The Relationship between UES Distension and Laryngeal Shortening

by

Samantha Casilli

Bachelor of Science in Communication Sciences and Disorders, James Madison University, 2022

Master of Science, University of Pittsburgh, 2024

Submitted to the Graduate Faculty of the
School of Health and Rehabilitation Sciences in partial fulfillment
of the requirements for the degree of

Master of Science

University of Pittsburgh

2024
This thesis was presented
by

Samantha Casilli

It was defended on
March 8, 2024
and approved by

Dr. James Coyle, Professor, Dept. of Communication Science and Disorders
Dr. Sarah Wallace, Professor, Dept. of Communication Science and Disorders
Dr. Jason Bohland, Assistant Professor, Dept. of Communication Science and Disorders

Thesis Advisor: Dr. James Coyle, Professor, Dept. of Communication Science and Disorders
Copyright © by Samantha Casilli

2024
The Relationship between UES Distension and Laryngeal Shortening

Samantha Casilli, MS
University of Pittsburgh, 2024

Abstract

Aims: We sought to determine whether correlations exist between UES distension (UESD) and laryngeal shortening (LS) in a patient group and healthy population, and whether there were clinically and statistically significant differences in LS and UESD between these groups.

Methods: Forty-seven inpatients referred for videofluoroscopic (VFSS) assessment due to clinical evidence or suspicion of dysphagia, and 47 healthy age-matched controls underwent standard VFSS examination. The maximal distention of the UES and the displacement of the laryngeal framework toward the hyoid, called laryngeal shortening (LS), were measured on each frame of each swallow event.

Results: There were no significant correlations between LS and UESD in either patients (p = 0.58) or healthy participants (p = 0.94). UESD was statistically and clinically greater (p<0.0001; d= -1.0, large effect) in patients than healthy participants. Conversely, patients exhibited statistically and clinically less LS than healthy participants (p=0.001; d=0.67 moderate effect).

Conclusion: UESD and LS were not correlated as hypothesized, however, the clinically significant differences between LS and UESD in patients and healthy participants suggest that LS may be affecting other aspects of the swallow. Limitations include a small sample size and a limited number of swallows per participant. Clinical implications of the results will be discussed.
# Table of Contents

Preface .................................................................................................................................................. 2

INTRODUCTION .................................................................................................................................. 3

1.0 Swallowing ..................................................................................................................................... 7

1.1 Muscles of Deglutition and their Innervation .............................................................................. 7

1.1.1 Biomechanics of Swallowing ................................................................................................. 9

1.1.2 Swallowing Rehabilitation ...................................................................................................... 11

1.2 Dysphagia ...................................................................................................................................... 12

1.2.1 Dysphagia Treatment/Management ......................................................................................... 15

1.3 Methods of Assessing Dysphagia ................................................................................................. 17

1.3.1 Screening ................................................................................................................................. 17

1.3.2 Clinical Examination: Non-Instrumental Bedside Swallow Assessment ......................... 19

1.3.3 Instrumental Swallowing Examinations ................................................................................... 20

  1.3.3.1 Videofluoroscopic Swallowing Study (VFSS) OR Modified Barium Swallow (MBS) ... 20

  1.3.3.2 Fiberoptic Endoscopic Evaluation of Swallowing (FEES) ................................................. 21

1.4 Central Pattern Generator and The Brain Stem .......................................................................... 21

1.5 Aspiration and Penetration .......................................................................................................... 22

1.6 Hyolaryngeal Elevation .............................................................................................................. 24

1.7 Upper Esophageal Sphincter (UES) and Lower Esophageal Sphincter (LES) .................... 25

1.8 Clinical Significance ..................................................................................................................... 27

1.9 Aims ............................................................................................................................................... 28
2.0 Methods..............................................................................................................................29

2.1 Participants ........................................................................................................................29

2.1.1 Procedures ....................................................................................................................30

2.1.2 Data Analysis ...............................................................................................................31

3.0 Results ..................................................................................................................................34

4.0 Discussion ............................................................................................................................36

4.1.1 Relationship between LS and UESD ............................................................................36

4.1.2 LS and UESD in Patient and Healthy Populations .........................................................37

4.2 Research Considerations and Limitations ........................................................................38

4.3 Conclusions .........................................................................................................................39

Appendix A ..................................................................................................................................40

Appendix A.1.1 Code used in R ..........................................................................................40

Appendix A.1.2 Means and SD for Measures Code .................................................................40

Appendix A.1.3 Welch Two Sample T-Test Codes .................................................................40

Appendix A.1.4 Effect Size Codes (Cohen’s d) .....................................................................40

Appendix A.1.5 Correlation between LS and UESD Codes .................................................41

Appendix B Scatterplot Diagrams – No Correlation ..............................................................42

Bibliography .................................................................................................................................44
List of Tables

Table 1 Swallowing Muscles, their Innervations, and Associated Cranial Nerves............... 8
Table 2 Dysphagia Projection Rates ................................................................................. 14
Table 3 Results Summary ................................................................................................. 35
List of Figures

Figure 1 Laryngeal Shortening........................................................................................................... 5
Figure 2 UESD.................................................................................................................................. 5
Figure 3 IDDSI Level....................................................................................................................... 17
Figure 4 8-Point Penetration - Aspiration Scale (PAS).................................................................... 24
Figure 5 Swallowing Annotation Application: The colored dots on the image correspond with the labels on the right-hand side............................................................................. 32
Preface

I would like to express gratitude to my research advisor, Dr. James Coyle. I would also like to thank Amanda (Mandy) Mahoney, Erin Lucatorto, and the University of Pittsburgh’s Computational Deglutition Lab and its staff for presenting me with this opportunity. I would like to thank our volunteers for participating in this study. Additionally, I wish to show my appreciation to the readers of this thesis, Dr. James Coyle, Dr. Sarah Wallace, and Dr. Jason Bohland. The Pitt faculty involved in this project have helped to guide, support, and provide me with overall insights into this field. I was provided with the opportunity to learn more about the research process and gain experience within my future profession. So again, thank you for shaping my experiences, providing strong leadership, and having such a significant impact on my education as a Pitt graduate student.
INTRODUCTION

Deglutition, another name for the act of swallowing, is the passage of matter from the oral cavity to the stomach by means of the pharynx and esophagus, and is a crucial and intricate function that develops in utero (Panara et al., 2022). Hyolaryngeal excursion (HLE) is an acknowledged significant swallowing protective mechanism that combines superior and anterior hyoid displacement to prevent food and liquid from entering the airway. This is caused by the activation of suprahyoid musculature and laryngeal superior displacement, which enables traction forces upon the anterior wall of the upper esophageal sphincter (UES), thereby causing opening. During HLE, the larynx is displaced out of the path of the bolus, the laryngeal vestibule closes, and the UES opens. Although the hyoid and larynx each have typical directions of displacement, they also move together as a complex system, and studies have shown that decreased hyoid elevation is associated with aspiration (Kim et al., 2019). The UES, the portal to the digestive system, is of major importance during swallowing since its normal function aids in averting air from entering the esophagus during inhalation, and more importantly, it assists in the defense against aspiration by preventing gastric or esophageal contents from entering the pharynx (Mittal, 2011). During swallowing, the UES must open both vertically (long) and horizontally (wide) to enable the bolus to pass through. This occurs through a relaxation of the cricopharyngeal (CP) muscles and the traction forces from HLE. The relationship between the UES and HLE is vital because they coincide with each other. Moreover, the opening of UES parallels the occurrence of HLE. HLE begins to pull the UES open, and this coordinated set of actions moves the larynx out of the path of an approaching bolus' trajectory, shortens the pharynx, and opens the normally closed UES to allow the bolus to enter the digestive system (Pearson et al., 2012).
Several conditions can impair swallowing function. A cardinal outcome of some of these conditions (e.g., medullary stroke, connective tissue disease, post-head-neck radiation therapy) directly impairs HLE and subsequently, UES opening, during swallowing. The contribution of laryngeal displacement, as a component of HLE, has not been systematically evaluated with objective measures using similar paradigms. In this study, we utilized a novel software package designed specifically for frame-by-frame analysis of videofluoroscopy images, and used anatomically based, reproducible, trigonometric analysis to measure the distance between the middle of the base of the larynx to the anterior medial point on the hyoid bone, called laryngeal shortening (LS), which is an understudied swallowing kinematic event. We then examined the correlation between maximum LS and previously labeled measurements for maximal UES distention (UESD) in a cohort of people referred for videofluoroscopy due to suspected dysphagia, and a cohort of age-matched healthy volunteers. LS is determined by labeling the hyoid and laryngeal base on each frame of a swallow video, calculating the distance between the two points in each frame, and choosing the shortest distance as the max.

As previously mentioned, UESD measurements were completed prior to beginning this study by other trained members of the lab. However, for illustrative purposes, Figure 2 depicts the measurement of max UESD at the height of the swallow. See Figure 1 and 2 below to visualize the points measured to determine LS and UESD, respectively.
Figure 1 Laryngeal Shortening

Figure 2 UESD
This study investigated LS from videofluoroscopic images and its correlation with maximal distention of the UES. We hypothesized that laryngeal shortening is correlated with UESD in patients and healthy participants, and that there will be clinically and statistically significant differences in LS and UESD between these groups. This hypothesis is based on the evidence that the hyolaryngeal traction forces that displace the hyoid and larynx during swallowing are responsible for distension of the UES.
1.0 Swallowing

Swallowing is described as "the action of moving food and liquids into the stomach at an adequate rate and speed through the oral cavity, pharynx, and esophagus" (Clavé & Shaker, 2015) (p. 259). Over 30 muscles and associated nerves collaborate reflexively and volitionally to produce this synchronized action. Swallowing is a crucial and nuanced compulsory action that is developed in utero before there is any conscious awareness of it. The nasopharynx begins as one tube and splits into the respiratory (i.e., trachea) and digestive (i.e., esophagus) tubes. During the process of swallowing, very intricate timing ensures delivery of food and liquids to the digestive system without entry into the respiratory system, which could result in adverse consequences (Panara et al., 2022). The arytenoid cartilages and the epiglottis are approximated during laryngeal closure to prevent airway invasion of swallowed materials.

1.1 Muscles of Deglutition and their Innervation

Swallowing requires the use of several muscles in the oral cavity, esophagus, larynx, and pharynx. A summary of the muscles engaged in swallowing are as follows:
Table 1 Swallowing Muscles, their Innervations, and Associated Cranial Nerves

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Innervation</th>
<th>Cranial Nerve (CN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tongue Muscles</td>
<td>hyoglossus, genioglossus, styloglossus, palatoglossus, and mylohyoid</td>
<td>CN XII, CN X, CN VIII</td>
</tr>
<tr>
<td>Muscle of Mastication</td>
<td>Masseter, Temporalis, and Lateral and Medial pterygoid</td>
<td>CN VIII</td>
</tr>
<tr>
<td>Larynx</td>
<td>posterior cricoarytenoid, lateral cricoarytenoids, oblique and transverse arytenoids (recurrent laryngeal nerve), and the aryepiglotticus (inferior laryngeal nerve)</td>
<td>recurrent laryngeal nerve, inferior laryngeal nerve</td>
</tr>
<tr>
<td>Pharynx</td>
<td>the tensor palatini, levator palatini (pharyngeal plexus), suprahypoid muscles (digastric, stylohyoid, geniohyoid, mylohyoid), infrahyoid muscles (Sternohyoid and sternothyroid thyohyoid, and omohyoid), longitudinal pharyngeal muscles (stylopharyngeus, salpingopharyngeus, palatopharyngeus), and superior, middle, and inferior pharyngeal constrictor muscles (cricopharyngeus muscle)</td>
<td>CN VII, CN IX, CN X, CN XII, mylohyoid nerve - a branch of CN VIII, ansa cervicalis, recurrent laryngeal nerve</td>
</tr>
</tbody>
</table>

(ASHA, 2023)

A key component of swallowing, the UES, is a high-pressure area located between the pharynx and the cervical esophagus. The UES’s physiological functions are to guard against air entering the digestive system as well as food reflux from the esophagus entering into the airways. The inferior constrictor complex, in particular its inferior-most cricopharyngeal portion, forms the superior portion of the UES, which is largely under autonomic control. Like other sphincters, it is tonically contracted (i.e., closed) at rest. Its resting tone diminishes momentarily before the onset of HLE to reduce its inertia and enable the traction forces to completely displace the hyoid leading to UES opening.

Other important muscles that assist in swallowing are the strap muscles. These muscles consist of the suprahypoid and infrahyoid which are bilaterally placed on each side of the neck, and
are primarily responsible for elevating and lowering the hyoid bone and larynx, which assists in UES opening.

### 1.1.1 Biomechanics of Swallowing

Depending on the bolus location, the process of swallowing can be divided into three stages: the oral, pharyngeal, and esophageal stages. The oropharyngeal swallowing phase can be divided into two stages (oral preparatory phase and oral transit phase). During swallowing, the UES function is extremely important.

Stage 1, the oral preparatory stage involves transport and food processing. With liquids, the linguavelar valve is closed, and the bolus is positioned for transit. With solids, the bolus becomes positioned for mastication. Mastication includes rotary mandible movement and the crushing of bolus. Then, the tongue moves the bolus for mastication. In this stage, oral cavity preparatory activity transpires, and the salivation/lubrication begins digestion. Mastication reduces the bolus to a "swallowable" texture and/or shape and begins to position the bolus for transit. The containment of bolus is held together by the tongue, palate, and facial muscles (Saitoh et al., 2007).

Stage 2, the oral transit stage, involves the bolus being propelled by the tongue to the palate. For liquids, this typically occurs all at once, and with gravity, they do not need to be propelled. Solids typically accumulate in the pharynx until a pharyngeal response begins, which is essentially volitional. During this stage, the lips and the linguavelar valve remain closed. The lingual tip makes palatal contact which starts the posterior propulsion of the bolus and generates intrabolus pressure. While this is occurring the linguavelar valve remains closed, and there is a continued posteriorward tongue-to-palate propulsion. Then the linguavelar valve is signaled to open, and the soft palate begins motion towards velopharyngeal closure. Finally, the lingual propulsive wave continues.
alongside the bolus tail until the bolus is entirely ejected from the oral cavity into the pharynx (Saitoh et al., 2007).

Stage 3, the pharyngeal stage onset, or stage transition, couples the oral stage to the pharyngeal stage, and constitutes the beginning of the pharyngeal response. With liquids, linguavelar closure ends, and velopharyngeal closure begins. For solids, the bolus head enters the pharynx. In young populations, the linguavelar closure ends and velopharyngeal closure begins, but in the aging population, the opposite may happen, which is considered a prolonged stage duration, or pharyngeal delay. In the phase transit portion of the pharyngeal stage, velopharyngeal closure completes, and pharyngeal tube constriction begins. The UES resting tone inhibition increases, which increases UES compliance, and the vocal folds adduct. HLE begins, and the bolus enters and passes through the UES, then HLE ends and the UES closes, and the structures return to rest (Saitoh et al., 2007) while the esophageal stage propagates.

The pharyngeal stage is the shortest of all stages of swallowing yet contains the majority of biomechanical events. During this stage, the bolus head penetrates the pharynx, and the soft palate lifts and makes contact with the "lateral and posterior walls of the pharynx, sealing the nasopharynx" (Matsuo & Palmer, 2008, p. 4). Bolus regurgitation into the nasal cavity is prevented by the elevated soft palate. During this process, the bolus is forced up against the pharyngeal walls when the base of the tongue retracts. The bolus is then forced downward by the successive contraction of the pharyngeal constrictor muscles superiorly to inferiorly. To minimize the capacity of the pharyngeal cavity, and to magnify the speed of the lingual-propelled bolus, the pharynx also shortens vertically toward the oncoming bolus. Before the UES opens, the vocal folds close sealing the glottis, and the arytenoids angle forward to make contact with the epiglottic base while the epiglottis inverts by means of lingual and intrabolus pressure forces. The thyrohyoid
muscles contract, approximating the larynx superiorly to the hyoid, and suprathyroid musculature, that pull both the hyoid bone and attached larynx forward. While HLE is the anterior and superior movement of the hyoid and the larynx, LS uses the thyrohyoid muscle to approximate the larynx to the hyoid. The larynx is placed under the tongue's base as an effect of this displacement. Bolus passage into the esophagus requires the commencing of the UES.

Stage 4, the Esophageal Phase, pertains to esophageal transit. During this phase, the UES remains tightly closed. Peristalsis (superior to inferior) of the esophageal muscles compress the bolus trail progressively toward the distal lower esophageal sphincter (LES), which is tightly closed at rest. Feed-forward inhibition via the myenteric plexus related to esophageal lumen stretching and intrabolus pressure causes the LES resting pressure to drop, and with assistance from the tongue, enables clearance to the stomach (Hiiemae & Palmer, 1999). However, when the UES closes at the incorrect time, the airway is wide open, which can lead to aspiration. Once inside the esophagus, the combined effects of posture (esophagus' positioning), bolus physical attributes, and volume, along with the amount and speed of rise in intraesophageal pressure (intrabolus pressure), will all have an impact on the UES response to esophageal diameter (Babaei et al., 2012).

1.1.2 Swallowing Rehabilitation

Patients can undergo exercises for muscle endurance that strengthen the mouth, lips, and jaw musculature to try and restore original function, and compensatory movements that are utilized to create safe alternatives when regaining original function is not feasible. The objective is a long-term change in swallowing control through neuroplasticity in patients with the capability to recover who are clinically stable, such as those who have recently experienced a stroke. Moreover, the
objective is to maintain present swallowing status for as long as possible in individuals with progressing illnesses (like Parkinson's disease), by using safe-swallow compensatory approaches which are instated to address dysfunction and weakness. Additionally, eating with proper upright posture and using methods like the chin-tuck maneuver minimizes the risk of aspiration during swallowing in individuals who have had a stroke or degenerative illness. This is viable by altering the proportions of the pharynx to redirect the bolus toward the pharynx and esophagus. Also, the head-turn technique, which involves rotating the head toward the weak side, pushes the bolus toward the side that is stronger via gravity (Wilkinson et al., 2021). In more serious cases, patients may have to go beyond compensatory measures and receive feeding tubes to be able to obtain nutrients while they are regaining their muscle function to properly swallow again. Overall, there are multiple maneuvers a patient can use. It is important to keep in mind that no compensatory maneuvers should be advised until a videofluoroscopic swallow study (VFSS) (described below) is performed, the impairment is determined, and the maneuver is trialed during VFSS. If not, adding compensatory measures may ultimately end up making the swallow worse.

1.2 Dysphagia

Dysphagia is widespread, and yet may not be well-reported. Dysphagia is a sign of a problem with swallowing that develops involving the mouth and the stomach. Oropharyngeal dysphagia, which results in difficulties or the inability to safely produce and transport the bolus from the mouth to the esophagus, is a symptom of swallow dysfunction. Dysphagia can involve choking and oropharyngeal aspiration, which is when food, drink, or secretions from the oropharynx enter into the trachea or the lungs (Clavé & Shaker, 2015). Oropharyngeal dysphagia
is a persistent neurologic illness that most frequently results from stroke, Parkinson's disease, or dementia, and presents as difficulty with swallowing by exhibiting coughing, choking, or aspiration. Due to the possibility of aspiration, symptoms should be carefully assessed. In esophageal dysphagia, patients may describe feeling as though food is trapped in the throat after swallowing. The most frequent causes of this syndrome are functional esophageal abnormalities and gastroesophageal reflux disease. Dysphagia affects a sizable portion of the vulnerable aging population with growing neurologic impairment, dramatically increasing their risk for aspiration pneumonia (AP) and malnutrition (Wilkinson et al., 2021).

Dysphagia affects more than half a million adult stroke survivors annually, as well as numerous others with neurological conditions, head and neck cancer, and iatrogenic accidents. There are approximately 59,000 deaths annually in the United States related to AP, with an additional 18,000 patient deaths per year directly attributable to AP (Gupte et al., 2022).

Swallowing disorders, or dysphagia, are caused by impaired sensorimotor function of one or more of these structures and can lead to a variety of adverse outcomes, such as airway obstruction, malnutrition, AP, choking, dehydration, a reduction in overall health, chronic lung disease, and death. Additionally, patients with dysphagia may find eating or drinking to be embarrassing, socially awkward, and/or less enjoyable, impairing their quality of life. Dysphagia may result in additional financial burden, stress, and workload for caregivers as well as substantial lifestyle changes for the patient and family (ASHA, 2023).

AP, in particular, is a common adverse outcome of dysphagia. Although AP is difficult to diagnose due to its similarity in symptoms with community-acquired pneumonia (CAP), it is always caused by inhalation of gravity-dependent solid or liquid foods while swallowing, or gastric
content reflux (i.e., gastroesophageal reflux; esophagopharyngeal reflux) or reflux that enters the airway due to impaired aerodigestive sensorimotor function (Patel et al., 2018).

The term "incidence" refers to the magnitude of new dysphagia cases that are discovered during a given time frame. The term "prevalence" describes the number of people who have dysphagia at any one moment. Multiple research studies have shown that the prevalence of oropharyngeal dysphagia (OPD) is somewhere between 2.3% and 16% across the world, with children and underserved areas consuming a majority of the statistic (Rajati et al., 2022). In the United States, one in every 25 individuals will have a swallowing deficit each year (Bhattacharyya, 2014). However, it is difficult to accurately assess the prevalence of dysphagia in adult populations since it affects so many different illnesses and age groups (ASHA, 2023).

According to several epidemiologic studies, aging is positively associated with dysphagia, as it is more prevalent in elderly people (Barczi et al., 2000; Bhattacharyya, 2014; Bloem et al., 1990; Cabré et al., 2014; Roden & Altman, 2013; Sura et al., 2012; Zhao et al., 2018). Projection rates of those who may be susceptible to dysphagia are as follows:

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Setting</th>
<th>Citation</th>
</tr>
</thead>
<tbody>
<tr>
<td>As high as 22%</td>
<td>Those over 50 years old</td>
<td>(Lindgren &amp; Janzon, 1991; National Foundation of Swallowing Disorders, n.d.; Patel et al., 2018; Tibbling &amp; Gustafsson, 1991)</td>
</tr>
<tr>
<td>As low as 3%</td>
<td>U.S. inpatients 45 years or older</td>
<td>(Layne et al., 1989)</td>
</tr>
<tr>
<td>As high as 30%</td>
<td>Older groups undergoing inpatient medical care can</td>
<td>(Layne et al., 1989)</td>
</tr>
<tr>
<td>Up to 68%</td>
<td>Patients in long-term care facilities</td>
<td>(National Institute on Deafness and Other Communication Disorders, n.d.; Steele et al., 1997)</td>
</tr>
<tr>
<td>13%-38%</td>
<td>Elderly individuals living independently</td>
<td>(Kawashima et al., 2004; Serra-Prat et al., 2011)</td>
</tr>
</tbody>
</table>

(ASHA, 2023)
Furthermore, researchers have found that as patients age (i.e., 50+), the likelihood of experiencing AP increases (Loeb et al., 1999). According to the Agency for Healthcare Research and Quality (1999), people with dysphagia are one-third more likely to get AP, which claims 60,000 lives yearly. Additionally, there is evidence linking dysphagia to several neurological conditions, although the exact epidemiological statistics for each disease or condition remain unclear. This lack of certainty is exacerbated in part by concurrent comorbidities, as well as the timing and type of techniques applied to diagnose swallowing deficits in neurological populations. As stated above, the prevalence of dysphagia has been estimated differently in multiple systematic reviews and studies.

To summarize, dysphagia may be caused by acute neurogenic, trauma, neurodegenerative disorders (NDD), iatrogenic accidents, head and neck cancer treatment, prolonged deployment of artificial airways, etc. Additionally, dysphagia may emerge as a result of harm to the cranial nerves, the central nervous system (CNS), and unilateral or bilateral cortical and subcortical lesions including but not limited to "stroke, TBI, spinal cord injury, Parkinson's disease, dementia, Amyotrophic lateral sclerosis, and Multiple sclerosis" (ASHA, 2023, p. 1). Swallowing disorders can occur due to impaired oral, pharyngeal, or esophageal function and structure, and are often caused by laryngeal-pharyngeal motor impairments secondary to neurological or traumatic etiologies.

1.2.1 Dysphagia Treatment/Management

To better synchronize and develop the swallowing muscles, and to align treatment with the mechanisms by which a disease impairs swallowing in people with dysphagia, individuals can undergo dysphagia rehabilitation to restore function, develop appropriate compensations, or both
(Panara et. al, 2022). There are compensatory swallowing strategies patients may try including, but not limited to, head-turn, chin-tuck, double swallow, Mendelsohn maneuver, etc. Restorative treatments are designed to improve the functional physiology, the structure of impaired mechanisms, and involve isometric, isotonic, and resistive exercises. In early recovery and when compensations and restoration fail to restore safe swallowing (i.e., acceptable airway protection), patients can undergo diet modifications like practicing mindful eating by "chewing carefully, cutting food into smaller pieces, drinking liquids to dilute food bolus, eating slowly, lubricating with sauces, and taking smaller bites" (Wilkinson et al., 2021) (p. 104). Additionally, there are different types of diet modifications such as changing the texture and viscosity. A more standardized version to enhance the safety and care for people who have trouble swallowing is the International Dysphagia Diet Standardization Initiative (IDDSI). The IDDSI has developed globally defined standards for "texture-modified diets (TMDs) and thickened liquids" (Wu et al., 2022, p. 1). These standards can be used across all sorts of healthcare situations and can be used for all ages. The IDDSI framework helps provide guidelines for healthcare facilities, such as nursing homes, to feed vulnerable patients (Wu et al., 2022). The IDDSI levels can be found in Figure 3:
1.3 Methods of Assessing Dysphagia

1.3.1 Screening

A minimally invasive process known as swallowing screening allows for the fast identification of the possibility that dysphagia is present, and whether the patient needs to be referred for additional swallowing assessment by the SLP. With an emphasis on detecting overt evidence of aspiration (i.e., coughing, choking), swallowing screening protocols reveal the existence of clinical signs and symptoms that are suggestive of dysphagia simply by observing the
patient systematically drink water. It is essential to remember that no bedside screening strategy has yet been demonstrated to offer a sufficient level of predictability for the occurrence of aspiration. Although several techniques have been shown to have good sensitivity, these protocols' repeatability and consistency have not been publicized (O'Horo et al., 2015).

Dysphagia screenings carry the disadvantage of being unable to detect signs of aspiration in patients who lack a reflexive airway response (e.g., cough). These silent aspirators lower test sensitivity by becoming false negatives. Conversely, most current dysphagia screening tests have a “fail criterion”, such as a patient’s inability to consume 90mL of water via continuous drinking (i.e., no pausing until the 90mL of liquid is consumed). As a result, these tests have excellent sensitivity, due to the restrictive fail criterion. Indeed, in the Computational Deglutition Laboratory, a prospective experiment testing the precision of the UPMC bedside dysphagia screen returned a sensitivity of 100%, and a specificity of 18%, with 82% of non-aspirators (based on VFFS) failing the screen (i.e., false positives rate = 82%) (ASHA, 2023).

Training non-speech-language pathology (SLP) clinical workers, such as nurses, to do swallowing screenings is referred to as "training other professionals” and happens frequently. By providing this type of training, dysphagia may be identified early and patients may be referred for SLP examination (ASHA, 2023, p. 1). Screening procedures may include but are not limited to: "questionnaires or interviews with the patient and/or caregiver to ask whether they are aware of any past or current swallowing difficulties (Mari et al., 1997), Toronto Bedside Swallowing Screening Test (TOR-BSST; Martino et al., 2009), and Simple Standardized Bedside Swallowing Assessment” (SSA; Perry, 2001) (ASHA, 2023, p. 1), as well as the Yale Swallow Protocol (YSP) and the Rapid Aspiration Swallowing Screen (Daniels et al., 2016).
1.3.2 Clinical Examination: Non-Instrumental Bedside Swallow Assessment

Dysphagia can be assessed non-instrumentally at the bedside by conducting a multidimensional examination of the patient’s sensorimotor function, cognitive performance, and speech production, and observing them consume boluses at the bedside. Examining the patient’s sensory motor function and speech production provides insights into potential sensory-motor impairments that are invisible at the bedside. By assessing speech production and sensory-motor function, observers may be provided with insight into the nature of patients’ swallowing ability based on lesion location and performance on the exam. Cognitive screens are typically implemented to identify the patients ability to participate in behavioral compensations and to prepare for the behavioral aspect of the VFSS procedures that may follow. Overall, during a non-instrumental bedside exam, we still cannot examine beyond the oral cavity, so we elicit behaviors that not only display patients’ typical behaviors, but also challenge their deglutitive subsystems to infer the nature of dysphagia.

A bedside swallow assessment is not "pass/fail", however, SLPs or other qualified personnel (e.g. nurses) can observe patients during eating and drinking trials. During these trials, the observer will check for coughing, choking, a "wet" voice, or multiple swallows per bolus when practicing swallows with various consistencies (thin liquid, thick liquid, puree, solid food). At the bedside, SLPs pay particular attention to signs of pulmonary decompensation such as precipitous declines in pulse oximetry during oral intake, along with a water swallowing test or trial swallows to observe for cardinal signs of aspiration. (Wilkinson et al., 2021).

Whereas a dysphagia screening is a pass/fail examination used to determine if a patient must undergo a more extensive dysphagia evaluation, a bedside swallow evaluation includes a comprehensive cranial nerve assessment and trials of boluses of liquids and varied textures. If a
swallowing impairment is suspected during the bedside swallowing evaluation, an instrumental
dysphagia study should take place before the patient’s diet is modified, or they begin dysphagia
rehabilitation. This assessment seeks to determine the swallowing deficits (e.g., decreased tongue
base retraction), and the influence of compensatory strategies (e.g., head turn) (Donovan et al.,
2013).

1.3.3 Instrumental Swallowing Examinations

1.3.3.1 Videofluoroscopic Swallowing Study (VFSS) OR Modified Barium Swallow (MBS)

An evaluation of the architecture and physiology of the oral cavity, throat, and screening
of the esophagus is done by an SLP using a process called a videofluoroscopic swallow study
(VFSS), also referred to as a modified barium swallow (MBS). It is a fluoroscopic procedure and
is performed in a video fluoroscopy suite by a radiologist and an SLP. Analysis of VFSS images
are performed by the clinician on a frame-by-frame basis to identify kinematic errors leading to
airway protection impairments, classify the airway protection impairment, and quantify
proportions of each bolus retained in the various pharyngeal recesses after each swallow; none of
which can be performed during a bedside examination. VFSS is one of the gold standards for
assessing dysphagia and is in more widespread use than fiberoptic imaging examination (see
below). These imaging studies provide direct physiologic observations of kinematic events to the
examiner, leading to accurate attribution of impairments to the disease’s mechanism of action, and
as a result, formulation of a treatment plan aligning with the findings (Wilkinson et al., 2021).
1.3.3.2 Fiberoptic Endoscopic Evaluation of Swallowing (FEES)

Another instrument for evaluating a patient’s swallow is fiberoptic endoscopic evaluation (FEES). FEES use a tiny flexible scope with a camera that goes down the person's nose and can look at the vocal folds when people swallow. This evaluation is performed by an SLP at the bedside or outpatient environment under the supervision of a doctor (Wilkinson et al., 2021). FEES is excellent at detecting a relationship between "aspiration and bolus residue in the pharynx and pharyngeal larynx" (Wilkinson et al., 2021, p. 104). FEES is easy to complete and well tolerated by patients. To possibly increase the effectiveness of the swallow, compensatory maneuvers can be trialed during FEES, such as varying the thickness (i.e., thin liquid, thick liquid, puree, solid food) of the bolus.

1.4 Central Pattern Generator and The Brain Stem

Throughout many years of research, it is now undeniably known that a central pattern generator (CPG) generates and coordinates the successive and rhythmic patterns of swallowing, as was initially hypothesized in the groundbreaking work of S.J. Meltzer (Jean, 2001). The dorsolateral medulla oblongata houses the bilateral swallowing CPG. This CPG lies within the reticular formation of the brainstem and is associated with the primary aerodigestive autonomic sensory nucleus (i.e. nucleus tractus solitarius, or NTS), the primary aerodigestive motor nucleus (i.e., nucleus ambiguus), and adjacent structures such as the vestibular nucleus and the spinal trigeminal tract. The CPG has been shown to be responsible for a) programming oropharyngeal swallowing sequence and b) enabling increased compliance to the UES via a pre-swallow inhibitory motor signal, as occurs in all human digestive sphincters prior to a swallow (Jean, 2001).
Damage to the CPG tends to disrupt or completely disable the onset of the oropharyngeal swallowing sequence onset. Likewise, the failure of medullary inhibition to the UES leaves the sphincter in a state of tonic contraction. Therefore, the patient is unable to overcome the inertia to facilitate clearance into the esophagus. As a result, bolus components tend to be propelled to the pharynx by the relatively unimpaired oral processing, at which point the absent pharyngeal response along with UES inertia, prevents clearance.

1.5 Aspiration and Penetration

Aspiration is the abnormal flow of any gravity-dependent material (e.g., solids) into the airway beneath the true vocal folds (i.e., the trachea). Penetration is when the bolus infiltrates the airway but stays in the larynx and does not enter the trachea. Penetration and/or aspiration is highly correlated with clinical dysphagia markers and has been associated with decreased hyoid and laryngeal excursion, and partial laryngeal closure.

Decreased hyoid excursion can put a person at an increased risk for aspiration. The suprathyroid muscles enable the hyoid bone to ascend superiorly and anteriorly during the swallow. Additionally, as the bolus reaches the pharynx, the tongue base, on which the hyoid bone rests, pulls the hyoid and larynx vertically and anteriorly, assisting in closing the laryngeal vestibule. The UES is pulled down, causing the epiglottis to invert, also assisting in laryngeal vestibular closure while the bolus advances toward the esophagus (Han et al., 2016).

Aspiration and laryngeal penetration can occur before, during, or after the swallow. Before the pharyngeal response, the bolus may escape into the larynx due to poor posterior oral containment, reduced tongue movement, etc. During the swallow, penetration or aspiration may
occur due to a delay in the pharyngeal response onset and delayed and incomplete airway closure. After the swallow, pharyngeal residue that has not cleared through the UES may result in penetration or aspiration, which can happen when there is impaired propulsion and limited UES opening. The bolus may fall into the airway passively, via gravity, after the swallow has ended.

In order to describe aspiration and penetration incidents, Rosenbek and colleagues first created and tested the 8-point Penetration Aspiration Scale (PAS) in 1996, with one signifying the least severe score and eight indicating the most severe score. PAS scores are complex (i.e., each score contains a few observations): (1) degree of airway infiltration (i.e., whether the material is above, touching, or below the level of the vocal folds); (2) whether the material is propelled outward or not after swallowing; and (3) the patient's reaction to the presence of the material in the airway (i.e., an effort to expel the material) (see Figure 4). Even though the PAS is frequently used, scoring conditions might vary. Although the PAS scale is an ordinal scale with some variation in the scoring criterion, it has been in widespread clinical and research use for more than 20 years (Alkhuwaiter et al., 2022).
<table>
<thead>
<tr>
<th>Score</th>
<th>Description of Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Material does not enter airway</td>
</tr>
<tr>
<td>2</td>
<td>Material enters the airway, remains above the vocal folds, and is ejected from the airway</td>
</tr>
<tr>
<td>3</td>
<td>Material enters the airway, remains above the vocal folds, and is not ejected from the airway</td>
</tr>
<tr>
<td>4</td>
<td>Material enters the airway, contacts vocal folds, and is ejected from the airway</td>
</tr>
<tr>
<td>5</td>
<td>Material enters the airway, contacts the vocal folds, and is not ejected from the airway</td>
</tr>
<tr>
<td>6</td>
<td>Material enters the airway, passes below the vocal folds, and is ejected into the larynx or out of the airway</td>
</tr>
<tr>
<td>7</td>
<td>Material enters the airway, passes below the vocal folds, and is not ejected from the trachea despite effort</td>
</tr>
<tr>
<td>8</td>
<td>Material enters the airway, passes below the vocal folds, and no effort is made to eject</td>
</tr>
</tbody>
</table>

**Figure 4 8-Point Penetration - Aspiration Scale (PAS)**

Derived from (Alkhuwaiter et al., 2022)

### 1.6 Hyolaryngeal Elevation

Laryngeal elevation is essential for ensuring the safety of the airway during the pharyngeal phase of swallowing. This motion assists in closing the vestibule and opening the UES in addition to pushing the larynx out of the boluses path (Zhang et al., 2016). Laryngeal elevation helps build the aryepiglottic sinuses to navigate the bolus laterally over the vestibule and aids in the adhesion of the arytenoids to the base of the epiglottis for laryngeal vestibule closure. In order for food or liquid to be propelled through the relaxed UES and into the esophagus, hyoid anterior movement in conjunction with laryngeal elevation must occur (Burnett, Mann, Cornell, & Ludlow, 2003).
Displacement of the larynx anteriorly and superiorly provides traction forces to the hyolaryngeal complex, distending the UES by displacing the anterior wall of the UES anteriorly away from the posterior wall. The paired long pharyngeal muscles, or the salpingopharyngeus, palatopharyngeus, and stylopharyngeus, along with the thyrohyoid muscle, are the longitudinal pharyngeal muscles that are contracted to elevate the larynx (Vose & Humbert, 2019). The stylopharyngeus muscle, which aids in raising the larynx and widening the pharynx during swallowing, is supplied by the "efferent motor fibers of the cranial nerve IX", the glossopharyngeal nerve (Erman et al., 2009) (p. 2).

If laryngeal elevation is impaired, food sticks at the top of the airway. The exhale that follows the swallow is then used to reduce the possibility of inhalation of a leftover bolus. Consequently, reduced laryngeal closure may cause food particles to enter the larynx while being swallowed through the pharynx (Logemann, 1988). Without proper HLE, the inlet to the laryngeal vestibule is open and unprotected, and therefore material may enter.

### 1.7 Upper Esophageal Sphincter (UES) and Lower Esophageal Sphincter (LES)

The UES and LES are similar in that they are both sphincter muscles, they work together to guarantee the boluses unidirectional flow, and they must distend sufficiently during swallowing to avoid interfering with adequate flow. However, they have some similar, and some different factors that contribute to their function. First, the esophageal and pharyngeal motor functions are innervated via the nucleus ambiguous of the dorsolateral medulla. Feedforward and feedback loops within the pharyngeal plexus and esophageal enteric plexus enable autonomic esophageal function that follows oropharyngeal swallowing in a stereotyped fashion. The UES, which is approximately
three inches below the hyoid bone (Mittal, 2011), seals the esophageal entry, preventing air from entering the esophagus during inspiration, as well as keeping the food and liquid down to prevent reflux. The sphincter's two main purposes are to keep air from entering the esophagus while breathing and to avoid esophageal contents from refluxing into the pharynx, protecting the airway against aspiration (Mittal, 2011). To execute this protective mechanism, the CP, which is the most proximal portion of the esophagus and the inferior pharyngeal constrictor muscles to make up the UES, remain constricted and firm for the majority of the time to stop gastroesophageal reflux. Further, the anterior wall of the UES, which is a musculocartilaginous structure, is made up of the entire posterior surface of the cricoid cartilage and, in the superior portion, the arytenoid, and interarytenoid muscles. The CP muscle is a key member of the UES, both posteriorly and laterally. The CP and thyropharyngeus (TP) muscles must relax in order for the UES to open, while the hyoid muscles must contract in order for the larynx to move forward to facilitate proper UES opening. Several physiological reflexes that involve afferent inputs to the motor neurons innervating the sphincter regulate the UES function. These inputs are used to govern a number of reflexes that affect its function. The UES opening is influenced by three key factors: 1) The CP muscle relaxes; this relaxation typically occurs prior to the UES opening or the bolus arriving. 2) The thyrohyoid and suprathyroid muscles contract. These muscles cause the sphincter to open by pulling the hyolaryngeal complex forward. 3) The descending boluses pressure, which stretches the UES, and helps it open (Matsuo & Palmer, 2008).

The LES, which is located at the lower end of the esophagus, divides the esophagus from the stomach. The LES stops the reflux of uncomfortable gastric contents into the esophagus. When the ingested bolus enters the pharynx, neuronal activity is suppressed, causing the UES to relax. Once the bolus enters the esophagus, it stretches the mucosa and submucosal muscle
fibers, producing reflexive anterograde (forward-moving) contractions of the esophageal longitudinal and circular fibers, a pattern referred to as esophageal peristalsis. Through the inhibition of excitatory neurons and activation of inhibitory nerves, rising intrabolus pressure causes the LES to relax as the bolus reaches the distal esophagus. Due to this process, the bolus can enter the stomach without difficulty (Rosen & Winters, 2024). Overall, the UES has to open long enough (duration) and wide enough (distention) for the entire bolus to go through, not leaving any residue that could result in esophageal stasis and subsequent aspiration.

1.8 Clinical Significance

The clinician's ability to identify the etiology of dysphagia depends critically on their knowledge of the physiology of swallowing. Dysphagia can be brought on by iatrogenic, functional, or anatomical factors which can impact any component in the swallowing process. Numerous negative effects, including dehydration and nutritional challenges, can arise from dysphagia or UES motility deficits. There may also be an intensified possibility of choking and AP due to the reflux of retained food. A thorough medical history can identify the origin of the condition 80% of the time, and procedures like barium swallows and endoscopies can be used by clinicians to assist in the diagnosis of dysphagia (Panara et. al, 2022). The UES is clinically significant because if it dysfunctions by not opening wide enough (distension), long enough (duration), or does not open at all, food will enter the incorrect location (e.g., larynx) and dysphagia-like symptoms may occur. If the UES fails to generate the proper distention, a patient’s quality of life is greatly affected. Therefore, this study investigated whether an understudied physiologic swallowing measure, LS, influences UESD. If LS is correlated with UESD it may
imply a role in displacement of the larynx in determining the degree of UESD. If so, clinicians and clinical scientists can determine whether LS is a reasonable treatment target to address UES dysfunction. By considering this measurement as a possible contributor to UES dysfunction, we can ensure we are not missing potential targets of intervention for our patients or overemphasizing current targets of intervention. Additionally, during VFSS, clinicians may be able to identify areas of weakness to address during future treatment sessions. By studying this kinematic event, we are deepening our comprehensive understanding of the physiologic mechanisms of swallowing, and relationships among the mechanisms in the system.

1.9 Aims

We sought to investigate whether LS was correlated with UESD in two cohorts of adults, specifically, healthy participants and patients with dysphagia. This understudied measurement of LS may provide insights for treatment targets to help improve UES function in people with dysphagia due to neurological disorders, radiation treatment, or iatrogenic accidents. My research questions aim to answer a) What is the correlation between LS and UESD in healthy people? In patients? and b) Is there a difference between groups?
2.0 Methods

2.1 Participants

As a part of a larger study conducted in the University of Pittsburgh’s Computational Deglutition Lab, 274 inpatients referred for suspected or confirmed dysphagia, and 156 healthy age-matched adults underwent VFSS in the lateral plane at the University of Pittsburgh Medical Center’s Presbyterian Hospital. The University of Pittsburgh Institutional Review Board authorized this research project, and all participants gave written consent prior to enrollment. Two distinct data sets were employed for data analysis.

Patients. For the purpose of this study, we investigated swallows from 47 patients (15 females; age range = 23-84; SD = 12.59). Exclusion criteria included a history of a tracheostomy, prior head or neck surgery, pregnancy during the study to reduce radiation exposure, or not being able to follow instructions as determined by the treating SLP. Inclusion criteria included being referred for VFSS due to suspected dysphagia. Diagnoses included stroke, neurodegenerative diseases, and prolonged mechanical ventilation after respiratory failure, with and without multiple comorbidities.

Healthy participants. Forty-seven (28 females; age range = 19-82; SD = 13.74), age-matched healthy participants were recruited via advertisements in the University of Pittsburgh’s Research Registry, “Pitt Plus Me”, and the University of Pittsburgh’s Claude Pepper Center Research Registry for older adults. Exclusion criteria included previous head or neck surgery, neurological diseases, history of swallowing difficulties, and pregnancy and pregnancy to avoid radiation exposure.
2.1.1 Procedures

Data sets were collected in a comparable manner at two separate timepoints. Patients and healthy participants were seated in a comfortable chair in the lateral projection. High-resolution cervical auscultation (HRCA) sensors were placed on the anterior neck at the level of the cricoid cartilage for collection of accelerometry and acoustic signals for another experiment. Participants swallowed boluses of various textures in the course of the examination, however only thin liquid boluses of two different volume conditions (i.e.: 3mL administered by examiner prompted with a swallow command three times; single continuous drinking of 90mL once from a cup without prompts) were investigated in this experiment (Varibar Thin liquid, barium sulfate for oral suspension, 81% w/w, manufactured by E-Z-EM Canada Inc.; Bracco Diagnostics, 2019). A standard fluoroscopy instrument (Precision 500D system, GE Healthcare, LLC, Waukesha, WI) with a pulse rate of 30 pulses per second (PPS) was used, and VFSS images were captured at 60 frames per second (fps) or greater. Bolus delivery protocols were standardized for healthy participants to reduce exposure to radiation during data collection (average fluoro time: 0.6 minutes per examination). Full swallow study videos containing multiple swallows were segmented into individual swallow segments (i.e., the point at which the bolus crossed the ramus of the mandible until the bolus tail passed through the UES) and down sampled to 30 fps to remove duplicate frames. One 3mL thin liquid swallow segment was randomly chosen and used for each patient and healthy participant in the analysis.
2.1.2 Data Analysis

Measurements were performed on each frame of each swallow segment. A web-based, custom-made Swallowing Annotation Application was created by a member of the Computational Deglutition Lab to label swallowing events of interest. Researchers uploaded down-sampled swallow segment videos to the application, and videos were analyzed on a frame-by-frame basis. Swallow segmentation and UESD measurements were completed prior to beginning this study and the judges were blinded to those results.

Members of the Computational Deglutition Lab were trained to perform swallow kinematic measures on VFSS videos including swallow segmentation, UES distention, and laryngeal shortening. A-Priori intra- and interrater reliability was established with Intraclass Correlation Coefficients (ICCs) greater than 0.80. Ongoing reliability of measurements on 10% of the swallows resulted in comparable ICCs to assure rater labeling did not drift during measurement. To avoid bias, raters were blinded to all participant information (Khalifa et al., 2023).

For LS, I labeled each frame for the points of interest. The labeling process included:

- marking the anterior point on the body of the hyoid bone
- posterior point on the body of the hyoid bone
- anterior-inferior corner of the body of the 2nd cervical vertebra (C2)
- anterior-inferior corner of the body of the 4th cervical vertebra (C4)
- anterior-superior corner of the body of the 3rd cervical vertebra (C3)
- anterior-inferior corner of the body of the 3rd cervical vertebra (C3)
- the point at which the anterior-superior point of the tracheal air column meets the anterior-inferior point of the laryngeal base
• the point at which the posterior-superior point on the tracheal air column meets the posterior-inferior laryngeal base.

See Figure 5 for the application and its components.

![Figure 5 Swallowing Annotation Application: The colored dots on the image correspond with the labels on the right-hand side.](image)

In total, I labeled 94 swallows (47 from the healthy participant swallows and 47 from patient swallows) to determine whether LS is a valid measurement and to further investigate, 1) if there is a correlation between LS and UESD in healthy people and in patients, and 2) if there is a difference in these measurements between groups. The maximal distance of LS (i.e., the shortest distance between the larynx and the hyoid) and maximal UESD, (although not labeled in this study) were used for data analysis.

All statistics were conducted using R (R Core Team, 2023), RStudio (Posit team, 2023), and the ggpubr (Kassambara, 2023), dplyr (Wickham et. al, 2023), tidyverse (Wickham et. al, 2019), and effsize (Torchiano, 2020) packages (see Appendix A for R code). All assumptions were
met for selected statistical tests. A Welch’s two-sample t-tests were performed to determine differences between healthy and patient participants with respect to maximum UESD and LS, as previously described.
3.0 Results

Research Question 1: What is the correlation between LS and UESD in healthy people? In patients?

A Pearson’s correlation coefficient was selected to assess the linear relationship between UESD and LS for patient participants and healthy participants. Across healthy participant groups, there was no significant correlation; $r(46)=0.01$, $p=0.944$. Likewise, across patient participant groups, there was no correlation; $r(46)=-0.08$, $p=0.581$. See Appendix B for scatterplot graphs of the plotted LS vs UESD in patient and healthy participants.

Research Question 2: Is there a difference in these measurements between groups?

There was a significant difference in maximum UESD between patient participants ($M=51.15$, $SD=15.77$) and healthy participants ($M=38.75$, $SD=7.64$); $t(67.90) = -4.9031$, $p < 0.001$. This difference carried a large effect size, according to Cohen’s d estimate ($d=-1.00$). Similarly, there was a significant difference in LS distance between patient participants ($M=0.24$, $SD=0.15$) and healthy participants ($M=0.32$, $SD=0.11$); $t(87.81)=3.2831$, $p=.001$. A medium effect size was noted for this difference ($d=0.670$). All data was measured in pixels and adjusted for patient size using the C2-C4 anatomical scalar.
<table>
<thead>
<tr>
<th>Kinematic Event</th>
<th>Patients Units = Pixels</th>
<th>Healthy Units = Pixels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>UESD</td>
<td>51.14872</td>
<td>15.77352</td>
</tr>
<tr>
<td>LS</td>
<td>0.2375728</td>
<td>0.1457652</td>
</tr>
</tbody>
</table>

UESD: Upper Esophageal Sphincter Distension
LS: Laryngeal Shortening
4.0 Discussion

In this study, we sought to investigate whether LS was correlated with UESD in two cohorts of adults, specifically, healthy participants and patients with suspected or diagnosed dysphagia. Such a finding could indicate LS as a new treatment target for UES dysfunction. Additionally, we examined whether LS and UESD were different between patients and healthy participants. We hypothesized that LS would be correlated with UESD in patients and healthy participants, and that there would be clinically and statistically significant differences in LS and UESD between these groups. Since LS is understudied, it has not been considered in conjunction with other physiologic swallowing events, thus our investigation into its possible contribution to swallow function. Below are the results of this study in terms of the two research questions, interpretation, and context for these results.

4.1.1 Relationship between LS and UESD

Research Question 1 aimed to determine the correlation between LS and UESD in healthy people and in patients. We hypothesized that LS and UESD would be correlated in both participant groups because of the relationship between HLE and UES function. HLE creates traction forces to open the relaxed UES, so the greater the HLE, the greater the UES opening. However, the results did not align with our predictions since there was no correlation between the two measures.

Results showed no correlation, which may suggest that LS should not be targeted in UESD dysfunction treatment. It is possible that these findings are due to the sequence of events during swallow. That is, in healthy swallowing, HLE takes place before UES opening, whereas LS
happens after UES opening (Herzberg et al., 2018). Therefore, perhaps the two are not correlated because they are not occurring at the same time; although, overlap of events is possible and should be studied further. To summarize, UES opening happens before LS. If UES has already occurred, then one could imagine that LS would not play a role in it. Another consideration is that LS aids more in airway protection than UES function since the larynx is moving up and closing off the laryngeal vestibule during LS, which seals off the airway.

4.1.2 LS and UESD in Patient and Healthy Populations

Research Question 2 stated is there a difference in these measurements between groups? As found by the Welch Two Sample t-test, there are clinically and statistically significant differences in LS and UESD between the patients and healthy participants. Although the two events are not correlated, LS is different in patient groups, which may suggest it is affecting something, just not UESD. Due to the clinically significant difference in LS between patients and healthy participants, LS has the potential to be a treatment target, but at this point, the outcome measure is unknown. Researchers may not need to focus on UES and LS together given the possibility that there is no correlation between them; however, a larger sample size may show differences in outcomes, so considering UES and LS is not out of the question.

Clinically (Cohens $d$) and statistically (t-test) significant differences in LS and UESD existed between the patient participants and healthy participants. The patient group was found to have greater UESD, and the healthy participants had greater LS (i.e., shorter distance between the larynx and hyoid during the swallow). Reduced LS in patient groups would result in a wider opening to the laryngeal vestibule during the swallow, perhaps suggesting the role of LS in airway protection. Future studies should investigate whether LS is correlated with other swallow events
(e.g., epiglottic inversion and laryngeal closure) that affect airway protection. If a correlation is found, LS has the potential to be a treatment target for airway protection.

4.2 Research Considerations and Limitations

This study provides directions for future research. To begin, participants in this study were referred for a VFSS for suspected dysphagia. Although not considered in this study, future research could investigate whether patients who aspirate have different LS than patients who do not. Future research could also explore LS function in patients who do not aspirate as compared to healthy people. It could be possible that patients who do not aspirate may still have inadequate LS because they are weak and/or decompensated.

The majority of the patient participants in this study were receiving services in inpatient rehabilitation. Time post-onset of swallowing problem was not recorded but should be considered for future data collection and analysis. Future studies should investigate larger samples such as more individuals, more swallows per person, and more measurements throughout the swallow as opposed to just the maximum LS and UESD distance. Since LS has not been researched extensively, future research could focus on LS and its correlation to swallow kinematic events other than UESD (e.g. epiglottic inversion) and its effect on airway protection. Determining the role of LS in the swallow could help to identify diagnostic and treatment targets for clinicians.

Researchers may not need to focus on UES and LS together given the possibility that there is no correlation between them; however, a larger sample size may show differences in outcomes, so considering UES and LS is not out of the question. If UES begins before LS, it’s still possible that the events are overlapping and could be correlated. Therefore, although the results did not
support the hypothesis that UESD and LS were correlated, the significant differences between the events in patients and healthy people do offer future research directions.

4.3 Conclusions

Based on our results, there were no significant correlations between LS and UESD in either patients with suspected or confirmed dysphagia or healthy participants. However, LS and UESD were both found to be statistically and clinically significantly different between patients and healthy participants, which offers directions for future research and clinical considerations.
Appendix A

Appendix A.1.1 Code used in R

Appendix A.1.2 Means and SD for Measures Code

```r
mean(Patient_UESDis$UESD, na.rm=TRUE)
sd(Patient_UESDis$UESD, na.rm=TRUE)
mean(Healthy_UESDis$uesd_width, na.rm=TRUE)
sd(Healthy_UESDis$uesd_width, na.rm=TRUE)
mean(ls_healthy_dis$LS)
sd(ls_healthy_dis$LS)
mean(ls_patients_dis$LS)
sd(ls_patients_dis$LS)
```

Appendix A.1.3 Welch Two Sample T-Test Codes

```r
t.test(Healthy_UESDis$uesd_width, Patient_UESDis$UESD)
t.test(ls_healthy_dis$LS, ls_patients_dis$LS)
```

Appendix A.1.4 Effect Size Codes (Cohen’s d)

```r
cohen.d(Healthy_UESDis$uesd_width, Patient_UESDis$UESD)
cohen.d(ls_healthy_dis$LS, ls_patients_dis$LS)
```
Appendix A.1.5 Correlation between LS and UESD Codes

> cor.test(Healthy_UESDis$uesd_width, ls_healthy_dis$LS)

> cor.test(ls_patients_dis$LS, Patient_UESDis$UESD)
Appendix B Scatterplot Diagrams – No Correlation
Bibliography


