. Males tended to have less negative skewness than females. This may be due to the fact that males generally have larger BMI, and hence by the arguments above, may experience greater signal attenuation than females. The relationship between gender and memory may be attributed to the longer duration of swallows and larger sip volumes of liquid in males in comparison with females.

In the AP direction, an inverse relationship was noted between age and memory, while a direct relationship was observed between age and kurtosis. The previous explanation for the inverse relationship between age and memory in the SI direction, likely applies for the AP direction as well. Lastly, with respect to the direct relationship between age and kurtosis, we note that kurtosis refers to the degree of peakedness of the amplitude distribution of the swallowing
signal. The discovered correlation implies that as age increases, the majority of the acquired accelerometry signals will become concentrated in small amplitude values. Weakened muscle tone, which is responsible for decreasing amplitude with age would account for the preponderance of weakened signals, leading to inflated kurtosis.

5.5 Conclusion

This study aimed to disclose any systematic relationships between accelerometry signal characteristics in healthy adult swallows and anthropometric/demographic variables. A lack of significant linear correlation between signal characteristics and anthropometric/demographic variables was observed in both dry and wet chin-tuck swallowing tasks. Relationships however, were observed for wet swallowing tasks. In the SI direction, strong inverse relationships were observed between weight, age and gender with amplitude distribution skewness and signal memory. In the AP direction, a strong inverse relationship between age and signal memory was observed while a direct relationship was noted between age and amplitude distribution kurtosis. These findings imply that anthropometric and demographic information associated with wet swallowing tasks should be taken into account in the detection of swallowing abnormalities using dual-axis accelerometry. Future work should focus on determining why significant relationships were found for wet swallows but not for dry swallows also in head-neutral position.
Chapter 6
Conclusion

Given the obvious benefits associated with accelerometry-based detection of aspiration over other instrumental techniques, it is necessary to construct a device that can be used in clinical bedside settings, which is comparable to the gold-standard of videofluoroscopy especially in the detection of silent aspiration but that is much more economical, less complex, more objective and does not expose the patient to doses of radiation. The aim of this thesis is contribute findings and components that will be used in the construction of the first version of such a device; the Aspirometer.

This chapter summarizes the main contributions provided during the course of this research and the projected research (future work) that will be required for the further development of this new accelerometry-based instrumental detection technique for aspiration.

6.1 Contributions

6.1.1 Methodological Contributions

Healthy adults were asked to participate in a study conducted at the OSC. The analysis presented in this thesis involved 25 randomly selected males and 25 females who were sampled evenly from four age groups within the larger dataset (18-35, 36-50, 51-65, 66 and older). Participants with a previous history of stroke, neurological conditions, swallowing difficulties, head or neck cancers, tracheotomies or who were unable to stand on their own were exempt from this study. Participants were also assessed by a SLP to ensure full functional swallowing health.

During data collection, each participant was involved in a 15-minute data collection session. In each session, anthropometric data collection took place first wherein participants had their age, gender, weight, height, body fat percent (using a Bioimpedance Analysis method), neck circumference, and mandibular length recorded. Height and weight were used to calculate the participant’s BMI. Questions regarding the participant’s activity level and smoking habits were also included. Thereafter, accelerometry signals for three swallowing tasks were obtained. Specifically, a dual-axis accelerometer was placed on the participant’s neck (anterior to the cricoid cartilage) using double-sided tape and the participant was cued to perform 5 saliva swallows (dry swallows) followed by 5 water swallows (wet swallows) with their chin in a
natural position and 5 water swallows in the chin tucked position (wet chin-tuck swallows). The accelerometer was oriented to record vibrations in the SI and AP directions.

Data acquisition involved the use of an accelerometer (Analog Devices: ADXL322) which was placed on the participant’s neck (anterior to the cricoid cartilage) using double-sided tape. Swallowing signals were amplified 10 times, band passed between 30Hz and 20kHz, sampled at 10 kHz using a USB data acquisition card (National Instruments, NI-USB 9215A) and a custom LabView program was used for data entry and acquisition.

6.1.2 Algorithmic Contributions

To study the vibrations associated with swallowing activity, it is necessary to isolate the actual segments where swallowing occurs. Two patient-independent automatic segmentation algorithms using discrete wavelet transforms of swallowing sequences were developed: one to segment saliva and wet swallows and another to segment wet chin-tuck swallows. The methods required for segmentation hinged on a dynamic threshold based on the signal statistics to correctly extract swallows within the sequence from background noise.

These algorithms were evaluated by two experienced SLPs who manually segmented swallows from 10 participants, thereby indicating the respective onset and offset times for each swallow. Evaluation of these algorithms in comparison with the SLP manual segmentation produced accuracy, specificity and sensitivity rates greater than 90%.

The created techniques employed to produce the desired automatic segmentation are necessary in the face of voluminous accelerometry recordings and can be subsequently used for real-time extraction of swallows in an accelerometry-based aspiration detection device.

6.1.3 Scientific Contributions

One of the fundamental aspects that is required for a thorough understanding of healthy adults swallowing accelerometry signals is to determine if such signals have a relationship with anthropometrics. That is, if swallowing accelerometry signals are affected by varying body compositions, age and/or gender.
Canonical correlation analysis was performed on a set of anthropometric and demographic variables and a set of swallowing signal variables. Two significant linear relationships were identified for wet swallowing tasks. In the SI direction, weight, age and gender were linearly correlated with amplitude distribution skewness and signal memory. In the AP direction, age was correlated with amplitude distribution kurtosis and signal memory. No significant linear relationship was observed for dry and wet chin-tuck swallowing tasks. Our findings suggest that swallowing accelerometry signals have task-specific associations with demographic and anthropometric factors. The uncovered correlations generally resonate with previously documented relationships between quantitative swallowing parameters and participant characteristics.

Significant linear correlation suggests, with respect to wet swallows, that anthropometric information should be taken into account in the classification of swallowing activity using dual-axis accelerometry. However, replication with a larger data set and other signal characteristics may be worthwhile.

6.2 Future Work

Future analysis involving larger sample sizes of healthy adult swallowing accelerometry signals is required for further validation of the outcomes of this study.

Also, now that data has been collected for healthy participants, a study is required for the collection of abnormal swallowing accelerometry signals in adults, particularly those with aspiration. Once such are acquired, processing of the acquired accelerometry signals is required. Therein, feature extraction is to be conducted for both healthy and abnormal accelerometry and distinguishing features of each swallowing signals are to be determined. This will assist in the construction of a classifier that can distinguish between healthy and abnormal swallowing in real-time.

Another analysis that is also required is to distinguish accelerometry signals associated with true swallows from noise sources, such as speaking or coughing. This is required to increase the accuracy and specificity of true swallow detection by the Aspirometer, since speaking and
coughing can be mistaken for swallowing, and could alter the results obtained by the Aspirometer.
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