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THE EFFECTS OF THE EFFORTFUL SWALLOW MANEUVER ON HYOLARYNGEAL MOVEMENT AND TONGUE-TO-PALATE PRESSURE

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ABSTRACT

Purpose: The purpose of this study was to investigate the effects of the effortful swallow maneuver under two different instructions on tongue-to-palate pressure and hyolaryngeal displacement in healthy adults. Studying typical kinematic parameters and pressure generation in healthy individuals is critical for differentiating normal from pathological patterns and for determining swallowing parameters that can be targeted to optimize and individualize treatment plans for people with swallowing disorders. The primary objectives in this study were: (1) to determine the physiological effects of two different types of effortful swallows on anterior and posterior tongue pressure generation, hyoid displacement, and hyoid-larynx approximation in healthy adults, (2) to determine age-related differences in tongue-to-palate pressure and hyolaryngeal displacement in healthy adults, and (3) to determine the association between perceived effort used to swallow and tongue pressure within swallowing conditions.

Method: Forty healthy adults (20 younger, 20 older) participated in this study. All participants were in general good health, were screened for normal oral structures, function, and swallowing skills, had normal tongue strength, were eating a normal diet, and had normal auditory comprehension skills. Experimental procedures included simultaneous data acquisition of tongue pressure, submental muscle activity, and hyolaryngeal movement during normal saliva swallows and effortful saliva swallows under two different instructions (tongue emphasis and neck squeezing). Measures of tongue pressure were obtained using the Iowa Oral Performance Instrument. Submental muscle activity during swallows was assessed using surface electromyography. Hyoid excursion and hyoid-larynx approximation were obtained during ultrasonography. All outcome measures were scaled to account for differences between participants and they reflected activity *during* swallowing. Moreover, participants rated their perceived effort used to swallow with a visual analog scale.

Results: Significant tongue pressure differences were observed between swallowing condition and tongue region. The effortful swallows performed with tongue emphasis (EFSst) and pharyngeal squeezing (EFSsp) produced greater tongue-to-plate pressures than normal swallows (NSs). Additionally, posterior tongue pressures were greater than pressures generated in the anterior tongue region during NSs and EFSst. Hyolaryngeal measures were also greater during EFSst and EFSsp than NSs. Significant differences were found between the two types of effortful swallows in tongue pressure and hyoid displacement measurements. Overall, EFSst produced greater changes in these physiological measures than EFSsp. Significant age-related differences were only found in hyoid-larynx approximation during the EFSst. Moderate correlations were identified between tongue pressure and hyoid displacement during NSs and EFSst and between tongue pressure and hyoid-larynx approximation during NSs and EFSst. Results also showed that participants perceived greater effort used to swallow during EFSst and EFSsp than NSs. Finally, there was a significant, moderate correlation between perceived swallowing effort and objectively measured tongue-to-palate pressure during NSs and EFSst.

Conclusions: The effortful swallow maneuver increases tongue-to-palate pressure and hyolaryngeal excursion in healthy adults across the age span. Additionally, different instructions for the effortful swallow affect those physiological measures. These findings have the potential to guide treatment decisions when recommending and training the effortful swallow maneuver. It may be helpful for clinicians to individualize and determine the optimal effortful swallow instructions for each patient based on their physiological swallowing impairments.

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This dissertation is dedicated in loving memory to my parents, Ademir and Sueli, who always encouraged me to pursue my dreams.

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LIST OF ABBREVIATIONS

BOT	Base of the tongue
EFS	Effortful swallow
EFSs	Effortful swallows
EFSp	Effortful swallow produced with pharyngeal squeezing
EFSsp	Effortful swallows produced with pharyngeal squeezing
EFSt	Effortful swallow produced with tongue emphasis
EFSst	Effortful swallows produced with tongue emphasis
FOIS	Functional Oral Intake Scale
FOM	Floor of the mouth
$Hrest$	Hyoid-mandible rest distance
$Hswallow$	Hyoid-mandible swallow distance
$H\%change$	Percent change of hyoid displacement
$HLrest$	Hyoid-larynx rest distance
$HLswallow$	Hyoid-larynx swallow distance
$HL\%change$	Percent change of hyoid-larynx approximation
HRIM	High-resolution impedance manometry
ICC	Intraclass Correlation Coefficient
IOPI	Iowa Oral Performance Instrument
MDTP	McNeil Dysphagia Therapy Program

NMES	Neuromuscular electrical stimulation
NS	Normal swallow
NSs	Normal swallows
PAS	Penetration-Aspiration Scale
PPW	Posterior pharyngeal wall
sEMG	Surface electromyography
SLP	Speech-Language Pathology
SLPs	Speech-Language Pathologists
RTT	Revised Token Test
TMS	Transcranial magnetic stimulation
$Tmip$	Maximum isometric tongue pressure
$Tpeak$	Peak tongue pressure during swallowing
$T\%peak$	Percentage of peak tongue pressure
UES	Upper esophageal sphincter
U.S.	United States
VAS	Visual analog scale
$VASnorm$	Normalized visual analog scale
VFSS	Videofluorocopic swallowing study

1. INTRODUCTION

Swallowing is a complex sensorimotor and neurological event involving precise and coordinated movements between structures from the oral cavity to the esophagus, and a synchronous network of afferent and efferent neurons located in cortical and subcortical areas of the brain, cerebellum, and brainstem regions (Alvar et al., 2021; Warnecke et al., 2021; Wilmskoetter et al., 2019). Safe and effective swallowing physiology includes multiple different and often overlapping events throughout the three swallowing phases (oral, pharyngeal, and esophageal; Martin-Harris et al., 2008). Any abnormality in these events will result in a swallowing disorder (i.e., dysphagia).

The oral phase of swallowing is volitional and includes structures within the oral cavity to prepare and transport the food to be swallowed (Matsuo & Palmer, 2008; Shaw & Martino, 2013). In the preparatory subdivision of the oral phase, liquids are properly contained in the oral cavity by the coordinated contraction among lips, cheeks, tongue, mandible, and soft palate muscles. However, the ingestion of solid food requires an active process of mastication and manipulation to break down the food and mix it with saliva, forming a cohesive bolus for swallowing (Matsuo & Palmer, 2008 and 2009). During mastication, a temporo-spatial coordination between the mandible and tongue occurs with participation of the floor of the mouth (i.e., anterior belly of the digastric, mylohyoid, and geniohyoid; FOM), soft palate, and cheek muscles (Matsuo & Palmer, 2008, 2009 and 2010). The mandibular muscles (i.e., masseter, temporalis, medial and lateral pterygoids), assisted by the FOM muscles, are responsible for the cyclic movement of the jaw for mastication. In contrast, whereas the tongue manipulates the food in the oral cavity for chewing and lubrication through its intrinsic and extrinsic muscles, and, in coordination with the soft palate, allows nasal breathing (Matsuo & Palmer, 2008 and 2009; Palmer et al., 1997). The hyoid bone also moves in coordination with the tongue and mandible due to anatomical connections among these structures (e.g., FOM and genioglossus muscles; Matsuo & Palmer, 2008, 2009, 2010). The oral transport or propulsive subdivision of the oral phase involves propelling the bolus posteriorly to the pharynx through a wave-like motion of the tongue (Matsuo & Palmer, 2008; Shaw & Martino, 2013). This movement begins with the contraction of the superior longitudinal muscle that raises the tip of the tongue to contact the alveolar ridge, and is followed by contact between the tongue dorsum and hard palate in an antero-posterior motion achieved by the contraction of the superior longitudinal and extrinsic tongue muscles (e.g., genioglossus, styloglossus, hyoglossus, and palatoglossus; Matsuo & Palmer, 2009). During this process, elevation and stabilization of the jaw by the contraction of the mandibular elevators and FOM muscles contributes to tongue-to-palate contact for pressure generation (Matsuo & Palmer, 2009 and 2010). Additionally, the tongue moves in coordination with the soft palate to open the back of the oral cavity allowing bolus passage (Matsuo & Palmer, 2008; Shaw & Martino, 2013).

The pharyngeal phase of swallowing is reflexive and involves structures within the pharynx and larynx (Matsuo & Palmer, 2008; Shaw & Martino, 2013). During this phase, the pharynx changes its original respiration-focused configuration to that of a swallowing tract. Furthermore, multiple successive, overlapping, and coordinated movements transfer the bolus (a prepared mouthful of food or liquid) through the pharynx and protect the airway (Matsuo & Palmer, 2008 and 2009; Shaw & Martino, 2013; Vose & Humbert, 2019). The timing and coordination of these events, including the cessation of breathing, are critical for preventing food or liquid from entering the airway (aspiration) by safely transferring material through the pharynx and into the esophagus and stomach for subsequent digestion. Both neural and biomechanical contributions are essential to achieve the precise timing and activation of these pharyngeal events.

The events involved in bolus transport include the movement of the soft palate, base of the tongue (BOT), and pharynx which contribute to pressure generation in the pharyngeal cavity for moving the bolus throughout the pharynx. Moreover, the opening of the upper esophageal sphincter (UES) allows bolus passage to the esophagus. This last event is influenced by different mechanisms, such as the relaxation of the cricopharyngeus muscle, hyolaryngeal displacement, and bolus pressure (Matsuo & Palmer, 2008 and 2009; Shaw & Martino, 2013). Hyolaryngeal displacement also contributes to airway protection. This movement is mostly influenced by the contractions of the suprahyoid muscles (e.g., digastric, stylohyoid, mylohyoid, and geniohyoid) that pull the hyoid anteriorly and superiorly through direct muscles attachments and by the activation of the thyrohyoid muscle that directly connects the hyoid and the larynx (Shaw & Martino, 2013). Other events that contribute to airway protection are adduction of the vocal folds to close the glottis, rotation and adduction of the arytenoids, adduction of the aryepiglottic folds, and epiglottic inversion for laryngeal vestibule closure (the area above the vocal folds and lower airways; Vose & Humbert, 2019). Lastly, the esophageal phase of swallowing, also involuntary, carries the bolus through the esophagus via peristalsis and into the stomach (Matsuo & Palmer, 2008; Shaw & Martino, 2013).

The physiologic complexity and precise timing of these events increases the likelihood that neurological or other disease processes will disrupt the normal execution of these swallowing behaviors. This explains the extremely high prevalence of dysphagia, estimated to affect 1 in 25 adults in the United States (U.S.; Bhattacharyya, 2014) and almost 44% of the global population (Rajati et al., 2022).

Multiple neurological disorders can disrupt the neurophysiologic control of swallowing and produce dysphagia. Stroke is the leading cause of dysphagia, accounting for more than 420,000 affected individuals, followed by other neurologic disorders (269,000 cases), head and neck cancer (184,000 cases), and presbyphagia (advanced age, 98,000 cases; Bhattacharyya, 2014). Post-stroke dysphagia, for example, affects 54 to 78% of the 795,000 annual stroke cases in the U.S. (Kumar et al., 2014; Martino et al., 2005; Rofes et al., 2018; Virani et al., 2021), representing 357,000 to 620,000 new cases of dysphagia per year. Approximately 50% of post-stroke patients will continue to demonstrate dysphagia after 6 months (Arnold et al., 2016; Cohen et al., 2016), a period which often characterizes the greatest degree of neural and functional recovery after stroke. Among those with persistent dysphagia, more than 20% of cases are considered severe, and these individuals experience long-term disability (Arnold et al., 2016; Kumar et al., 2014). In other disorders, the prevalence of dysphagia varies from 45% in the head and neck cancer population (Hutcheson et al., 2019), to 82% in individuals with Parkinson's disease (Suttrup & Warnecke, 2016), and is as high as 93% in individuals with moderate to severe dementia (Affoo et al., 2013).

Given the rising proportions of individuals over the age of 65, age-related disorders such as stroke, dementia, and Parkinson's disease are all projected to increase. It is estimated that an additional 34 million adults will suffer a stroke by 2030 (Virani et al., 2021), with an associated increase of 15.3 to 26.5 million cases of dysphagia. Among neurodegenerative disorders, Parkinson's disease is the fastest growing disorder, affecting approximately 8.5 million individuals in 2019 and projected to increase by 155% in the upcoming decades (Ou et al., 2021). In 2019, 57.4 million individuals worldwide had dementia; projections indicate that 83.2 million individuals will have dementia by 2030 and 152.8 million by 2050 (Nichols et al., 2022), representing up to 142 million dysphagia cases secondary to dementia. Therefore, there is a critical need to improve and develop swallowing strategies targeting the physiological swallowing impairments that are associated with these disorders, thus mitigating the negative swallowing consequences.

Although multiple physiologic events are important during swallowing, movement of hyolaryngeal structures and pressure generated in the oral cavity and pharynx are critical for safe and efficient food transport. Hyolaryngeal movement includes superior *and* anterior displacement of the hyoid bone and the larynx. The resulting changes in anatomic configuration contribute to the approximation of structures that close the laryngeal vestibule for airway protection. Moreover, hyolaryngeal anterior movement contributes to the opening of the UES, due to anatomic connections between the cricoid cartilage and the UES (Vose & Humbert, 2019). The appropriate opening of this sphincter is necessary for bolus clearance through the pharynx and into the esophagus. Weakness of muscles that contribute to hyolaryngeal elevation, as well as neural changes that disrupt the timing and coordination of these events within the pharyngeal phase, will compromise swallowing safety and increase the likelihood of aspiration.

Adequate driving pressures throughout all phases of swallowing are essential for propelling the bolus posteriorly along the aerodigestive tract, preventing the bolus from entering the airway and contributing to oropharyngeal clearance (Matsuo & Palmer, 2008). Effective clearance of bolus materials in the pharynx is important for preventing aspiration post-swallowing. The tongue plays a critical role in the swallowing process, participating in bolus formation, manipulation, containment, and transport. The oral portion of the tongue contacts the hard palate to generate pressure for transferring the bolus from the oral cavity to the pharynx, whereas the BOT contacts the posterior pharyngeal wall (PPW), generating pressure to drive the bolus throughout the pharynx (Matsuo & Palmer, 2008 and 2009; Shaw & Martino, 2013). Therefore, tongue weakness or disrupted duration of tongue movements will impact the ability to generate pressures, with repercussions in bolus transport and clearance.

The occurrence of neurologic disorders as well as advanced age affect the neuromuscular system involved in the swallowing process. Multiple brain regions control the sensory and motor pathways of swallowing. Any disruption in these pathways can lead to impaired deglutition, but the specific physiological deficits will depend on the etiology of the damage. Deficits that are common with neurogenic swallowing disorders include muscle weakness, reduced propulsive pressures, and discoordination of biomechanical events (Alvar et al., 2021; Jani & Gore, 2016; Kim et al., 2014; Kwon & Lee, 2019; Lee et al., 2017; Seo et al., 2017; Stierwalt & Youmans, 2007; Warnecke et al., 2021; Wilmskoetter et al., 2019). In advanced age, the common associated etiology of dysphagia is sarcopenia, a syndrome that affects muscle mass, tone, strength, and function (Namasivayam-MacDonald & Riquelme, 2019; Ozer et al., 2021). Hence, several of the most widely implemented swallowing treatment strategies target biomechanical swallowing events (e.g., hyolaryngeal movement) and swallowing driving pressures, which are muscular and neuromotor-driven processes.

Swallowing strategies to address hyolaryngeal movement and driving pressure generation can rehabilitate swallowing function, reducing the burden of clinical complications such as malnutrition, dehydration, and aspiration pneumonia. The effortful swallow (EFS) maneuver, frequently recommended in dysphagia management, has the potential for improving both hyolaryngeal movement and pressure generation. This strategy improves the contact between the BOT and the PPW during swallowing, thus increasing pressure on the bolus (Pouderoux & Kahrilas, 1995). Oral cavity muscles contribute to BOT retraction, whereas the pharyngeal constrictor muscles improve PPW motility. Furthermore, increased contact between the BOT and the PPW generates higher pressure amplitude in the pharyngeal region, *reducing residue* at the BOT, valleculae (the space adjacent to the BOT), and upper PPW (Kahrilas et al., 1992, 1993; Pouderoux & Kahrilas, 1995). Additionally, during an EFS, suprahyoid muscles are strongly activated (Huckabee & Steele, 2006; Steele & Huckabee, 2007), which may contribute to increased hyolaryngeal movement and airway protection.

In summary, safe and efficient swallowing must involve cross-system interactions that depend on adequate muscle function, intact sensation, and sensorimotor integration. Therefore, inappropriate structural displacement, slow or delayed responsiveness, and insufficient pressure generation can all lead to swallowing disorders. The complexity of the swallowing process makes dysphagia particularly prevalent in the adult population because many diseases or medical conditions can affect one or more elements involved in safe swallowing execution.

This study addresses two main physiological aspects of swallowing biomechanics: oral pressure generation during swallowing and hyolaryngeal movement during the EFS maneuver in healthy adults. The Literature Review chapter provides an overview of dysphagia and its consequences (sections 2.1 and 2.2), a discussion of age-related changes in overall swallowing physiology (section 2.3), pressure generation and hyolaryngeal movement during swallowing (sections 2.4 and 2.5), and evidence-based effects of the EFS maneuver with a critique addressing the limitations of current research (section 2.6). The subsequent chapters present a study which investigates the effects of the EFS maneuver under two different instructions on hyolaryngeal movement and tongue-to-palate pressure in healthy participants across two different age groups. Finally, chapter 8 describes the contributions of this study and future directions.

2. LITERATURE REVIEW

2.1 Impact of Dysphagia

Swallowing disorders are associated with significant clinical complications, including aspiration pneumonia, malnutrition, and dehydration. Dysphagia and aspiration pneumonia are the primary contributing factors for increased length of hospitalization, cost of medical and hospital care, high mortality rates, and institutionalization (Bray et al., 2017; Kumar et al., 2010; Patel et al., 2018). Between 2009 and 2013, 3% of the U.S. inpatients, ages 45 or older, received a diagnosis of dysphagia (Patel et al., 2018). Patients with dysphagia stayed 3.8 additional days at the hospital relative to patients without dysphagia and were 1.7 times more likely to die during their hospital stay. Moreover, patients with dysphagia cost 33% more than non-dysphagic patients, adding a hospital cost of $4.3 to 7.1 billion per year (Patel et al., 2018).

Aspiration pneumonia is one of the most frequent complications in neurogenic swallowing disorders, contributing to an increased mortality rate and disability (Bosch et al., 2012; Kumar et al., 2010; Virani et al., 2021; Wilson, 2012; Won et al., 2021). It is estimated that 23 to 44% of dysphagia cases following a stroke have pneumonia during their hospital stay. Moreover, 10% of the deaths within 30 days of a stroke are directly caused by pneumonia (Arnold et al., 2016; Emsley & Hopkins, 2008; Kumar et al., 2014), and individuals with post-stroke pneumonia have a mortality risk that is 3.3 to 5.9 times higher than patients without pneumonia (Katzan et al., 2003; Ovbiagele et al., 2006; Wilson, 2012). In individuals with Parkinson's disease, the risk for aspiration pneumonia is 2.2 times higher than in other patients (Won et al., 2021). Additionally, aspiration pneumonia is associated with 1-year mortality in 65% of the individuals with Parkinson's disease and responsible for 70% of the deaths in this population (Mehanna & Jankovic, 2010; Won et al., 2021). Among patients with dementia, more than 28% of them experience recurrent episodes of aspiration pneumonia. Moreover, 33% of the deaths that occur during hospital stays for people with dementia are directly associated with aspiration pneumonia (Bosch et al., 2012).

Dysphagia can also negatively impact overall quality of life, as it is associated with social isolation, loss of self-esteem, loss of independence, depression, fear, and anxiety (Ekberg et al., 2002; Eslick & Talley, 2008). Around 40% of adults 55 years or older who lived in nursing homes reported that eating was not an enjoyable experience anymore due to their dysphagia. Additionally, 36% of these nursing home residents avoided eating with others, 37% reported embarrassment, and 41% reported anxiety during mealtimes because of their swallowing problems (Ekberg et al., 2002). The negative social and psychological consequences of dysphagia can lead to further complications such as malnutrition and dehydration due to lower food intake.

Effective nutrition and hydration are dependent on a person's eating and drinking experiences, including swallowing skills, food presentation and preferences, oral care, and motor and sensory abilities (Bunn et al., 2018; Ueshima et al., 2021). Malnutrition and dehydration are associated with sarcopenia, frailty, infections, and falls, which increase medical complications and hospital admissions, impacting quality of life (Bunn et al., 2018; Ueshima et al., 2021). The prevalence of dehydration among patients with swallowing disorders varies between 44% to 75%, whereas malnutrition is estimated to affect 29% of dysphagia patients. Both clinical complications are more common in older patients and in those with multiple comorbidities or medical illnesses (Reber et al., 2019; Ueshima et al., 2021). A large study (n = 779) including non-institutionalized older adults (*Mage* = 81.97, *SD* = 7.10) showed that 62% of the participants were at risk of malnutrition and 30% at risk of dysphagia. Additionally, the risk of dysphagia and malnutrition co-occurred in 33%, and dysphagia was present in 54% of the participants with a diagnosis of malnutrition (Tagliaferri et al., 2019).

2.2 Etiology and Clinical Characteristics of Dysphagia

The clinical presentation of dysphagia may vary according to its etiology and severity. Due to the complexity of the neural network involved in the swallowing process, neurological or neurodegenerative disorders such as stroke, Parkinson's disease, and Alzheimer's disease are the most common causes of dysphagia (Bhattacharyya, 2014; Clavé & Shaker, 2015). Other populations at high risk for dysphagia are individuals with head and neck cancer and older adults.

Neuroimaging studies identified multiple brain areas involved in the swallowing process and their association with specific swallowing events, suggesting that the right hemisphere of the brain plays a critical role in swallowing (Malandraki et al., 2009, 2010; Suntrup et al., 2015; Suntrup-Krueger et al., 2017; Wilmskoetter et al., 2019). Evidence suggests that the primary motor cortical area is associated with laryngeal elevation, whereas the primary somatosensory area is related to laryngeal vestibule closure and the occurrence of pharyngeal residue (i.e., bolus residue post-swallow). Moreover, regions responsible for sensorimotor integration (e.g., insula and supramarginal gyrus) and areas connecting the cortex and brainstem (e.g., thalamus and corona radiata) are responsible for swallowing kinematics involved in airway protection and pharyngeal residue (Malandraki et al., 2009, 2010; Suntrup et al., 2015; Suntrup-Krueger et al., 2017; Wilmskoetter et al., 2019). These studies suggest that brain lesions in sensory and motor areas can affect hyolaryngeal elevation and driving pressure generation with consequent safety and efficiency impairments.

Dysphagia severity varies according to its physiological impairments and consequences on swallowing function. Clinical features of dysphagia can be categorized into three areas of deficits: altered structural movement, timing deficits, and inefficient pressure generation. Nevertheless, these categories are interrelated; for example, decreased movement of swallowing structures may affect the timing of swallowing events and impair pressure generation. Collectively, these biomechanical and physiological swallowing impairments can cause penetration (entry of material into the larynx at or above the vocal folds), aspiration (entry of material into the larynx below the vocal folds), or pharyngeal residue.

Common impairments in swallowing physiology are reduced lip closure, soft palate elevation, tongue movement and strength, pharyngeal contraction, BOT retraction, and hyolaryngeal displacement (Baijens et al., 2021; Jani & Gore, 2016; Kim et al., 2014; Kwon & Lee, 2019; Lee et al., 2017; Seo et al., 2017; Stierwalt & Youmans, 2007; Warnecke et al., 2021; Wilmskoetter et al., 2019). Each of these physiological impairments is associated with one or more features observed through clinical or instrumental assessment. For example, altered tongue movement and strength may affect the ability to hold the bolus in the oral cavity, form the bolus, and transport the bolus (Ono et al., 2009; Palmer et al., 2000; Robbins et al., 2007). Consequences of these deficits include bolus spillage into the pharynx or airway prior to swallow initiation, inadequate pressure generation for bolus transport to the esophagus, oral residue post-swallow, and aspiration before swallowing. Decreased pharyngeal contraction and BOT retraction impact pressure generation for efficient bolus transport, resulting in increased pharyngeal transit time, post-swallow residue, and aspiration during or after swallowing. Individuals may require multiple swallows to clear bolus residue. Finally, diminished hyolaryngeal movement can compromise laryngeal vestibule closure and, consequently, airway protection, resulting in penetration or aspiration before and during swallowing (Curtis et al., 2018; Steele et al., 2011; Vose & Humbert, 2019; Wong et al., 2020). In this case, individuals may show coughing, choking, or voice changes.

2.3 Age-related Physiological Changes in Swallowing

Older adults are more susceptible to swallowing disorders due to the combination of age-related changes in swallowing anatomy and physiology, existing comorbidities and chronic diseases that accumulate with age, and frailty that can occur with aging. Natural changes in the swallowing process in the elderly may impact the preparation of food due to loss of dentition, decreased oral sensation and texture discrimination, or reduced salivary flow (Butler et al., 2009; Namasivayam-MacDonald & Riquelme, 2019; Ney et al., 2009; Wirth et al., 2016). These changes potentially affect bolus transfer through the aerodigestive tract. Additionally, studies have shown that the aging process can decrease hyolaryngeal movement, tongue pressure and force, pharyngeal pressure, and overall muscle function due to sarcopenia (Butler et al., 2009; Namasivayam-MacDonald & Riquelme, 2019; Ney et al., 2009; Wirth et al., 2016). These natural anatomical and physiological age-related changes add to an impaired system when associated with neurologic disorders such as stroke and Parkinson's disease.

Studies addressing age-related changes to tongue-to-palate pressure showed *decreased* pressure with advancing age (Fei et al., 2013; Stierwalt & Youmans, 2007; Tamine et al., 2010; Youmans & Stierwalt, 2006). Fei et al. (2013) studied 40 healthy younger adults (age range = 18-40 years old) and 38 healthy older adults (age range = 60-87 years old) using oral manometry (quantitative measurement of pressure) and found that older adults had *lower* maximum anterior isometric pressure (tongue strength) than younger individuals (d = 0.99). However, these authors did not find swallow pressure differences between younger and older adults during saliva and water swallows. Investigations conducted by Youmans and Stierwalt (2006, 2007) also showed that healthy individuals ages 60 or older had *lower* maximum anterior isometric tongue pressure than younger healthy adults (age range = 19-39 years old). However, these authors noted that mean tongue-to-palate pressure generated *during swallowing* and the percentage of maximum swallowing pressure (swallowing pressure divided by maximum isometric tongue pressure) were similar across age groups.

Tamine et al. (2010) used oral manometry (five sensors) to investigate differences in order, duration, and peak pressure during 15 ml water swallows between 37 healthy younger adults (*Mage* = 26.9, *SD* = 3.6 years) and 35 healthy older adults (*Mage* = 66.6, *SD* = 5.0 years). Findings suggested changes in older adults for tongue movement patterns, swallowing timing, and oral pressure. Older adults showed earlier tongue pressure activation in the posterior tongue than in the mid tongue, whereas younger adults activated anterior tongue pressure before posterior activation. Older adults also presented with *prolonged* oral phase duration during swallowing and *decreased* maximum pressure during swallowing in the anterior to mid-palate region relative to younger adults.

Overall results from these studies indicate changes in tongue movement and strength with aging, which may explain the prolonged oral phase duration and decreased tongue-to-palate pressure generated during swallowing in older versus younger adults in some studies. Additionally, the changes in tongue movement patterns in older adults may indicate a normal compensation to account for muscle weakness and increase tongue pressure for a more efficient bolus transport.

Milford et al. (2020) investigated the impact of aging on mastication in 185 healthy adults while eating a cookie and visualized with a videofluoroscopic swallowing study (VFSS). A VFSS examination involves a running x-ray (digital video) recording of a patient while they prepare and swallow various food and liquid items, and can display the oral cavity, pharynx, larynx, and esophagus throughout the swallowing process. In the Milford et al. study, participants were divided into four sex-balanced age groups: 21–39-year-olds (n = 66), 40–59-year-olds (n = 66), 60–79-year-olds (n = 45), and those 80 and older (n = 8). Results indicated that as age increased, total mastication duration also *increased*, controlling for sex and race differences. However, the number of masticatory cycles was not different among age groups. The authors concluded that muscle weakness and missing teeth, which occur more frequently in older adults, may have contributed to these age-related differences.

Sarcopenia changes in the pharyngeal muscles were reported by Molfenter et al. (2015). These authors measured pharyngeal wall thickness and pharyngeal cavity area using magnetic resonance imaging in 20 healthy younger adults (*Mage* = 25.4, *SD* = 2.8 years) and 38 healthy older adults (n = 20, *Mage* = 63.8, *SD* =2.5 years; n = 18, *Mage* = 76.6, *SD* = 5.4 years). This study showed that pharyngeal wall thickness *decreased* with advanced age, whereas pharyngeal lumen area during swallowing *increased*. These findings suggest that the healthy aging process is associated with atrophy of the pharyngeal muscles with consequences to pharyngeal constriction and shortening during swallowing, which impact swallowing efficiency.

Custir and colleagues (2018) evaluated age-related differences in hyoid anterior and superior displacements using VFSS in a sample of 161 healthy adults (n = 85, ages 18-64 years and n = 76, ages 65-96 years). Findings showed *greater* hyoid anterior movement in younger than older adults but *no* age-related differences in hyoid superior movement. These results suggest that appropriate airway closure is not affected by aging, as superior movement of the hyoid bone contributes to laryngeal vestibule closure, whereas residue may occur as age increases due to decreased hyoid anterior movement during swallowing in older adults.

A notably comprehensive project on age-related changes in swallowing parameters (Mancopes et al., 2021; Steele et al., 2019) included 38 healthy younger adults (age range = 21-59 years old) and 38 healthy older adults (age range = 61-82 years old). Swallowing timing, kinematics, safety, and efficiency parameters were measured during three trials of a single sip of thin liquid using VFSS. Findings indicated that penetration episodes were rare, and episodes of aspiration were absent in both groups, suggesting that penetration and aspiration are pathological swallowing consequences and are not associated with aging. However, age-related differences were observed in swallowing timing, such as *longer* swallow reaction time, UES opening duration, and laryngeal vestibule closure duration. Interestingly, UES opening diameter *increased* with aging (which would promote bolus clearance through the UES), and incomplete laryngeal vestibule closure was rare. Thus, although healthy aging impacts swallowing duration events, healthy older adults maintain an efficient and safe swallow. In addition, no age differences were observed in hyoid peak displacement and hyoid movement speed, corroborating the other findings that indicated appropriate airway protection, such as rare episodes of penetration and absent episodes of aspiration. Finally, the authors found that as age increased, pharyngeal cavity area at rest and at maximum constriction also *increased.* These pharyngeal configuration changes are consistent with a decrease in pharyngeal constrictor muscle mass, which could negatively impact pharyngeal constriction during swallowing.

Age-related anatomical and physiological changes have potential clinical implications when evaluating and treating older individuals with swallowing disorders. Typical physiological patterns in older adults must be differentiated from pathological patterns to optimize treatment decisions. However, additional studies addressing normal changes in swallowing due to the aging process are necessary to establish normative expectations for swallowing behaviors across different age ranges. Furthermore, investigations are needed to identify the impact of age-related changes on swallowing maneuvers and exercises, as diverse age groups may respond to these strategies in different ways and unintended negative effects may occur.

2.4 The Evaluation of Hyolaryngeal Movement and Pressure Generation during Swallowing

A comprehensive clinical (bedside) swallowing evaluation is the first step in swallowing assessment. Its primary purpose is to obtain a general overview of swallowing function and determine the need and readiness for an instrumental evaluation. However, the clinical swallowing assessment should not be used to make a definitive diagnosis of dysphagia due to its limited information regarding specific swallowing events, such as hyolaryngeal movement and pressure generation.

Objective or instrumental evaluations of swallowing, such as VFSS, manometry, the Iowa Oral Performance Instrument (IOPI), and ultrasonography, are essential for assessing biomechanical or pressure generation parameters. Together, these instrumental methods provide information on the presence and severity of dysphagia, such as timing, pressure, kinematics, bolus flow, bolus clearance and efficiency, airway protection and invasion, and sensation. However, they do not give similar information on the swallowing parameters; thus, different methods often complement each other and should be selected according to individual patient needs.

The VFSS or modified barium swallowing study is the standard diagnostic evaluation of swallowing due to its potential for identifying physiological impairments, timing and coordination of biomechanical events, and airway invasion. This exam captures sequential videoradiographic images of the swallowing mechanism using liquids and foods mixed with barium sulfate, a contrast agent (Martin-Harris et al., 2020). This allows dynamic, real-time visualization of bolus flow in relation to the movement of structures from the oral cavity to the esophagus. Nevertheless, the VFSS has disadvantages, including lack of direct information on driving pressure generation, poor direct measurement of sensation, poor visualization of secretions, and exposure of ionizing radiation (Martin-Harris et al., 2020). Videofluoroscopic swallowing study also requires extensive calibration for measuring structural movement (e.g., hyolaryngeal displacement).

High-resolution impedance manometry (HRIM) of the pharynx and UES evaluates the propulsive forces involved in the swallowing process. It provides pressure-flow information over time during various swallowing events, for example, pressure generation in the velopharynx (upper pharynx), BOT, hypopharynx (lower pharynx), and UES (Cock & Omary, 2017; Omari et al., 2020). Furthermore, from these pressure parameters, it is possible to derive functional measurements related to airway invasion risk (swallowing risk index) and residue (post-swallow impedance ratio; Cock & Omari, 2017). Thus, HRIM can be performed with other imaging techniques, such as VFSS, to provide simultaneous information on hyolaryngeal movement and driving pressure generation.

The IOPI is a widely employed research and clinical device for recording tongue-to-palate pressure (Adams et al., 2013; McKenna et al., 2017). It provides a noninvasive method for measuring pressure using an air-filled plastic bulb inside the mouth that senses pressure changes and is connected to a digital hand-held recording and display device (Robbins et al., 2005; Yeates et al., 2008). Decreased maximal isometric tongue-to-palate pressure has been associated with impaired hyolaryngeal displacement, pharyngeal constriction, UES opening, and airway invasion in individuals with dysphagia from various etiologies (Curtis et al., 2021). Moreover, studies suggest that decreased maximal isometric tongue pressure is associated with reported symptoms of dysphagia and lower swallowing-related quality of life in individuals with Parkinson's disease (Pitts et al., 2018, 2019). In post-stroke dysphagia, lower maximal isometric tongue pressure was related to penetration and aspiration (Lee & Choi, 2020), and tongue-to-palate pressure was decreased during water swallows (Konaka et al., 2010). Decreased tongue-to-palate pressure was also associated with dysphagia risk in older adults (Namasivayam-McDonald et a., 2017). These findings suggest that decreased tongue strength and tongue pressure generated during swallowing affect subsequent swallowing events, being associated with airway invasion and post-swallow residue.

Ultrasonographic examination uses a transducer on the skin surface to transmit high-frequency sound waves through soft tissue and then capture the echoes that are returned to the transducer to subsequently produce images of structures (Allen et al., 2021). This alternative imaging method is noninvasive, lower-cost, portable, radiation-free, and does not require calibration for measurement (Allen et al., 2021; Macrae et al., 2012). In swallowing, ultrasonography is used to analyze specific components of swallowing biomechanics and physiology, such as tongue movement (Galén & Jost-Brinkmann, 2010; Peng et al., 2000; Tamburrini et al., 2010), hyolaryngeal displacement and duration (Chen et al., 2017; Huang et al., 2009; Komori et al., 2008; Kuhl et al., 2003; Kwak et al., 2018; Lee et al., 2016; Macrae et al., 2012; Yabunaka et al., 2011), suprahyoid muscles characteristics (Feng et al., 2015; Macrae et al., 2013), UES function (Morinière et al., 2013), and aspiration (Miura et al., 2014).

Hyolaryngeal excursion in healthy adults and individuals with dysphagia is one of the swallowing components that has been studied most frequently with ultrasonography. Notably, some of these studies compared ultrasonography and VFSS findings, providing an indicator of the accuracy and reliability of ultrasound measurements for swallowing compared to the standard for assessing these physiologic events (Chen et al., 2017; Huang et al., 2009). Five studies investigated hyoid bone movement during swallowing (Chen et al., 2017; Kwak et al., 2018; Lee et al., 2016; Macrae et al., 2012; Yabunaka et al., 2011). Yabunaka et al. (2011) addressed age-related changes in hyoid movement and duration in healthy adults during water swallows of 5 ml. The authors found that maximal hyoid movement during swallowing *decreased* with age. The difference was prominent between the younger group (n = 10, age range = 20-39 years old) and older group (n = 10, age range = 60-79 years old), but no difference was observed between the younger and middle-age group (n = 10, age range = 40-59 years old) or between the middle-age and older group. Additionally, total duration of hyoid movement *increased* with age, being statistically different between younger and middle-age and younger and older adults. Of relevance, the duration of maximal hyoid displacement *decreased* with age, indicating that older adults decreased the time of maximal airway protection during swallowing, thus making them more susceptible to airway invasion. This finding was observed between younger and older adults and between middle-age and older adults.

Macrae et al. (2012) investigated intra- and inter-rater reliability of hyoid movement during saliva swallows in five healthy individuals using ultrasonography. Three evaluators analyzed 25 swallows (5 for each participant) for inter-rater reliability, and one evaluator repeated the measurements for intra-rater reliability. This study showed high agreement between evaluators, highlighting that hyoid movement measures using ultrasound are a valid method. Intra-rater (ICC = 0.93) and inter-rater

(ICC = 0.70) reliability were higher for percentage of change in movement than for the absolute measure of hyoid displacement (intra-rater ICC = 0.90; inter-rater ICC = 0.64). Another study reported similar reliability measures in hyoid displacement using ultrasound (Chen et al., 2017). Based on investigations of a single swallow of 5 ml of water in 10 participants with dysphagia from varied etiologies, Chen et al. (2017) found excellent inter-rater (ICC = 0.89) and intra-rater (ICC = 0.99 and 0.961) reliability in hyoid displacement between two evaluators. Moreover, a strong positive correlation was found between hyoid movement measured during VFSS and ultrasound ($r = 0.81$ and 0.91), indicating high agreement between measurements of hyoid bone movement during swallowing using these two instrumentations.

Lee et al. (2016) associated hyoid movement with swallowing safety and efficiency in 52 adults with dysphagia. Patients were evaluated for penetration, aspiration, and residue episodes during 5 ml of thin liquid swallows on VFSS, whereas hyoid movement was assessed via ultrasound. The findings showed that hyoid displacement was *greater* in patients without penetration or aspiration than in patients with safety impairments and in patients with penetration than with aspiration. Additionally, hyoid movement was *greater* in patients without post-swallow residue than in patients who presented with mild residue in the valleculae and moderate to severe residue in the pyriform sinus and valleculae. *Greater* hyoid movement was also reported in patients who showed mild residue than in patients who presented with moderate to severe residue in the pyriform sinus and valleculae. Therefore, these results support the association between decreased hyoid movement and risk of airway invasion. Inefficient hyolaryngeal displacement affects UES opening with consequent post-swallow residue in the pyriform sinus. However, residue in the valleculae is less related to hyoid movement and may indicate that multiple swallowing events were compromised in individuals with severe dysphagia.

Finally, Kwak et al. (2018) studied the impact of nasogastric tube feeding on hyoid movement during swallows of 1 ml of water, comparing healthy individuals (n = 25), post-stroke patients with dysphagia without tube feeding (n = 25), and dysphagic patients with tube feeding (n = 20). Results indicated that hyoid displacement was *greater* in healthy individuals than in post-stroke patients with dysphagia independent of the presence of a tube feeding. Post-stroke patients without tube feeding also showed *greater* hyoid movement than patients with tube feeding. Interestingly, when the tube feeding was removed, patients improved hyoid excursion, but this improvement was not equivalent to healthy individuals' measures.

Laryngeal elevation was reported in one ultrasonography study (Komori et al., 2008). The authors examined the distance and timing of laryngeal elevation in healthy younger individuals (n = 8) during simultaneous VFSS and ultrasonography imaging acquisition. Findings showed a strong positive correlation between both imaging modalities for laryngeal elevation (r = 0.91) and duration of maximal laryngeal elevation (*r* = 0.98) during barium swallows of 15 ml (n = 24 swallows), indicating high agreement between measurements of laryngeal movement during swallowing using ultrasound and VFSS.

Lastly, the approximation between the hyoid and the larynx was measured in two studies using ultrasonography (Huang et al., 2009; Kuhl et al., 2003). Kuhl et al. (2003) compared healthy individuals (n = 42) and patients with neurogenic dysphagia (n = 18) during 5 ml liquid swallows. Results indicated that healthy participants showed *greater* hyoid-larynx approximation than patients with dysphagia. Huang and colleagues (2009) investigated hyoid-larynx approximation in post-stroke patients with dysphagia (n = 10), as well as the reliability of those measures. Findings indicated that hyoid-larynx approximation was equivalent between VFSS and ultrasound during 5 ml swallows of thin liquid. Additionally, the authors reported excellent inter-rater (ICC = 0.98) and intra-rater (ICC = 0.97 and 0.99) reliability in ultrasonography measurement during 2-3 ml liquid swallows in healthy participants (n = 5). The degree of hyoid-larynx approximation was *greater* in healthy individuals (n = 15) than in post-stroke patients with and without dysphagia. However, this difference was only observed in the normalized measure reported as a percentage of position at rest; differences were not observed in the absolute approximation distance. Finally, a cutoff point of 40% in the degree of hyoid-larynx approximation differentiated participants with and without dysphagia with a sensitivity of 75% and specificity of 77%.

These studies measuring hyoid and larynx displacement using ultrasound suggest that hyolaryngeal movement is *greater* in healthy individuals than those with dysphagia, and *decreased* hyoid movement is observed with advanced age. The findings also indicate that ultrasound measures of hyolaryngeal displacement have strong reliability and correlate well with VFSS measures. Therefore, ultrasonography provides a reliable, valid, and sensitive method for determining hyoid and larynx movement during swallowing and for determining potential differences across age, task, or group (healthy versus dysphagic).

2.5 Therapeutic Strategies for Improving Hyolaryngeal Movement and Driving Pressure during Swallowing

Dysphagia treatment addresses specific physiologic swallowing deficits that can cause airway invasion or significant post-swallow residue that add risk for aspiration. Therefore, the primary aim of swallowing management is to optimize safe and efficient swallowing to facilitate oral feeding with the least restrictive diet while ensuring appropriate nutrition, hydration, and food pleasure. Due to the variability of the physiologic deficits associated with dysphagia, rehabilitative and compensatory strategies must be chosen to target the muscular, biomechanical, or pressure deficits underlying dysphagia signs and symptoms. Furthermore, an effective treatment program in dysphagia must consider the specific physiologic swallowing impairments as determined from instrumental evaluation, the overall health and function of the patient (e.g., cognitive ability, medical status, motivation), evidence-based clinical practice, and the individual patient's needs and desires.

Carnaby and Harenberg (2013) studied dysphagia management patterns in the U.S. and evidence-based practice to tailor decision-making in swallowing. Although 60% of the speech-language pathologists (SLPs) who responded reported using VFSS for evaluation, only 4% of them indicated that their treatment techniques were based on the physiologic impairments found during instrumental assessment. Additionally, 96% of the SLPs used a combination of techniques (more than four) during a session when treating dysphagia patients. Only 37% stated that their recommended therapeutic techniques were based on scientific evidence. These patterns of treatment were reflected in the responses of the SLPs for an example case study that Carnaby and Harenberg sent them, in which the researchers asked the SLPs to choose an appropriate therapy. The SLPs recommended more than 47 different strategies for the case and 96 combinations of techniques, without agreement among them. Unfortunately, nearly 60% of these therapeutic approaches were not related to the physiological impairments described in the case study. Vose et al. (2018) found similar results for treatment recommendations, emphasizing that SLPs target swallowing consequences (e.g., penetration, aspiration, and residue) during their assessment and treatment of patients rather than physiological impairments such as hyolaryngeal movement and driving pressure deficits.

Archer et al. (2013) investigated which exercises and behavioral swallowing strategies were recommended by SLPs for treating post-stroke dysphagia in the United Kingdom and Ireland. Surprisingly, more than 50% of the responding SLPs reported rarely or never using instrumental evaluation to indicate swallowing interventions, although 90% of SLPs declared having access to VFSS. In this study, factors rated as important for clinical decision-making were a patient's alertness (82%), cognitive status (53%), motivation (53%), and medical status (49%). Similarly, Jones and colleagues (2018) identified the usual care for post-stroke dysphagia treatment in Australia and the factors influencing therapy recommendations. These authors found high variability in management practices, with SLPs implementing an average of 13 different therapeutic approaches in their usual care. Moreover, SLPs reported that they based their decision-making for therapy recommendations primarily on their patient's cognitive ability (42%), with less emphasis given to the results of the instrumental evaluation (19%) and the medical diagnosis of the patient (18%). Evidence-based treatment was listed as the 10^{th} factor influencing dysphagia management in this study (11%).

These studies addressing patterns of swallowing management suggest that SLPs focus on patient characteristics and swallowing consequences rather than on physiologic deficits. Furthermore, evidence-based practice and instrumental evaluation are under-utilized when planning dysphagia treatment, with consequent recommendation of a variety of rehabilitation approaches not related to the physiologic impairments. This helps explain why dysphagia management frequently relies on compensatory techniques such as postural changes and diet modifications including thickened fluids (Jones et al., 2018), which do not directly target rehabilitation of a physiologic deficit.

Compensatory techniques include adjustments to pharyngeal and laryngeal dimensions, bolus flow, or timing to prevent dysphagia consequences, such as aspiration and penetration (Logemann, 1999). However, these techniques primarily reduce immediate swallowing risk, for example, aspiration, rather than promote long-term changes in swallowing physiology. Conversely, exercises and behavioral swallowing strategies alter physiologic aspects of swallowing, potentially promoting long-lasting changes by improving coordination and strength of oral and pharyngeal muscles, as well as the timing of biomechanical events (Cohen et al., 2016; Vose et al., 2014). Several swallowing maneuvers are implemented in dysphagia rehabilitation to provide both immediate improvements in swallowing function and long-term changes in strength and coordination of swallowing muscles when those maneuvers are implemented over an extended period. Common maneuvers used in swallowing rehabilitation include the EFS and Mendelsohn maneuver, which involve volitional altering of strength or timing of swallowing events to facilitate safer and more efficient deglutition.

The literature highlights the need for therapeutic strategies that can enhance neuromuscular components of swallowing using neuroplasticity principles and motor learning to restore or improve swallowing function, thus mitigating the burden of dysphagia on the individual's quality of life. Neuroplasticity involves the central nervous system's ability to alter synaptic transmissions and enhance neural networks in response to stimuli (Nahum et al., 2013), such as exercises. These changes promote structural and functional brain modifications, which benefit learning/relearning (Nahum et al., 2013). Kleim and Jones (2008) described 10 principles of neuroplasticity based on seminal studies with animal models and investigations in humans using neuroimaging and neuromodulatory techniques. These studies were essential for demonstrating the capability of the central nervous system to recover and adapt after a brain insult, and the role of motor learning in cortical reorganization. Since then, the link between the acquisition of motor skills and neuroplasticity has introduced a new paradigm in rehabilitation, and it has been the foundation for developing therapeutic programs to treat patients.

2.5.1 Evidence-Based Strategies for Improving Hyolaryngeal Movement

Adequate hyolaryngeal displacement is important for closing the laryngeal vestibule and opening the UES, contributing to swallowing safety and efficiency.

Studies have determined the effects of several therapeutic strategies on hyolaryngeal movement and their impact on airway protection and bolus clearance through the pharynx and into the esophagus. The Mendelsohn maneuver, for example, requires the individual to hold the larynx in an elevated position at the peak of the swallow for two seconds or more (McCullough & Kim, 2013). This maneuver increases hyoid displacement and prolongs maximal hyoid excursion duration and laryngeal vestibule closure (Inamoto et al., 2018).

The use of the Mendelsohn maneuver was studied as part of a rehabilitative program where post-stroke patients with dysphagia (n = 18) practiced 30-40 swallows twice a day for two weeks (McCullough et al., 2012; McCullough & Kim, 2013). The findings suggested that hyoid elevation improved after the program, but other kinematic measures such as laryngeal movement did not change (McCullough & Kim, 2013). Additionally, maximum duration of hyoid elevation and anterior movement was prolonged following treatment (McCullough et al., 2012). Increased hyolaryngeal movement and duration of maximum displacement contribute to airway protection by facilitating the closure of the laryngeal entrance. The movement of the hyoid and larynx also promotes UES opening and subsequent bolus passage to the esophagus. However, the Mendelsohn maneuver involves complex instructions and training, limiting its use with patients with impaired cognition.

The Shaker exercises consist of isometric (sustained) and isokinetic (repeated) head-lift movements in the supine position, targeting the strengthening of the suprahyoid muscles which are critical for hyolaryngeal elevation (Shaker et al., 1997). The program includes three head-lifts sustained for 60 seconds each and 30 consecutive head-lifts practiced three times a day for six weeks. Consistent findings suggest that the Shaker exercises improve UES opening and anterior movement of the larynx (Easterling et al., 2005; Shaker et al., 1997, 2002). However, there is no evidence of increased hyolaryngeal elevation (Easterling et al., 2005; Shaker et al., 1997; Shaker et al., 2002).

The McNeil Dysphagia Therapy Program (MDTP) is a systematic and hierarchical exercise-based rehabilitation approach, targeting the coordination and strengthening of swallowing musculature (Carnaby-Mann & Crary, 2010). The program involves practicing hard swallows for one hour, five days a week, for three weeks, progressing to thicker food consistencies and greater volumes as patients improve dysphagia symptoms (Carnaby-Mann & Crary, 2010). Studies suggest that the MDTP improves hyoid and larynx elevation during thin liquid swallows, but not with other liquid/food consistencies in individuals with persistent severe dysphagia following head and neck cancer or stroke (Crary et al., 2012; Sia et al., 2015). Moreover, the program was found to increase tongue-to-palate pressure during pudding swallows, but BOT retraction improvement did not occur (Crary et al., 2012). Although the above noted improvements may benefit swallowing safety and efficiency, the evidence on how and why the MDTP benefits swallowing dynamics is not well understood.

Neuromuscular electrical stimulation (NMES) is a tool that provides electrical current to swallowing muscles (e.g., suprahyoid muscles). Studies investigating immediate physiological effects of NMES showed detrimental outcomes in hyolaryngeal elevation (Humbert et al., 2006; Ludlow et al., 2007). Humbert et al. (2006) examined the effects of NMES with different electrode placements (e.g., submental area, submental and laryngeal regions) in healthy adults (n = 29) and found that most placement combinations resulted in *decreased* movement of the hyoid bone and larynx. Moreover, this study indicated that NMES impaired swallowing safety in these healthy individuals. Ludlow et al. (2007) also reported a *descent* of the hyoid bone in the vertical position but not in the larynx during stimulation applied in the submental and laryngeal regions in individuals with chronic pharyngeal dysphagia (n = 11). Despite this measured lowering of the hyoid bone, no detrimental effects in swallowing safety occurred during stimulation at motor levels and improved airway protection was reported during sensory levels of stimulation.

Bülow and colleagues (2008) compared post-treatment outcomes between swallowing therapy (e.g., compensatory and behavioral strategies) and NMES in the laryngeal region during hard swallows. In this randomized trial, post-stroke participants with dysphagia (n = 25) received therapy for 60 minutes, 5 days/week for 3 weeks. Findings indicated no differences in post-treatment outcomes between swallowing therapy and NMES for dependent measures such as self-perceived swallowing difficulty, nutritional status, oral motor function, airway invasion, and post-swallow residue.

Subsequent investigations have used NMES coupled with behavioral swallowing therapy in individuals with post-stroke dysphagia. However, differences in electrode placements, dysphagia severity, timing post-stroke, and therapeutic regimens make comparison of findings difficult. Xia et al. (2011) conducted a randomized controlled trial including acute stroke patients with dysphagia (n = 120). Participants received therapy twice a day for 30 minutes, 5 days/week for 4 weeks in one of three conditions: swallowing therapy, NMES alone with varied electrode placements, or swallowing therapy with adjunctive NMES. The results showed that submental peak amplitude during regular swallows, perceived swallowing quality of life, and clinical swallowing assessment improved post-treatment in all three treatment modalities, but swallowing therapy with NMES was more beneficial than the other conditions.

Kushner et al. (2013) found that NMES with swallowing therapy (n = 65) resulted in greater improvement in oral intake than swallowing therapy alone (n = 27) for acute stroke patients with severe dysphagia. In this study, participants received therapy for 60 minutes, 5-6 days/week for 3-4 weeks. Additionally, electrode placement in individuals who received NMES varied among participants (e.g., laryngeal, submental, or facial regions). Lastly, Carnaby et al. (2020) compared post-treatment results between swallowing therapy (n = 16), MDTP with sham NMES (n = 16), and MDTP with active NMES (n = 17). Post-stroke participants (subacute stroke) with dysphagia received therapy for 60 minutes, 5 days/week for 3 weeks. NMES electrodes were placed in the laryngeal region in patients who received sham or active stimulation. Overall, MDTP with sham NMES showed greater improvements from baseline than swallowing therapy or MDTP with active NMES in the clinical swallowing assessment, oral intake, and airway invasion as determined by instrumental assessment. However, self-perception of swallowing ability was equivalent between therapeutic modalities.

2.5.2 Evidence-Based Strategies for Improving Driving Pressure

Because adequate oral and pharyngeal driving pressures are required for effective clearance of the bolus during swallowing and directly impact swallowing safety, multiple studies have determined the effects of various therapeutic techniques on swallowing-related driving pressure. The tongue-hold or Masako exercise consists of saliva swallows with a protruding tongue position (Fujiu-Kurachi, 2002, 2014). However, the literature does not delineate a specific exercise regimen for practicing the tongue-hold. This exercise was first developed to improve the anterior movement of the PPW in individuals with pharyngeal motility deficits due to oral cancer (Fujiu-Kurachi, 2002), thus, strengthening the PPW (Fujiu-Kurachi, 2014). Improving the anterior movement of the PPW facilitates its contact with the BOT and, therefore, driving pressures generated in the region (Fujiu-Kurachi, 2002 and 2014). However, Doeltgen et al. (2009) showed that the tongue-hold exercise *decreased* pressure amplitudes and *shortened* pressure durations in the upper and lower pharynx compared to regular saliva swallows in healthy adults (n = 40). Additionally, their results indicated that UES relaxation pressure was *lower* during the tongue-hold exercise than normal swallows (NSs), and pressure duration did not change. Another study using simultaneous high-resolution manometry, surface electromyography (sEMG; submental muscles) and intramuscular EMG (genioglossus, superior pharyngeal constrictor, and cricopharyngeus muscle) in healthy adults (n = 8) showed an *increase* in tongue (i.e., genioglossus) and pharynx (i.e., superior pharyngeal constrictor) peak muscle amplitudes and durations during the tongue-hold, but not in the UES (i.e., cricopharyngeus). Nevertheless, peak pressures and pressure durations did not change (Hammer et al., 2014).

Overall, these studies investigated the immediate effects of tongue-hold exercises in healthy adults and suggest that increased anterior movement of the PPW does not change pressure generated in the pharynx to drive the bolus downward. However, these findings differ from the results reported in disordered populations with pharyngeal dysphagia. A possible explanation is that healthy individuals have normal pharyngeal pressure; thus, the tongue-hold maneuver does not increase pressure in the pharynx above the already normal levels demonstrated prior to the maneuver. Contrarily, individuals with pharyngeal dysphagia have *pressure deficits* and the maneuver helps to re-establish normal pressure levels. Nevertheless, further effects of the tongue-hold exercise should be addressed when using it in a rehabilitation program.

Maximum isometric tongue pressure or tongue strength varies from 28 to 94 kilopascals (kPa) in healthy adults with a mean peak pressure around 60 kPa (Stierwalt & Youmans, 2007; Youmans & Stierwalt, 2006), though swallowing pressure represents, on average, only 51% of maximum tongue pressure (Youmans & Stierwalt, 2006). The literature also shows that maximum isometric tongue pressure is higher in the anterior than posterior tongue, greater for men than women, and is greater in younger (<60 years old) than older adults (Gingrich et al., 2012; Stierwalt & Youmans, 2007; Todd et al., 2013; Youmans & Stierwalt, 2006; Youmans et al., 2009). Additionally, anterior maximum isometric tongue pressure is considered normal above 40 kPa (Lazarus et al., 2003; Stierwalt & Youmans, 2007; Youmans et al., 2009; Youmans & Stierwalt, 2006). During swallowing, pressure generated in the anterior tongue is greater than pressure produced in the posterior tongue, and tongue pressure increases as food consistencies thickens (Gingrich et al., 2012; Todd et al., 2013; Youmans & Stierwalt, 2006). In individuals with dysphagia, tongue strength is impaired, with a mean isometric tongue pressure of 35 kPa (pressure range = 2-80 kPa; Stierwalt & Youmans, 2007).

Isometric tongue exercises are widely used and improve tongue strength in the anterior and posterior tongue and maximum tongue pressure during swallowing in healthy and post-stroke individuals (McKenna et al., 2017; Oh, 2015; Robbins et al., 2005, 2007; Yeates et al., 2008). Moreover, one study suggests that post-stroke patients with dysphagia decreased pharyngeal residue and airway invasion during swallowing after an 8-week treatment of isometric tongue exercises (Robbins et al., 2007). In contrast to several other dysphagia treatments, the effects of these exercises were determined for people with dysphagia and within an extended rehabilitation paradigm. This offers greater strength of evidence than studies that have only determined the immediate effects of a swallowing strategy or have only investigated the effects of a technique in healthy adults. However, there is no consensus regarding the ideal frequency, repetition, intensity, and duration of isometric tongue exercises (McKenna et al., 2017).

Transcranial magnetic stimulation (TMS) is a noninvasive neurostimulation and neuromodulatory procedure, which generates magnetic field pulses to modulate cortical excitability (Michou et al., 2016). The effects of TMS in healthy adults indicated that repetitive TMS (100 to 1000 pulses at 5 Hz) over the pharyngeal motor cortex increased the excitability of the corticobulbar projections in both hemispheres (Gow et al., 2004; Jefferson et al., 2009). Additionally, the literature shows several benefits of TMS in post-stroke dysphagia (Khedr et al., 2009, 2010; Park et al., 2013; Pitts et al., 2020; Verin & Leroi, 2009). Verin and Leroi (2009), for example, showed that repetitive TMS in the *non-lesioned* motor cortical area representing the mylohyoid (a suprahyoid muscle involved in hyolaryngeal movement) improved swallow response time and decreased aspiration and residue scores for at least three weeks. Participants (n = 7) received stimulation at 1 Hz for 20 minutes for five days. Khedr et al. (2009 and 2010) found that repetitive TMS in the *lesioned* or *both* lesioned and non-lesioned esophageal motor cortex decreased dysphagia severity for up to two months in the group receiving real TMS but not in participants who received sham stimulation. Active stimulation was delivered at 3 Hz (10 blocks of 30 pulses) for 5 days (10 minutes per day). Park et al. (2013) found improvement in pharyngeal phase swallowing and better penetration-aspiration scores in the group who received repetitive TMS in the *non-lesioned* pharyngeal motor cortex hemisphere but not in the control group. In this randomized clinical trial, stimulation was delivered at 5 Hz (10 blocks of 50 pulses) for 10 days (10 minutes per day). Finally, Pitts et al. (2020) found that single-pulse TMS applied to the tongue motor cortex increased tongue pressure in healthy individuals (n = 5) as well as individuals with post-stroke dysphagia that included impaired tongue strength (n = 4).

Lastly, the EFS maneuver is a widely used therapeutic approach in dysphagia management. The first proposed instruction for the EFS, "as you swallow, squeeze hard with all your muscles" (Logemann, 1998, p. 221), elicits *increased oral and pharyngeal* muscle involvement. This improves the contact between the BOT and the PPW during swallowing and increases driving pressure in the region, thereby facilitating bolus passage and clearance (Kahrilas et al., 1992, 1993; Pouderoux & Kahrilas, 1995). In addition to these immediate, compensatory improvements in the safe transfer of the bolus through the oropharynx, the EFS is also used as a therapeutic or rehabilitative technique due to its role in altering long-term physiological components of swallowing (Büllow et al., 1999; Lazarus et al., 2002; Pouderoux & Kahrilas, 1995).

Observations during instrumental (e.g., VFSS) swallowing assessments prompted the first studies addressing the effects of the EFS. Subsequently, several authors have shown additional effects of the EFS on swallowing physiology in controlled studies (Fritz et al., 2014; Huckabee et al., 2005; Jang et al., 2015; Molfenter et al., 2018; Steele & Huckabee, 2007; Wheeler-Hegland et al., 2008; Witte et al., 2008), supporting its role as a rehabilitative maneuver rather than just a compensatory strategy. Because of the multifocal, positive physiologic impacts of the EFS as well as its ease in performing, this maneuver is widely incorporated in clinical practice (Archer et al., 2013; Carnaby & Harenberg, 2013; Jones et al., 2018; Luchesi et al., 2015; Vose et al., 2018).

2.5.3 Use of Biofeedback in Swallowing Rehabilitation

Feedback is emphasized as a critical component in motor learning with effects in the central nervous system to upregulate task accuracy and learning (Nahum et al., 2013). Biofeedback is a critical component in motor learning of new, complex behaviors, providing information about movement patterns to help individuals shape and modify their behavior to reach a specific target (Archer et al., 2021; Benfield et al., 2019; Zimmenman et al., 2020). Furthermore, biofeedback modalities may increase an individual's motivation and compliance with the therapeutic program, which benefits learning and promotes generalization (Archer et al., 2021; Azola et al., 2017). In swallowing management, the simultaneous use of biofeedback tools and swallowing strategies or exercises improves task performance, swallowing function and physiological outcomes (Archer et al., 2021; Azola et al., 2017; Bogaardt et al., 2009; Crary et al., 2004; Nordio et al., 2021; Vose et al., 2019).

The most frequently employed biofeedback tools in swallowing are sEMG and lingual pressure transducers (e.g., IOPI). Other common instrumentations used for biofeedback are ultrasonography, fiberoptic endoscopic evaluation of swallowing, accelerometry, respiratory plethysmography, and external laryngeal pressure transducers (Benfield et al., 2019). In swallowing management, biofeedback is beneficial because swallowing is an intangible process, producing little external observable information. Additionally, most people swallow without conscious awareness of the events and structures involved in the swallowing process. Thus, biofeedback tools provide objective visual information about complex events during swallowing for clinicians and patients (Crary & Groher, 2000; Crary et al., 2004).

Surface EMG is a noninvasive tool that places surface electrodes on the skin to target a group of superficial muscles (e.g., FOM muscles). The electrodes capture electrical activity of the surrounding muscles during swallowing, which is displayed on a computer screen as a waveform of the changes in amplitude of muscle contractions over time, providing real-time visual feedback of the degree and duration of muscle activity (Crary & Groher, 2000; Ding et al., 2002). The literature has described the use of sEMG in determining patterns of muscle activation during swallowing tasks, the maximum amplitude during swallowing conditions, and the temporal relationships between swallowing kinematics and sEMG signals (Crary et al., 2006; Ding et al., 2002; Huckabee et al., 2005, 2012; Huckabee & Steele, 2006; Perlman et al., 1999; Wheeler-Hegland et al., 2008; Yeates et al., 2010). Moreover, sEMG was found to enhance the learning and execution of swallowing strategies such as the EFS (Archer et al., 2021; Bogaardt et al., 2009; Huckabee et al., 2005; Huckabee & Steele, 2006; Wheeler-Hegland et al., 2008) and Mendelsohn maneuver (Azola et al., 2015; Bogaardt et al., 2009; Ding et al., 2002).

The clinical use of sEMG biofeedback as an adjuvant to swallowing therapy was evaluated in several studies (Archer et al., 2021; Bogaardt et al., 2009; Crary et al., 2004). Crary et al. (2004) implemented a structured swallowing therapy program in individuals with pharyngeal dysphagia (n = 45) supplemented by sEMG biofeedback, 5 sessions per week for 50 minutes until discharge. The findings showed improved oral intake in 87% of the patients. Another investigation assessed the efficacy of sEMG as a biofeedback tool during swallowing rehabilitation in post-stroke individuals with chronic dysphagia (Bogaardt et al., 2009). In this study, patients (n = 11) performed the Mendelsohn maneuver every 30 seconds for 20 minutes once a week. Results indicated improvements in oral intake, as well as tube feeding removal in most patients. However, these studies were observational and did not include a control group receiving swallowing therapy without simultaneous use of sEMG biofeedback. Therefore, direct contributions of sEMG in the therapeutic process cannot be determined from these studies as individuals may have improved swallowing outcomes due to therapy alone.

Finally, Archer et al. (2021) investigated whether the use of sEMG enhances the performance of effortful swallows (EFSs) in healthy and post-stroke participants and whether this tool facilitates learning of the swallowing strategy. The authors found *greater* sEMG peak amplitude in the FOM muscles with biofeedback than without biofeedback in healthy younger and older adults, as well as in post-stroke individuals. Additionally, more than 80% of the participants perceived that sEMG was helpful to learn and execute the EFS, and they reported that it was easier to perform the EFS with biofeedback than without biofeedback. The three most frequently cited reasons why the participants liked this biofeedback modality were the visual feedback about performance, the provision of a clear goal to achieve, and biofeedback being an enjoyable tool.

The IOPI provides visual biofeedback through the device's LCD screen, which displays a real-time numerical pressure measurement during isometric (sustained) tongue press or swallowing, and a green light when individuals reach the desired target during tongue isokinetic (endurance) exercises (Robbins et al., 2005, 2007). Studies using the IOPI with visual feedback to increase tongue pressure during swallowing, isometric tongue strength, or tongue endurance reported positive outcomes (Robbins et al., 2005, 2007; Yeates et al., 2008).

Aoki et al. (2015) compared an intervention group who received tongue exercises with biofeedback (n = 17) using a similar device to the IOPI and a control group (n = 14) who received tongue exercises without biofeedback. The findings indicated that the group who performed tongue strengthening exercises with adjuvant visual biofeedback showed *increased* maximum tongue pressure and swallowing tongue pressure post-intervention, as well as overall improvements in swallowing function. These benefits were not observed in participants who completed the therapy program without biofeedback. These investigations support the benefits of visual biofeedback modalities such as sEMG and the IOPI in tasks that target increased strength and output of swallowing-related muscles. Moreover, sEMG was found to improve learning and performance of the EFS in both healthy and post-stroke individuals, and the IOPI promoted increased pressure generation during swallowing and maximum tongue strength.

2.6 Evidence for Specific Physiologic and Functional Effects of the EFS

A critical evaluation of the evidence on the physiologic and functional effects of the EFS alone indicates that most of the studies (n = 20) reported on healthy younger and older adults with no history of swallowing disorders or diseases that may affect swallowing structures or physiology (Bahia & Lowell, 2020). Only three studies (13%) addressed findings of the EFS in a disordered population, including individuals with stroke, head and neck cancer, and Parkinson's disease (Bülow et al., 2001, 2002; Felix et al., 2008; Table 1). A strength of this overall body of work is that most of the studies utilized objective assessments to differentiate a normal swallow (NS) and an EFS, such as VFSS, manometry, and adjunctive sEMG.

Table 1: Characteristics of the effortful swallow studies.

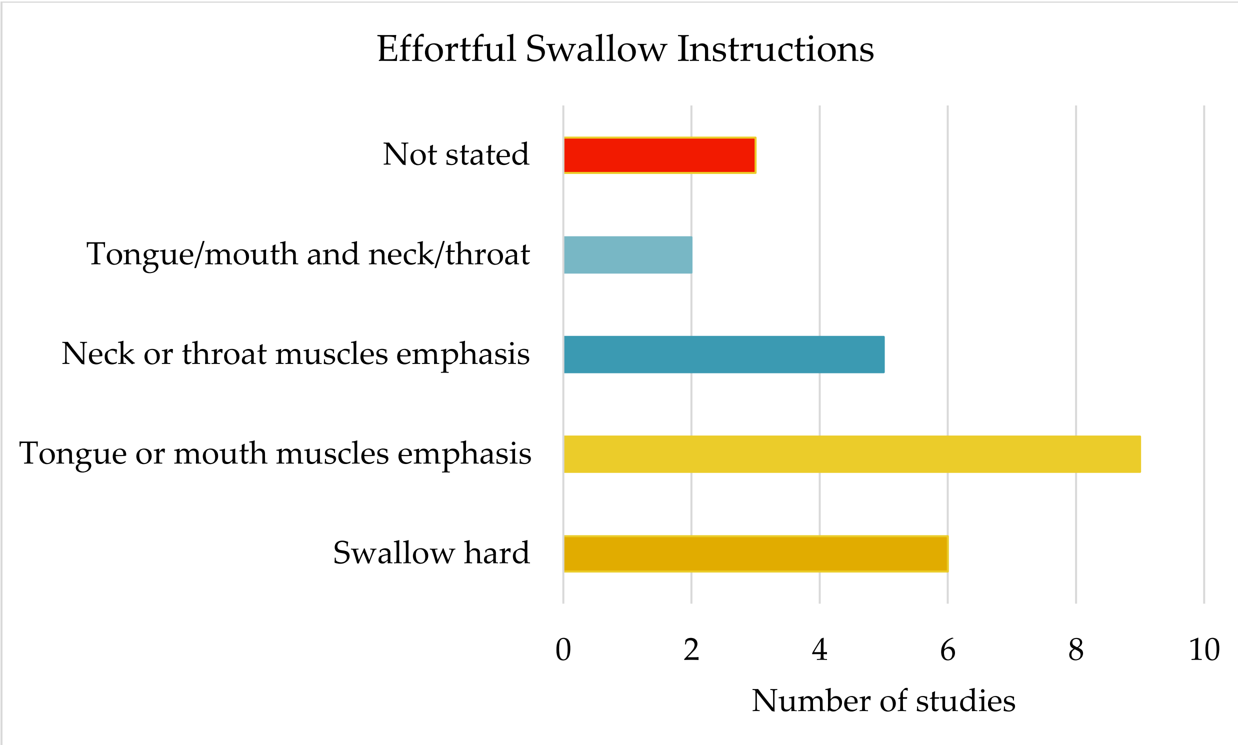
Study	Population	*n*	Age (years)	Sex (F/M)	EFS Instruction
Bülow et al., 1999	Healthy	8	25-64	4/4	"Swallow very hard while squeezing the tongue in an upward-backward motion toward the soft palate"
Bülow et al., 2002	Disordered (HNC/Stroke)	8	46-81	4/4	"Swallow very hard while squeezing the tongue in an upward-backward motion toward the soft palate"
Bülow et al., 2001	Disordered (HNC/Stroke)	8	46-81	4/4	"Swallow very hard while squeezing the tongue in an upward-backward motion toward the soft palate"
Coulas et al., 2009	Healthy	12	26±4	14/13	"Squeeze hard with all your muscles as you swallow your saliva"
Doeltgen et al., 2017	Healthy	12	21-48	9/3	"As you swallow, squeeze hard with all your muscles"
Felix et al., 2008	Disordered (PD)	4	66-78	1/3	"Swallow by contracting the muscles of the mouth and throat with the greatest possible force"
Fritz et al., 2014	Healthy	20	18-30	20/0	"Swallow really hard, squeezing hard with your throat muscles"
Fukuoka et al., 2013	Healthy	14	21-41	4/10	"As you swallow, push your tongue really hard against the roof of your mouth"
Hind et al., 2001	Healthy	64	45-93	NA	"Swallow hard"
Hiss & Huckabee, 2005	Healthy	18	28±5	NA	NA
Hoffman et al., 2012	Healthy	14	19-25	7/7	"Swallow hard and contract your muscles forcefully"
Huckabee et al., 2005	Healthy	22	28±5	11/11	NA
Huckabee & Steele, 2006	Healthy	20	20-35	20/0	"As you swallow, I want you to squeeze hard with the muscles of your throat, but not use your tongue to generate extra force" "As you swallow, push really hard with your tongue"

Jang et al., 2015	Healthy	41	23-78	21/20	“Squeeze the muscles of your throat and tongue hard during swallowing”
Lever et al., 2007	Healthy	10	20-35	5/5	"Squeeze hard with all of the muscles in the mouth while swallowing"
Molfenter et al., 2018	Healthy	44	77±7	23/21	"Squeeze really hard with all of your throat muscles, as if you are trying to get down a piece of steak that is stuck in your throat"
Nekl et al., 2012	Healthy	18	23-58	9/9	"Swallow as hard as you can with all of your muscles in the mouth but make sure you do not recruit any of the abdominal or stomach muscles"
O’Rourke et al., 2014	Healthy	10	25-53	4/6	"Swallow hard using lingual focus"
Steele & Huckabee, 2007	Healthy	20	20-35	NA	"As you swallow, I want you to squeeze hard with the muscles of your throat, but not use your tongue to generate extra force" "As you swallow, push really hard with your tongue"
Takasaki et al., 2011	Healthy	18	23-28	0/18	NA
Wheeler-Hegland et al., 2008	Healthy	25	19-35	15/10	"As you swallow, squeeze hard with all of your throat and neck muscles"
Witte et al., 2008	Healthy	40	20-43	20/20	"Squeeze hard with all of your muscles as you swallow"
Yeates et al., 2010	Healthy	72	18-35, >60	80/0	"Put your tongue behind your upper teeth and push hard as you swallow"

n: number of participants. F/M: female/male. EFS: effortful swallow. HCN: head and neck cancer. PD: Parkinson’s disease. NA: Not available.

A challenge in interpreting the findings from these studies was the high variability of the EFS instructions (Figure 1), indicating a lack of agreement among researchers about what the maneuver was targeting. Overall, four groups of instructions for the performance of the EFS were identified (Bahia & Lowell, 2020). General instructions included "swallow hard" or "swallow hard with all your muscles." In contrast, more specific directions indicated the recruitment of a particular group of muscles, for example, emphasizing tongue-to-palate or mouth muscles (EFSt) and squeezing the neck or throat muscles (EFSp). Moreover, other studies instructed the participants to use both tongue/mouth and throat/neck muscles to complete the EFS. Different instructions for the EFS may produce distinct physiological and functional effects. Therefore, it is critical to understand these differences and improve the specificity of instructions when teaching and training patients to individualize and optimize treatment approaches and associated outcomes.

Figure 1: Effortful swallow instructions identified in the literature.



Note: Total number of studies = 23. However, two studies were counted twice due to the comparison of two different types of effortful swallows (Huckabee & Steele, 2006; Steele & Huckabee, 2007).

Two studies specifically compared the effects of two different instructions for the EFS: emphasizing tongue-to-palate contact and using the throat muscles while restricting tongue-to-palate contact (Huckabee & Steele, 2006; Steele & Huckabee, 2007). These investigations found that EFS performance when elicited with instructions that emphasized a tongue-to-palate focus produced *greater* tongue and pharyngeal pressures, as well as *greater* submental sEMG peak amplitude than the EFS produced with instructions emphasizing the neck/throat muscles (Table 2).

Several additional studies investigated the EFS in conjunction with other swallowing strategies as part of a rehabilitation program in older individuals (Balou et al., 2019), head and neck cancer (Carroll et al., 2008), or multiple sclerosis (Tarameshlu et al., 2019). These investigations showed improvements in pharyngeal initiation (Balou et al., 2019), contact between the BOT and the PPW (Carroll et al., 2008), epiglottic inversion (Carroll et al., 2008), penetration-aspiration score (Tarameshlu et al., 2019), and residue (Tarameshlu et al., 2019). Moreover, studies combining the EFS with NMES in a rehabilitation program in both healthy (Park et al., 2009) and post-stroke (Kim et al., 2017; Park et al., 2012, 2016) individuals found better hyoid displacement, laryngeal elevation, pharyngeal constriction, and less airway invasion post-treatment (Kim et al., 2017; Park et al., 2009, 2012, 2016). Finally, the EFS combined with tongue resistance exercises showed improved maximum tongue pressure in healthy (Oh, 2021; Park & Kim, 2016) and post-stroke (Park et al., 2019) individuals. However, the specific effects of the EFS alone cannot be determined in those investigations.

Table 2: Description of the studies addressing the effects of the effortful swallow maneuver.

Study	Instrument(s)	Swallow trials	Main results (Consistent results across studies are bolded)
Bülow et al., 1999	VFSS Manometry	10ml thin liquid	Reduced maximum hyoid movement Reduced maximum laryngeal elevation Reduced hyoid-mandible distance pre-swallowing (at rest) No difference in hyoid-larynx distance pre-swallowing (greatest distance) and during swallowing (shortest distance), pharyngeal peak pressure and pressure duration, UES opening diameter and duration, UES minimum pressure during relaxation, UES peak pressure during contraction, UES duration between relaxation and initial contraction, and bolus transit time
Bülow et al., 2002	VFSS Manometry	10ml thin liquid	No difference in peak intrabolus pressure amplitude and pressure duration (at the level of inferior pharyngeal constrictor)
Bülow et al., 2001	VFSS Manometry	10ml thin liquid	Reduced depth of contrast penetrated/aspirated No difference in maximum hyoid movement, maximum laryngeal elevation, hyoid-larynx distance before and during swallowing, hyoid-mandible distance pre-swallowing, number of penetration/aspiration episodes, post-swallow residue (valleculae and pyriform sinuses), pharyngeal peak pressure amplitude and pressure duration (at the level of inferior pharyngeal constrictor), initial of pharyngeal swallow, UES opening diameter and duration, UES minimum pressure during relaxation, UES peak pressure during contraction, UES duration between relaxation and initial contraction, and bolus transit time
Coulas et al., 2009	Piezolectric neck transducer	Saliva	Greater positive and negative mean peak pressure amplitudes in the neck circumference No effect of sex or sex and swallowing type in neck circumference pressure amplitude
Doeltgen et al., 2017	HRIM FOM sEMG	5ml thicker liquid	Greater FOM sEMG peak amplitude and amplitude across swallowing duration Greater pressure amplitude between velopharynx-superior pharyngeal constrictor and superior pharyngeal constrictor-UES during UES opening and closure Greater peak pressure amplitude between superior pharyngeal constrictor and UES

			Shorter duration between UES opening and hypopharyngeal distention No difference in swallow risk index (residue, penetration/aspiration), duration of bolus in the lower pharynx, duration between maximum pharyngeal distention and pharyngeal peak pressure amplitude, duration peak lower pharynx distention and UES closure, duration between UES opening-closure, UES pressure before UES opening, UES maximum distention during UES closure, UES lowest pressure during relaxation, UES peak pressure after closure, UES pressure amplitude between UES distal margin-proximal esophagus during and after UES closure, and intrabolus pressure (at lower pharynx)
Felix et al., 2008	Clinical evaluation Neck transducer	Saliva Thicker liquid Solid	Greater neck pressure amplitude post-treatment during saliva and solid swallows Better oral transit time post-treatment Decreased pharyngeal residue post-treatment Decreased signs and symptoms of penetration/aspiration post-treatment (voice changes and couching/choking)
Fritz et al., 2014	Dynamic MRI	5ml pudding	Reduced pharyngeal area pre-swallowing Longer pharyngeal closure duration during maximal contraction No difference in pharyngeal area, transverse and antero-posterior length post-swallowing, and pharyngeal antero-posterior and transverse length pre-swallowing
Fukuoka et al., 2013	Manometry	Saliva 5ml liquid	**Greater peak tongue pressure amplitude in anterior, mid, posterior, and posterior circumferential arch regions (saliva and water swallows)** **Longer anterior tongue pressure duration (EFS vs. water swallows)** Greater tongue pressure during swallowing duration in anterior, mid, posterior, and posterior circumferential arch regions (EFS vs. water swallows), and in anterior, mid, and posterior tongue (EFS vs. saliva swallows) During EFS: greater tongue peak pressure amplitude in anterior tongue than other regions, greater tongue pressure during swallowing duration in anterior tongue than other regions, and smaller tongue pressure during swallowing duration in posterior tongue than anterior and posterior circumferential arch regions No difference in tongue pressure duration in the mid, posterior, and posterior circumferential arch regions
Hind et al., 2001	VFSS	3ml thin liquid	**Greater oral pressure amplitude in anterior, mid, and posterior tongue**

	Manometry		Age-related difference in oral pressure amplitude (younger adults > older adults) Higher hyoid elevation Reduced hyoid anterior movement Longer duration of hyoid maximum anterior excursion Longer laryngeal vestibule closure duration Longer pharyngeal response duration Longer UES opening duration Longer total swallowing duration Positive correlation between residue in the pyriform sinuses and older adults (r=0.41) No difference in oral transit duration, oral clearance duration, penetration/aspiration score, oral and pharyngeal (vallecular, PPW, pyriform sinuses, and UES) residue, pharyngeal clearance duration, duration of maximum hyoid elevation, maximum UES opening diameter and duration, and duration pharyngeal swallow initiation
Hiss & Huckabee, 2005	Manometry FOM sEMG	Saliva	Delayed pharyngeal pressure (upper and lower pharynx) and UES pressure onset relative to FOM sEMG onset **Longer pharyngeal and UES pressure durations** During EFS: longer pharyngeal pressure duration in upper than in lower pharynx
Hoffman et al., 2012	HR manometry	5ml liquid	**Greater peak pressure amplitude and pressure line integral in velopharynx** Greater pressure per time (area integral) (pressure per time) and line integral in UES Longer shortest UES pressure duration No difference in BOT peak pressure, pressure duration, pressure rise rate, area integral, line integral; velopharyngeal pressure duration, pressure rise rate, area integral, and velocity; UES minimum pressure during opening, pressure duration change, peak pressure amplitude before and after UES opening, peak pressure amplitude difference before and after UES opening, and total swallow pressure duration and velocity
Huckabee et al., 2005	Manometry FOM sEMG	Saliva	**Greater pharyngeal pressures in upper and mid-pharynx** Lower pressure in UES **Greater FOM sEMG peak amplitude** Weak negative correlation between FOM sEMG peak amplitude and pharyngeal and UES pressures

			During EFS: greater pressure in the upper pharynx than mid-pharynx No sex effect in pressure generation
Huckabee & Steele, 2006	Manometry FOM sEMG	Saliva	Tongue-to-palate emphasis produced greater change from normal swallowing than neck emphasis: FOM sEMG peak amplitude, mid and posterior tongue pressure peak amplitudes, upper and lower pharyngeal pressure peak amplitudes
Jang et al., 2015	VFSS	10ml thin liquid	Higher hyoid elevation and total displacement Higher laryngeal elevation, anterior movement, and total displacement Larger maximal angle of epiglottic tilt Longer total hyoid elevation duration, anterior movement duration, maximum-to-end elevation duration, and start-to-maximum anterior movement duration Longer total laryngeal elevation duration and maximum-to-end elevation duration Longer total epiglottic tilt duration and maximum-to-end duration Greater hyoid elevation total displacement velocity Greater laryngeal elevation, anterior movement, and total displacement velocity Age-related differences in all kinematic measures (younger adults > older adults) No difference in maximum hyoid anterior movement, maximum hyoid anterior movement velocity, start-to-maximum hyoid elevation duration, maximum-to-end hyoid anterior movement duration, start-to-maximum laryngeal elevation duration, and start-to-maximum epiglottic tilt duration
Lever et al., 2007	Manometry FOM sEMG	5ml liquid	**Greater oral pressure amplitude at anterior and posterior tongue** **Greater pressure amplitude at inferior smooth esophageal muscle** Lower LES residual pressure Shorter LES relaxation duration Age-related difference in LES residual pressure (female < male) No difference in esophageal pressure amplitude at striated (proximal esophagus), mixed (transition zone), and smooth (below the transition zone) muscles, pressure duration and velocity at striated, mixed, and smooth muscles
Molfenter et al., 2018	VFSS	5ml thicker liquid	Longer hyoid movement duration (d=0.86) Longer laryngeal closure duration (d=0.72) Greater residue in pyriform sinuses (d=0.02) Reduced pharyngeal shortening (d=0.29)

			Longer stage transition duration (hyoid burst-bolus pass mandible; d=0.27) Longer pharyngeal transit time (d=0.49) Longer pharyngeal response duration (d=0.39) Longer UES opening duration (d=0.53) No sex and age effects, area pharyngeal contraction at maximum constriction, residue in valleculae, and penetration/aspiration scores
Nekl et al., 2012	Standard or HR manometry FOM sEMG	5ml thin liquid 5ml thicker liquid	**Greater esophageal peak pressure amplitudes at striated, mixed, and smooth muscles** Decreased risk of incomplete esophageal bolus clearance (OR= 0.51, 95% CI 0.30-0.86) No difference in esophageal pressure durations and velocities at striated, mixed, and smooth muscles, sex effect in esophageal peak pressure amplitudes, pressure durations, and velocities at striated, mixed, and smooth muscles, and sex effect in incomplete bolus clearance
O'Rourke et al., 2014	HR manometry FOM sEMG	5ml liquid, saliva	During EFS: less frequent nonperistaltic swallows during EFS water vs. EFS saliva swallows No difference in number of peristaltic and nonperistaltic swallows, intrabolus pressure (pressure behind the bolus), distal contractile integral (length, strength, and duration of esophageal smooth muscle contraction), contractile front velocity (speed of muscle contraction), and transition zone defect
Steele & Huckabee, 2007	Manometry FOM sEMG	Saliva	**Longer absolute pressure generation duration at mid and posterior tongue** **Longer relative pressure generation duration at mid-tongue (d=0.81)** **Longer total pressure duration at mid-tongue (d=0.34)** **Longer total pressure duration at upper pharynx (d=0.83) and UES (d=0.34)** Earlier onset pressure relative to FOM sEMG amplitude at posterior tongue (d=0.41), upper pharynx (d=0.68), and UES (d=0.58) Faster peak pressure amplitudes relative to FOM sEMG amplitude at upper pharynx (d=0.76) and UES (d=0.62) Shorter rise time to peak pressure in upper pharynx (d=0.73) and UES (d=0.57)

			No difference in relative pressure generation duration at posterior tongue, total pressure duration at posterior tongue Tongue-to-palate emphasis produced greater change from normal swallowing than neck emphasis: interval between FOM sEMG peak amplitude and peak upper pharyngeal pressure (d=0.71) No difference in total pressure durations, percent of rise time to peak pressure, and onset lag times.
Takasaki et al., 2011	HR manometry	5ml liquid Saliva	Greater total swallow pressure Longer total swallow pressure duration **Greater peak pressure at velopharynx, meso-hypopharynx, and UES** (saliva and water EFS) No difference in peak pressure between saliva and water EFS at velopharynx, meso-hypopharynx, and UES
Wheeler-Hegland et al., 2008	VFSS FOM sEMG	10ml thin liquid	**Greater FOM sEMG peak amplitude** and mean amplitude during swallowing Greater FOM sEMG peak amplitude at start of hyoid movement and peak amplitude at maximum hyoid movement Positive correlation between FOM sEMG peak amplitude and maximum hyoid movement (r=0.40), maximum angle of hyoid elevation and maximum hyoid movement (r=0.40) Positive correlation between timing of FOM sEMG peak amplitude and timing of maximum hyoid movement (r=0.76), timing of FOM sEMG peak amplitude and timing of maximum angle of hyoid elevation (r=0.61) No difference in hyoid maximum movement, angle of hyoid elevation at maximum movement, hyoid movement at maximum angle of elevation, maximum angle of hyoid elevation, total hyoid movement, duration between onset and peak FOM sEMG amplitude, correlation between timing of maximum hyoid movement and timing of maximum angle of hyoid elevation, sex effects
Witte et al., 2008	Manometry	10ml liquid, saliva	**Longer pressure duration at mid-pharynx** Lower UES minimum pressure During EFS: lower UES minimum pressure in saliva than water swallows, longer pressure with saliva than water swallows at upper and mi-pharynx

			Sex-related difference in pressure duration (female > male) at mid-pharynx, total pressure duration (male > female) No difference in peak pressure amplitude at upper and mid-pharynx, pressure duration at upper pharynx and UES
Yeates et al., 2010	Manometry FOM sEMG	Saliva	**Greater tongue-to-palate peak pressure amplitude at anterior and mid tongue regions** **Longer tongue-to-palate pressure rise times at anterior and mid tongue regions** **Greater FOM sEMG peak pressure amplitude** Age-related difference in pressure rises times (older adults > younger adults) at anterior and mid tongue regions No difference in FOM sEMG pressure rise time, age difference in peak pressure amplitude at anterior and mid tongue regions, age difference in FOM sEMG peak pressure amplitude.

VFSS: videofluoroscopic swallow study. UES: upper esophageal sphincter. HRIM: high-resolution impedance manometry. FOM: floor of the mouth. sEMG: surface electromyography. MRI: magnetic resonance imaging. EFS: effortful swallow. PPW: posterior pharyngeal wall. HR: high-resolution. BOT: base of tongue. LES: lower esophageal sphincter. OR: odds ratio. CI: confidence interval.

2.6.1 Physiological Effects of the EFS in the Healthy Population

In the oral phase of swallowing, a consistent finding across studies was that maximum tongue-to-palate pressure generation was *higher* during the EFS than NS with both saliva and water trials and across different ages (Fukuoka et al., 2013; Hind et al., 2001; Lever et al., 2007; Yeates et al., 2010). However, discrepancies relative to age-related swallowing differences exist between studies (Hind et al., 2001; Yeates et al., 2010), making it difficult to draw conclusions about age-related physiologic changes such as oral pressure and submental sEMG peak amplitude. Additionally, timing differences in pressure onset and duration indicated *longer* anterior tongue-to-palate pressure duration during effortful water swallows (Fukuoka et al., 2013) and *longer* total pressure duration in the mid-tongue area during effortful saliva swallows (Steele & Huckabee, 2007). Interestingly, the EFS changed the order of onset pressure, producing earlier pressure in the anterior palate (i.d., alveolar ridge), whereas the NS had onset pressures in the posterior-circumferential portions of the palate (Fukuoka et al., 2013). Also, onset pressure was earlier in the posterior tongue-to-palate region relative to submental sEMG activity (Steele & Huckabee, 2007). Finally, pressure rise time was *longer* in the anterior and midpalate regions during the EFS (Yeates et al., 2010). Older adults showed *longer* rise times than younger adults in the anterior palate but not in the midpalate. Sustained intra-oral pressure is necessary for bolus propulsion from the oral cavity to the pharynx. Therefore, the increase in the amount and duration of intra-oral pressure suggests that the EFS may facilitate bolus clearance, potentially decreasing oral residue, which can then decrease aspiration risk.

Findings relative to the pharyngeal phase of swallowing included pharyngeal pressure measures, duration of pharyngeal events, hyolaryngeal movement measures, and UES events. Pharyngeal peak pressure was assessed via manometry (three or four sensors) or high-resolution manometry (32 to 36 sensors). Investigations using high-resolution manometry consistently reported *greater* peak pressure in the velopharynx, oropharynx, and hypopharynx during the EFS than in NS (Doeltgen et al., 2017; Hoffman et al., 2012; Takasaki et al., 2011). Other studies using standard manometry also showed *greater* pressure in the upper and mid-pharynx (Huckabee et al., 2005; Huckabee & Steele, 2006). The higher peak pharyngeal pressures shown in these studies suggest that the EFS may also facilitate bolus passage through the pharynx, decreasing pharyngeal residue.

Pressure duration showed conflicting results across studies. *Longer* pressure durations in the velopharynx, oropharynx, and hypopharynx during EFSs were reported in multiple studies assessing healthy participants (Hiss & Huckabee, 2005; Steele & Huckabee, 2007; Takasaki et al., 2011; Witte et al., 2008). In contrast, two other studies indicated *no difference* in pharyngeal pressure duration in the velopharynx (Hoffman et al., 2012) or lower pharynx region (Bülow et al., 1999). Increased pressure duration in pharyngeal regions also assists downward bolus propulsion, allowing appropriate bolus clearance.

Apart from pressure measures, researchers have determined other pharyngeal and laryngeal physiology changes associated with the EFS. Pharyngeal area and transverse length were *reduced* immediately before swallowing initiation for the EFS compared to NS (Fritz et al., 2014), suggesting better pharyngeal shortening and constriction during swallowing. The authors proposed an anticipation of BOT retraction and prolonged pharyngeal closure time, which promoted pharyngeal pressure to assist bolus passage.

Additionally, studies were consistent in demonstrating *prolonged* laryngeal closure duration with the EFS (Hind et al., 2001; Molfenter et al., 2018) and *increased* durations among different pharyngeal phase events (Molfenter et al., 2018). *Greater* epiglottic inversion (tilt angle) and *prolonged* epiglottic inversion were also associated with the EFS compared to NS (Jang et al., 2015). Higher pharyngeal pressure amplitudes and longer pressure durations may increase the contact of the BOT and the PPW, allowing continuous pharyngeal contraction (Logemann, 1998). Both BOT retraction and PPW constriction may facilitate epiglottic inversion, contributing to laryngeal vestibule closure (Vose & Humbert, 2019). Thus, the increased epiglottic inversion and prolonged duration of inversion may be associated with the greater pharyngeal contraction that occurs during the EFS. Finally, the only two studies investigating laryngeal vestibule closure duration showed *prolonged* duration times during the EFS (Hind et al., 2001; Molfenter et al., 2018), supporting its potential for airway protection.

Biomechanical and physiological changes in the hyolaryngeal complex during the EFS, such as hyolaryngeal excursion amplitude, duration, and velocity of movement during swallowing, were measured via VFSS. The findings of maximal hyoid displacement varied among the investigations. One study reported that the EFS *reduced* maximal hyoid excursion (Bülow et al., 1999), whereas another showed a significant *increase* in this measure (Jang et al., 2015). A third study did not find any difference in maximum hyoid displacement (Wheeler-Hegland et al., 2008). These studies addressed both superior and anterior hyoid movement together. Other investigations analyzed hyoid elevation and anterior movement separately. The maximal *superior* movement of the hyoid was *greater* during the EFS than NS (Hind et al., 2001; Jang et al., 2015), but *anterior* movement was *reduced* (Hind et al., 2001) or *similar* (Jang et al., 2015) to NS. Sex differences in hyoid excursion were not found (Wheeler-Hegland et al., 2008), but age differences were; younger adults showed *greater* hyoid displacement from baseline (NS) than older adults (Jang et al., 2015).

Total hyoid movement duration (in both anterior and superior directions) was *prolonged* during the EFS (Jang et al., 2015). Moreover, when analyzed separately, the total duration of *anterior* hyoid movement (Jang et al., 2015; Molfenter et al., 2018) was *greater* during the EFS than NS, but the total duration of superior movement showed inconsistent results (Hind et al., 2001; Jang et al., 2015). Finally, *greater* maximal velocity of overall hyoid displacement and *superior* hyoid movement were also observed during the EFS, but no differences in velocity of *anterior* movement occurred (Jang et al., 2015).

Conflicting results have also been reported on laryngeal elevation. Laryngeal elevation was *reduced* (Bülow et al., 1999) or *increased* (Jang et al., 2015) during the EFS. However, Bülow et al. (1999) reported in their study that the hyoid-mandible distance in the image frame just prior to the EFS was shorter than before a NS, indicating that the hyolaryngeal complex was already elevated before the EFS. Jang et al. (2015) also showed that laryngeal superior and anterior movements, when analyzed separately, were *greater* during the EFS than NS. Only one investigation analyzed the duration of laryngeal elevation, showing that durations of total laryngeal elevation, anterior, and superior movements were all *prolonged* (Jang et al., 2015). Moreover, both superior and anterior movements of the larynx had *greater* maximal velocities during the EFS than in NS (Jang et al., 2015). Increased superior and anterior laryngeal excursion, as well as prolonged duration of movement, would facilitate airway protection during swallowing.

Findings regarding the UES indicated that opening duration was *prolonged* during the EFS (Hind et al., 2001; Hiss & Huckabee, 2005; Hoffman et al., 2012; Molfenter et al., 2018), and total UES pressure was *increased* (Hoffman et al., 2012; Steele

& Huckabee, 2007). However, the EFS did not change UES opening diameter (Bülow et al., 1999; Doeltgen et al., 2017; Hind et al., 2001). Upper esophageal sphincter relaxation and opening are crucial for bolus transport to the esophagus, and they are facilitated by hyolaryngeal elevation and the pressure within the bolus. Impaired UES opening or duration may lead to residue due to inefficient bolus clearance. Huckabee and Steele (2006) found that the EFS produced with tongue emphasis showed a *greater* difference in UES pressure from NS than that which occurred when the EFS was performed with an emphasis on neck/throat muscles. Hence, different EFS instructions may facilitate specific swallowing events.

Finally, results about the esophageal phase of swallowing showed a consistent *increase* in pressure during the EFS for the mid and distal regions of the esophagus, including mixed and smooth muscle, respectively (Lever et al., 2007; Nekl et al., 2012). However, for the proximal esophagus (area closest to the UES and comprised of striated muscle), Lever and colleagues (2007) found *no* pressure change during the EFS as measured by perfusion manometry. In contrast, Nekl et al. (2012) showed pressure increases throughout the entire esophagus, including the proximal region, with combined standard and high-resolution manometry measurement. Pressure duration, velocity, and pressure on the bolus were similar across swallowing condition in both studies (Lever et al., 2007; Nekl et al., 2012). Greater esophageal pressures in areas beyond the level of the UES may facilitate bolus propulsion to the stomach, assisting in esophageal bolus clearance.

2.6.2 Effects of the EFS on Efficiency and Safety in the Healthy Population

Reduced degrees of tongue propulsion, tongue-to-palate contact, posterior tongue retraction, epiglottic inversion, pharyngeal constrictor muscle function, and opening of the UES are all factors that can result in less effective clearance of the bolus through the oral cavity and pharynx. The consequence of this reduced bolus clearance is residue in the oral and pharyngeal regions, increasing the probability of post-swallow penetration and aspiration (Molfenter & Steele, 2013; Shapira-Galitz et al., 2019). The studies that examined *swallowing efficiency* (effectiveness in clearing the bolus throughout the oropharyngeal regions) used residue scales based on analysis of VFSS images. Molfenter et al. (2018) applied the Normalized Residue Ratio Scale (Pearson et al., 2013), which objectively measures the area of residue while dividing it by the area of the space it is filling, thus normalizing for individual anatomical differences. This study reported *worsening* of residue in the pyriform sinuses during the EFS but *not* in the valleculae, suggesting a possible negative effect of the EFS. Nevertheless, the authors reported a small effect size of this finding (d = 0.02). Hind et al. (2001) utilized a 3-point ordinal scale to rate residue severity in different oropharyngeal regions. In contrast to the prior study, there were *no* differences in oropharyngeal residue (oral cavity, valleculae, PPW, pyriform sinuses, and UES) during the EFS compared to NS. Age and post-swallow residue were correlated; younger adults presented with more residue in the pyriform sinuses in normal thin liquid swallows, whereas older adults showed greater post-swallow residue in the same region during the EFS (Hind et al., 2001).

Swallowing safety (penetration and aspiration) was assessed by the Penetration-Aspiration Scale (PAS), an 8-point scale to detect the presence and characteristics of airway invasion (Rosenbek et al., 1996). Not surprisingly, the studies did not show differences in the PAS score between NSs and EFSs (Hind et al., 2001; Molfenter et al., 2018), as scores for healthy individuals are already at the lowest end of the scale for NSs. The Swallow Risk Index is another measure of swallowing dysfunction that is derived from manometric variables and indicates risk for bolus residue and associated aspiration (Omari, Dejalger, van Backevoort, Goeleven, Davidson, et al., 2011; Omari, Dejalger, van Backevoort, Goeleven, de Cock, et al., 2011). Doeltgen et al. (2017) found *no* differences in the Swallow Risk Index for the EFS and NS in healthy participants.

2.6.3 Physiological Effects of the EFS in Disordered Populations

The only oral phase measure analyzed in a disordered population was oral transit time. Changes in oral transit time, assessed subjectively via clinical evaluation, were reported after a 2-week rehabilitation program using the EFS in patients with Parkinson's disease (Felix et al., 2008). The authors stated that adequate oral transit time was observed after the EFS training with solids in patients who had exhibited slow oral transit times before the rehabilitation program. However, the investigation was qualitative in nature, describing swallowing performance before and after treatment using a clinical (non-imaging) swallowing examination. The subjective nature of this assessment method makes interpretation of these findings challenging, because it lacks visualization of the oral cavity and other swallowing structures and, therefore, does not allow for quantification of oral transit time.

In the pharyngeal phase, no significant differences in oropharyngeal or hypopharyngeal pressure amplitudes and durations were observed in individuals with dysphagia during the EFS compared with NS (Bülow et al., 2001, 2002). The EFS did *not* alter UES diameter, opening duration, maximal relaxation, or maximal pressure during contraction (Bülow et al., 2001). Maximum laryngeal elevation and hyoid movement were also *not different* between the EFS and NS (Bülow et al., 2001). However, some of these parameters produced different results in the healthy population. The studies including individuals with dysphagia have a limited sample size (n=8), which may reduce statistical power. The differences in findings between studies highlight the critical need for more investigations in disordered populations to clarify the physiological changes produced by the EFS in the population for which the maneuver is intended. The effects of the EFS on the esophagus have not been studied in adults with dysphagia.

2.6.4 Effects of the EFS on Efficiency and Safety in Disordered Populations

Swallowing efficiency and safety were reported in individuals with dysphagia due to head and neck cancer, stroke, and Parkinson's disease (Bülow et al., 2001; Felix et al., 2008). These data were critical for assessing the effects of swallowing strategies such as the EFS because the ultimate goal of swallowing management is to improve the mechanisms that influence a safer and more efficient bolus transfer through the aerodigestive tract. The first study implemented a 3-point ordinal rating scale to determine residue severity in the valleculae and the pyriform sinuses. Results indicated that the EFS did *not* change residue in these regions (Bülow et al., 2001), contradicting the findings that the EFS improves pharyngeal pressure and improves the contact between the BOT and the PPW to facilitate bolus passage and clearance. In contrast, *decreased* overall residue in patients with Parkinson's disease was reported for the EFS (Felix et al., 2008). However, this investigation used clinical judgment in comparing pre- and post-intervention variables rather than a VFSS or other imaging technique to determine the presence or absence of post-swallow residue, which is inadequate to assess the occurrence and severity of residue due to the lack of ability to visualize material in pharyngeal regions.

Swallowing safety was determined from analysis of VFSS images using a 3-point rating scale that judged the depth of the contrast in laryngeal structures (Bülow et al., 2001), or clinical (non-imaging) signs and symptoms, such as voice quality changes, coughing, and choking (Felix et al., 2008). In the first study, findings indicated that the EFS *reduced* the depth of penetrated contrast but did not decrease the number of penetration/aspiration episodes. In contrast, in the second study, the EFS *decreased* signs and symptoms of penetration/aspiration. Future investigations are necessary that include a larger cohort of disordered populations, while determining the functional effects of the EFS in those individuals using objective assessment methods.

2.6.5 Critique of the Effects of the EFS on Hyolaryngeal Movement

Hyolaryngeal displacement during the EFS was investigated in healthy individuals and in patients with dysphagia due to head and neck cancer and post-stroke (Bülow et al., 1999, 2001; Hind et al., 2001; Jang et al., 2015; Wheeler-Hegland et al., 2008). All studies used VFSS for kinematic measurement of the hyoid bone and the larynx during regular and EFSs using similar procedures. Additionally, the studies included 2-3 swallows of thin liquid for each participant and NSs were performed before EFSs to avoid carryover effect of strategy learning, which facilitates comparison of results. However, swallow trials varied in volume (3ml or 10ml), a potential factor for conflicting results as larger bolus volumes increase hyoid displacement and velocity (Nagy et al., 2014).

A substantial limitation of these investigations is the inadequate training and verification of the EFS. Two studies included practice of the EFS prior to data collection

(Jang et al., 2015; Wheeler-Hegland et al., 2008) but only one of these studies trained participants on performing the EFS under submental sEMG visual biofeedback guidance (Wheeler-Hegland et al., 2008). The other studies that did not include specific training of the EFS relied on verbal instructions before each swallow. Moreover, appropriate execution of EFSs were only verified in one study during experimental swallows, which used submental sEMG with a consistent criterion (Wheeler-Hegland et al., 2008). Appropriate performance of the EFS requires increased activity of muscles and related structures that are interior and not observable during swallowing (e.g., closed oral cavity and internal pharyngeal and laryngeal muscles). Therefore, visual biofeedback on degree of muscle activation is critical for training and verifying the accurate use of the EFS. The lack of standardized procedures for training and verifying EFSs may have affected data analysis as some individuals may not produce an appropriate EFS.

Furthermore, EFS instructions varied across investigations (four different instructions were identified), a possible reason for different outcomes among studies as different instructions may produce varied physiological effects as demonstrated by Huckabee and Steele (2006) and Steele and Huckabee (2007). While Bülow et al. (1999 and 2001) and Wheeler-Hegland et al. (2008) emphasized a specific muscle group in their instruction (tongue and neck/throat, respectively), Jang et al. (2015) recommended the use of both tongue and neck/throat muscles, and Hind et al. (2001) used a broad instruction to swallow hard.

One study also investigated age-related differences in hyolaryngeal kinematics between NSs and EFSs (Jang et al., 2015). Findings indicated that, although both younger and older healthy adults increased hyoid and larynx displacements and movement durations, younger adults showed more prominent differences across swallowing conditions than older participants. Nevertheless, the study did not report whether these differences between groups were statistically significant. A potential limitation in the analysis of age-related changes is the lack of a clear distinction in ages between groups in this study. The younger group included individuals ages 20 to 59, whereas the older group included participants ages 60 to 79. Therefore, the upper age limit in the younger group was only one year different than the lower age limit in the older group, potentially confounding the ability to determine age-related differences.

2.6.6 Critique of the Effects of the EFS on Tongue Pressure

Studies investigating tongue-to-palate pressure during NSs and EFSs reported consistent findings relative to greater peak pressures amplitudes and durations during the EFS (Fukuoka et al., 2013; Hind et al., 2001; Huckabee & Steele, 2006; Lever et al., 2007; Steele & Huckabee, 2007; Yeates et al., 2010). These studies included healthy participants only and adopted similar methods, facilitating comparison. Most investigations (n = 5) used oral sensors attached to the hard palate (2-5 sensors) in comparable locations (e.g., alveolar ridge, mid-palate, and at the junction between the hard and soft palates), and one study measured pressure using air-filled plastic bulbs (Lever et al., 2007). Additionally, the EFS instruction was similar across five studies and emphasized mouth/tongue muscles. Two of these investigations also compared differences between EFSs produced with tongue emphasis and EFSs performed with neck squeezing (Huckabee & Steele, 2006; Steele & Huckabee, 2007), showing different outcomes. The findings showed that the EFS produced with tongue emphasis produced greater tongue-to-palate peak pressure amplitudes than the EFS produced with neck squeezing, but pressure durations were similar across EFS strategies. Therefore, the EFS instruction can be a potential limitation when comparing different studies due to possible physiological differences. Finally, four studies used submental sEMG for training and tracking EFSs (Huckabee & Steele, 2006; Lever et al., 2007; Steele & Huckabee, 2007, Yeates et al., 2010). However, it was not clear whether a specific threshold was adopted for verifying correct performance. Although studies varied in bolus consistencies (e.g., saliva, water, and thin liquid), when saliva and water swallow trials were directly compared, peak pressure amplitudes and durations were found to be similar (Fukuoka et al., 2013).

A major limitation of these studies is the lack of comparison among sensors located from front to back in the oral cavity. Although the EFS *increased* peak pressure amplitudes and durations in the anterior, mid, and posterior oral tongue regions, differences among sensors were described in only one study (Fukuoka et al., 2013). This investigation showed that sensors were activated forward to backward, and the most anterior sensor (alveolar ridge) produced *greater* peak pressure amplitude with *longer* pressure duration than the other sensors. The tongue has multiple functions during swallowing, participating in bolus formation, manipulation, containment, and propulsion (transport). Oral pressure is generated through contact between the tongue and the hard palate, a critical component for transporting the bolus toward the oropharynx. Additionally, the BOT provides driving pressure when contacting the PPW to transport the bolus throughout the pharynx. Adequate tongue pressure is critical for oral and pharyngeal clearance, as well as airway protection. Although the contributions of the oral tongue and the BOT during swallowing are well-known, the role of each part of the oral tongue is not fully understood. The literature shows that maximum isometric tongue pressure (tongue strength) and tongue endurance are greater in the anterior than posterior oral tongue regions (Adams et al., 2013), but individual contributions of the anterior and posterior oral tongue regions in pressure generation during NSs and EFSs are currently unclear.

Furthermore, studies investigating the EFS did not compare the effects of different instructions on anterior versus posterior tongue-to-palate pressure or the influence of tongue pressures on hyolaryngeal displacement. Differences in oral pressure generation during swallowing may influence how clinicians instruct and train patients in the execution of the EFS, as well as in the development of new lingual exercises. The posterior oral tongue region, for example, may contribute to hyolaryngeal movement during the EFS. In this case, patients with lingual *and* hyolaryngeal displacement deficits could be instructed to emphasize the contact between the posterior oral tongue and the hard palate, and tongue strength exercises could focus on the posterior oral tongue.

Two studies also described age-related changes in tongue-to-palate pressure during NSs and EFSs (Hind et al., 2001; Yeates et al., 2010). However, these investigations found conflicting results relative to peak oral pressure amplitudes. While Hind et al. (2001) reported an age effect with younger healthy adults showing greater differences in peak pressure amplitudes between NSs and EFSs, Yeates et al. (2010) did not find age differences. Although these studies used similar instrumentation for measurement and locations of sensors, other methodological differences possibly produced the conflicting findings such as EFS instruction and bolus volume and consistency. Moreover, the age span of participants varied between studies. Yeates et al. (2010) included two age groups with a large age distinction (ages 18 to 35 for the younger group and ages 60 and older for the older group), whereas Hind et al. (2001) included middle-aged and older adults (ages 45 to 93) without specifying the age range of each group. Therefore, future investigations are necessary to explore age-related differences in tongue-to-palate pressure in healthy adults and whether pressures produced in different tongue regions are affected by age.

2.7 Evidence for Perceived Effort to Swallow

Perceived effort used to swallow can be influenced by lubrication and food properties, such as size, consistency, and volume (Chen & Lolivret, 2011; Matsuyaman et al., 2021). Studies investigating perceived swallowing effort addressed the relationship between this perception measurement and lubrication (Rogus-Pulia et al., 2018), food properties (Chen & Lolivret, 2011; Matsuyama et al., 2021; Nyström et al., 2015), meal consumption (Brates & Molfenter, 2021; Kays et al., 2010), and the EFS maneuver (Bahia & Lowell, 2022). Rogus-Pulia and colleagues (2018) studied the effects of an artificial saliva product on perceived effort to swallow saliva and perceived mouth dryness in 42 healthy adults (age range = 20-94 years old; *M*age = 65 years) using a visual analog scale (VAS; 0-100 mm). The findings of this study showed that participants who perceived higher mouth dryness scores also perceived greater effort to swallow. Additionally, participants perceived lower swallowing effort after using the artificial saliva compared to before using the product.

Most studies used measurements of perception of effort to swallow (easiness of swallowing) to investigate food properties, such as viscosity, hardness, cohesiveness, and adhesiveness (Chen & Lolivret, 2011; Matsuyama et al., 2021; Nyström et al., 2015).

Chen and Lolivret (2011) used a 10-level ordinal scale to evaluate swallowing easiness following consumption of 5 grams of 18 different commercial products with varied consistencies (thin liquids, thicker liquids, and puree) in 19 healthy adults (age range = 21-57 years old, *M*age = 28.7 years). The results of this research showed that as food consistency thickness increased, easiness to swallow decreased, indicating that participants perceived greater swallowing effort with thicker food consistencies (e.g., puree). Moreover, a linear relationship was identified between perceived easiness to swallow and total swallow duration, for example, foods that were easier to swallow (less effort associated with swallowing) were swallowed faster (shorter transit times). The study conducted by Nyström et al. (2015) descriptively reported the association between perceived effort to swallow 5 ml of three different laboratory-prepared liquids with oral transit time and pharyngeal transit time in 12 patients (age range = 24-84 years old; *M*age = 63 years, *SD* = 19) with dysphagia from varied etiologies. Perception of swallowing effort was assessed using a 5-point ordinal scale and transit times were evaluated via VFSS. Overall score of perceived effort to swallow (sum of all patients) indicated that as viscosity increased, the perception of effort to swallow also increased. However, individual patient scores showed that some individuals found that the thinner liquid was harder to swallow (being associated with more effort) due to their swallowing difficulty. The findings also indicated that oral and pharyngeal transit times increased as effort to swallow increased. Matsuyama et al. (2021) investigated the association between perception of swallowing effort using a VAS (0-100 mm) with physiological swallowing measurements, such as laryngeal movement (sensors on skin to detect displacement), suprahyoid muscle activity (FOM sEMG), and tongue pressure (sensors attached to the hard palate) during swallowing of 10 grams of nine laboratory-prepared gel foods in eight healthy adults (*M*age = 30 years, *SD* = 6.9). Results showed that as bolus consistency and hardness increased, effort to swallow increased. Additionally, as total duration of swallowing, laryngeal movement, FOM sEMG muscle activity, and tongue pressure during swallowing increased, perceived effort to swallow also increased.

Kays et al. (2010) examined the perception of swallowing effort using a VAS (0-100 mm) before, during, and after a meal consumption in 11 healthy younger adults (age range = 20-35 years old, *M*age = 25.7 years) and 11 healthy older adults (age range = 65-82 years old, *M*age = 70.7 years). Participants used a VAS to assess perception of effort to swallow 4 ounces of water and 4 ounces of applesauce that were administer before, mid-way, and after consumption of a meal consisting of half bagel spread with peanut butter, baby carrots, and chocolate milk. Findings indicated that perception of swallowing effort increased pre to post meal intake (*d* = 1.13), pre to mid meal consumption (*d* = 1.16), and mid to post meal intake (*d* = 0.56). Similarly, Brates and Molfenter (2021) evaluated perception of swallowing effort before and after a similar meal consumption used in the Kays et al. (2010) study, but limiting their study group to females. In the Brates and Molfenter (2021) study, 15 healthy younger females (age range = 18-35 years old, *M*age = 25.5 years, *SD* = 5.5) and 15 healthy older females (age range = 70 and older, *M*age = 77.2 years, *SD* = 5.7) used a 10-point ordinal scale to assess their perceived effort to swallow the meal (0 indicating ease to swallow/less effort and 10 indicating hard to swallow/more effort). Results did not show differences in perceived effort to swallow for any meal intake time points.

Finally, Bahia and Lowell (2022) compared perceived effort to swallow during NSs and EFSt and investigated the association between perception of swallowing effort and masseter sEMG peak amplitude during NSs and EFSs. Twenty healthy adults (age range = 18-41 years old, *M*age = 24.55 years, *SD* = 6.87) completed five normal saliva swallows and five effortful saliva swallows, rating their perception of swallowing effort after each swallow using a VAS (0-100 mm). Findings from this study indicated that perceived effort to swallow was associated with swallowing condition. Overall, perceived swallowing effort increased 63.5 mm with EFSs compared to NSs. Moreover, perceived effort to swallow was associated with masseter sEMG peak amplitude, indicating that for each 1 mm change in perceived effort to swallow, masseter sEMG peak amplitude increased by 0.6 μV.

Overall results from these studies indicate changes in perceived swallowing effort with different levels of oral lubrication, different food properties, timing differences of before and after meal intake, and when using swallowing strategies.

Additionally, changes in perceived effort to swallow were associated with objective physiological swallowing measurements, suggesting that individuals can be aware of swallowing effort when required and that their perception associates well with physiological swallowing events.

3. OBJECTIVES AND HYPOTHESES

Objective 1: *To determine the effects of the EFS on tongue-to-palate pressure and hyolaryngeal displacement in healthy individuals under two different instructional conditions, and the association between tongue-to-palate pressure and hyolaryngeal movement during swallowing.*

Tongue-to-palate pressure will be quantified using the IOPI in the anterior and posterior oral tongue positions, hyoid movement, and hyoid-larynx approximation will be measured using ultrasound to determine:

1a. To determine the individual contributions of the anterior and posterior oral tongue in pressure generation during swallowing and whether instructions for the EFSt compared with the EFSp differentially affect tongue-to-palate pressure.

Hypothesis 1a.1: The EFSs will produce *greater* tongue-to-palate pressure relative to NS. **Hypothesis 1a.2:** Pressures will differ between EFS conditions, with g*reater* pressure generation during the strategy produced with tongue to palate emphasis (EFSt) as compared to the strategy produced with pharyngeal squeezing (EFSp). **Hypothesis 1a.3:** The anterior tongue will generate *greater* pressure than the posterior tongue during NSs and effortful swallows produced with tongue emphasis (EFSst).

1b. To determine the effects of the EFS on hyolaryngeal excursion and whether instructions for the EFS emphasizing tongue-to-palate contact (EFSt) compared with those emphasizing pharyngeal squeezing (EFSp) differentially affect hyolaryngeal excursion.

Hypothesis 1b.1: The EFS will produce *greater* hyoid movement and hyoid-larynx approximation than the NS. **Hypothesis 1b.2:** The EFSt will produce *greater* hyolaryngeal displacement than the EFSp.

1c. To determine whether tongue-to-palate pressure is associated with hyoid displacement and hyoid-larynx approximation during NSs and EFSst.

Hypothesis 1c: A positive correlation will be identified between hyoid movement or hyoid-larynx approximation and tongue pressure during NSs and EFSst.

Rationale: Previous studies have demonstrated multifocal physiological changes produced by the EFS, including changes in pressure and kinematics of swallowing events, supporting its potential to increase tongue-to-palate pressure and hyolaryngeal displacement. Prior studies comparing the effects of the EFS under two different instructions highlighted that the EFSt produced *greater* differences in swallowing physiology (e.g., tongue and pharyngeal pressures) than the EFSp. Additionally, the tongue and the hyolaryngeal complex work as a functional and structural unit during swallowing, with each component affecting the movement and position of the other, thus, supporting the hypothesis that the EFSt will *increase* hyoid and larynx excursions. A linear association between tongue pressure and hyolaryngeal movement during swallowing is also anticipated. Finally, the literature has shown that anterior maximum isometric tongue pressure is greater than posterior maximum isometric tongue pressure, and that anterior swallowing pressure is higher than posterior pressure. Therefore, a similar trend in tongue pressure generation is expected during the EFS.

Objective 2: *To determine age-related differences in the effects of the EFS on tongue-to-palate pressure and hyolaryngeal displacement in healthy adults.*

Two age groups of younger (ages 18-40) and older (ages 60 and older) healthy adults will be compared to determine whether age-related changes affect strategy performance and its effects on tongue-to-palate pressure and hyolaryngeal displacement during swallowing.

Hypothesis 2: Younger adults will show *greater* tongue-to-palate pressure and hyolaryngeal displacement than older adults during NSs and EFSs.

Rationale: The literature comparing younger and older healthy adults has indicated age-related differences in several swallowing events, including maximum isometric tongue pressure, pressure during swallowing, and hyoid movement, supporting the hypotheses that tongue-to-palate pressure and hyolaryngeal displacement will be different during the EFS with advanced age.

Objective 3: *To determine the association between perceived muscle effort used during swallowing and tongue-to-palate pressure generated during swallowing.*

Perceived muscle effort during swallowing will be measured using a VAS. This measurement will be used to determine how perceived effort used to swallow (NSs and EFSst) correlates with objectively determined physiological measurement of tongue-to-palate pressure generated during swallowing.

Hypothesis 3: Perceived muscle effort to produce NSs and EFSst will positively correlate with objective tongue-to-palate pressure measurement.

Rationale: Data from a study involving 20 healthy younger adults indicated a positive correlation ($r = 0.75$) between perceived swallowing effort (VAS measurement) and sEMG peak amplitude in the oral region (Bahia & Lowell, 2022), supporting the potential association of perceived swallowing effort and oral pressures in the present study.

4. SIGNIFICANCE AND INNOVATION

Dysphagia contributes to significant functional impairments with a direct impact on quality of life. Swallowing strategies addressing long-term physiological changes may reduce clinical complications, such as malnutrition, dehydration, and aspiration pneumonia. The EFS maneuver, frequently recommended in dysphagia management, has multiple benefits for swallowing physiology with the potential to improve tongue strength and hyolaryngeal displacement. During an EFS, tongue and suprahyoid muscles are strongly activated.

Tongue muscles are essential for bolus manipulation and transport, optimizing the efficiency of the oral phase of swallowing while also improving the contact between the BOT and the PPW, which facilitates bolus clearance. Moreover, tongue weakness is a major contributing factor to dysphagia. Increased tongue-to-palate contact during the EFS may provide an anchor point from which greater anterior-superior hyolaryngeal movement can be achieved during swallowing. Suprahyoid muscles are essential for hyolaryngeal movement, which is necessary for airway protection during the pharyngeal phase of swallowing. Additionally, the anterior movement of the hyoid bone contributes to UES opening, facilitating bolus flow and clearance in the lower pharynx.

To better understand the effects of the EFS on hyolaryngeal excursion and tongue-to-palate pressure, it is imperative to study the effectiveness of the EFS across the life span. Clinical decision-making in speech-language pathology (SLP) is based on evidence-based practice that integrates the current best research evidence available in the field with clinical expertise. Studying healthy individuals across the life span offers the first level of evidence on swallowing rehabilitation. A healthy system and its normal variants (e.g., aging process) help determine the physiological changes to various swallowing parameters without the confounding elements of multiple deficits in patients with dysphagia. Moreover, investigating healthy individuals is critical to show potential benefits and undesirable effects of treatment techniques, thus providing a foundation for informed application of swallowing strategies in individuals with dysphagia. Nevertheless, initial studies clarifying the physiologic effects of the EFS and differences across the life span should be followed by studies addressing the effects of the EFS in individuals with dysphagia.

Upon completion, this study will significantly advance our clinical understanding of the physiological effects of the different types of EFSs in healthy individuals across the life span, potentially guiding treatment decisions when recommending this strategy for individuals with dysphagia. This study will determine the influence of regional tongue differences in pressure generation during swallowing and the potential contributions of the tongue in improving the movement of the hyoid bone and the larynx during swallowing. Moreover, it will identify any negative effects of the EFS in hyolaryngeal movement. These findings could impact clinical decisions regarding the appropriateness of the EFS for populations with specific swallowing deficits, how we train the EFS maneuver, and will help determine the optimal EFS instructions for each patient. Emphasizing tongue-to-palate contact or pharyngeal squeezing may impact how patients execute the strategy and could yield differences in how patients execute the strategy and its subsequent physiological effects.

This study will also extend our current knowledge of age-related differences in strategy performance, determining differences in physiologic patterns relative to oral pressure generation and hyolaryngeal displacement during the EFS, and whether older adults can appropriately complete the EFS. These results will better inform recommendations for the use of the EFS in older adults with dysphagia, potentially highlighting the need for alternative instructions or training. Lastly, this research may establish a valid, subjective tool to help patients and clinician differentiate NSs from EFSs during training, providing measures of perceived swallowing effort that relate to objectively determined physiological measurement of muscle effort. The visual analog scale (VAS) is a more widely accessible quantification method and may reflect the accuracy of the EFS during training, because it rates physical effort (e.g., tongue press to swallow) and perceived exertion (e.g., subjective individual characteristics), capturing effort in the specific moment of swallow. The VAS may therefore provide a good estimation of how hard the individuals perceives they are swallowing during the EFS based on physical sensation, helping patients to modify their level of exertion during swallowing. These overall contributions will have significant implications for the use of the EFS in rehabilitation. In addition, this study will guide evidence-based clinical practice in swallowing management, as the EFS is the most recommended swallowing strategy in dysphagia rehabilitation.

5. METHODS

5.1 Participants

5.1.1 General Characteristics

Forty heathy adults without swallowing disorders divided into two groups, younger (n = 20, ages 18-40 years) and older (n = 20, ages 60 years and older), participated in this study. Research ethics approval was obtained from the Institutional Review Board at Syracuse University (protocol #20-152). All participants provided written informed consent to participate in this study prior to data collection and they received monetary compensation for their time.

5.1.2 Inclusion and Exclusion Criteria

Inclusion criteria for all participants were as follows: (i) younger (18-40 years old) and older adults (≥60 years old), (ii) good general health condition per self-report, (iii) no history of swallowing difficulties as determined by a questionnaire and the 3-ounce Water Swallow Test (DePippo et al., 1992) performed with the researcher, (iv) on a regular diet (Functional Oral Intake Scale - FOIS = 7; Crary et al., 2005), (v) normal oral structure and function as determined by a screening performed by the researcher, (vi) no auditory comprehension disorder (Revised Token Test – RTT Subtest I ≥ 14.75 and Subtest II ≥ 14.59; McNeil & Prescott, 1978), and (vii) normal anterior maximum isometric tongue pressure as measured by the researcher using the IOPI (>40 kPa; IOPI

Medical). In addition, exclusion criteria were any history of dysphagia, neurologic disorders or trauma, head and neck cancer or surgery to the head and neck beyond routine procedures, chronic major respiratory (e.g., active pneumonia and chronic obstructive pulmonary disease) or gastrointestinal disorders (e.g., Crohn's disease), or severe voice disorders. These medical conditions can negatively impact swallowing function, and a severe voice disorder may indicate problems with vocal fold structure or function, which may impact the protection of the larynx during swallowing.

5.2 Procedures

5.2.1 Screening Procedures

An initial telephone screening determined preliminary eligibility criteria for all participants. Screening questions included age, general health status, and self-reported normal swallowing. Severe voice problems were determined perceptually by the researcher during the telephone conversation. Participants who passed the initial telephone screening were scheduled for an in-person, 2-hour session at the Voice and Swallowing Physiology Laboratory. At the start of the in-person visit, the researcher reviewed the study procedures and the consent form with each participant and answered potential questions. After participants signed the consent form, the researcher completed the following procedures: (i) a brief questionnaire regarding the participant's demographics and medical and swallowing history, (ii) the FOIS, (iii) the RTT (Subtests

I and II), (iv) an oral mechanism examination, (v) the 3-ounce Water Swallow Test, and (vi) three trials of maximum isometric tongue pressure (*Tmip*) in each bulb location (anterior and posterior) using the IOPI. The questionnaire was designed for the study and contained closed-ended questions to identify possible exclusion criteria (see Appendix A).

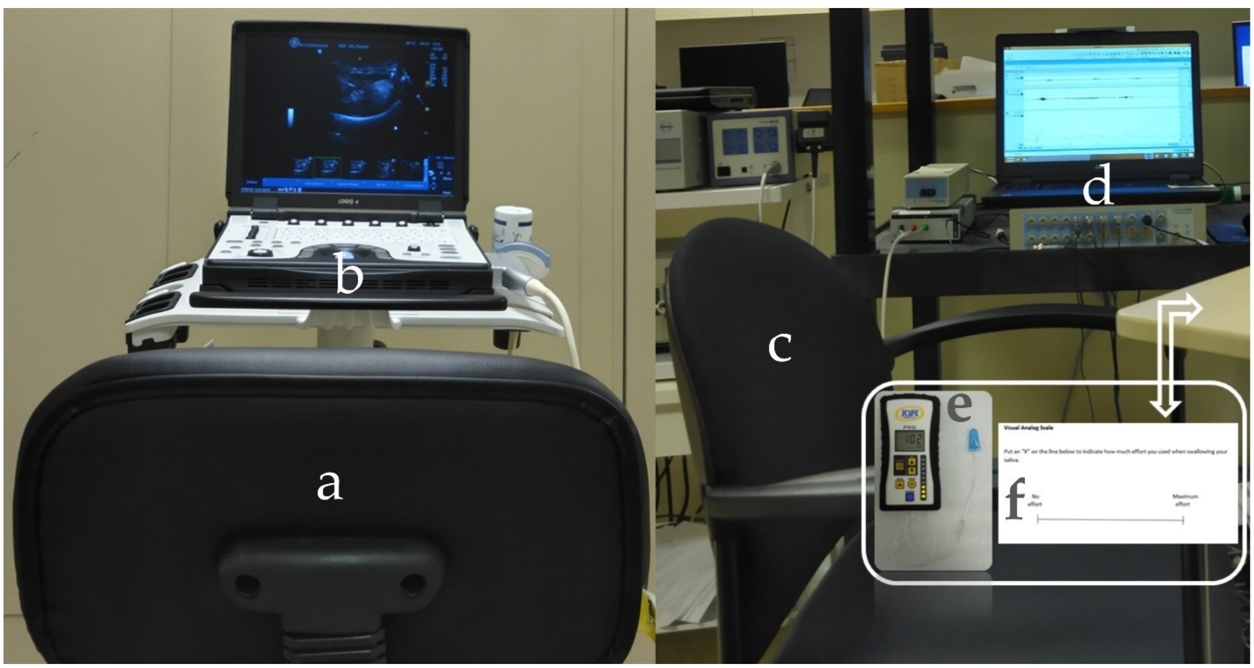
Younger and older participants had to pass the health and swallowing questionnaire, score 7 on the FOIS, pass the RTT (Subtests I and II), pass the oral mechanism examination, pass the 3-ounce Water Swallow Test, and show a maximum anterior isometric tongue pressure greater to 40 kPa.

5.2.2. Experimental Procedures

Simultaneous data acquisition using ultrasound, the IOPI, and sEMG were performed with all participants (Figure 2). Participants were blinded to the ultrasound image acquisition, IOPI's LCD screen, and the sEMG signal during the experimental procedures. Participants sat in a comfortable upright position, with the head in a neutral position. The sEMG signal was obtained from a triode self-adhesive, disposable snap electrodes (Ag/AgCl; Thought Technology Ltd., Montreal, QC, Canada; Model T3402M). The skin was prepared by light abrasion with alcohol wipes before electrode placement. Electrodes were placed on the skin on the left submental region, targeting the FOM muscles (e.g., mylohyoid, anterior belly of the digastric, and geniohyoid;

Figure 3), consistent with prior studies (Huckabee et al., 2005; Huckabee & Steele, 2006; Ng et al., 2021; Steele & Huckabee et al., 2007; Wheeler-Hegland et al., 2008; Yeates et al., 2010). Surface EMG signals were recorded and processed using a multichannel digital acquisition system and software for EMG recordings (PowerLab 16/30 and Bio Amp with LabChart 8 Pro, ADInstruments). Signals were sampled at a rate of 1000 Hz. The raw signal was filtered (50-200 Hz) and smoothed by the root mean square method.

Figure 2: Example of data collection set up.



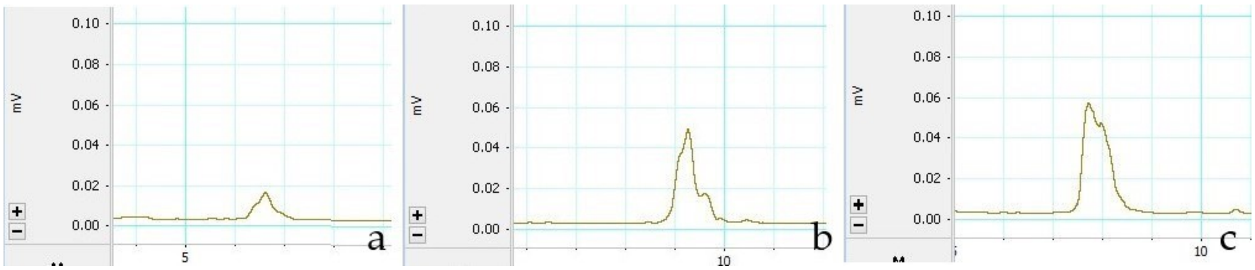
Notes: a: researcher's chair. b: ultrasound machine. c: participant's chair. d: surface electromyography computer and software. e: Iowa Oral Performance Instrument with tongue bulb. f: visual analog scale.

Figure 3: Example of sEMG electrode placement in the submental region.

Notes: The two recording electrodes were positioned longitudinally on the left, anterior neck, slightly away from midline, between the mental spine of the mandible and the hyoid bone. The reference electrode was positioned to the left side.

Surface EMG signals were used to verify that participants performed each EFS trial at or above muscle activation criterion level relative to their NS trials (doubling the submental sEMG peak amplitude). Surface EMG signals were also used for training the EFSs, providing an objective visual target as feedback for participants to facilitate the motor learning process of the EFSs (Figure 4). Participants practiced the EFS until reaching a criterion of three trials that doubled the submental sEMG peak amplitude relative to the average peak amplitude produced in their three NSs (Wheeler-Hegland et al., 2008). During the training period, participants observed their real-time sEMG signal throughout each swallowing trial. A guideline was placed on the display screen to demonstrate the target peak amplitude that participants needed to achieve during each swallow. Furthermore, participants were encouraged to increase their swallowing peak amplitude until the specific target was reached or exceeded.

Figure 4: Example of submental sEMG signal.



Notes: a: normal saliva swallow (peak amplitude = 0.013 mV). b: effortful saliva swallow produced with tongue emphasis (peak amplitude = 0.045 mV). c: effortful saliva swallow produced with pharyngeal squeezing (peak amplitude = 0.053 mV) in the same participant.

The IOPI (IOPI Pro, IOPI Medical LLC) was used to measure tongue-to-palate pressure during swallowing with the pressure sensing bulb located in the anterior and posterior tongue regions. The adult human tongue has different regional tissue composition, arrangement, and concentration (Miller et al., 2002; Stål et al., 2003). For example, the anterior tongue region has a higher concentration of adipose and connective tissue, whereas the mid and posterior tongue has a higher concentration of muscle tissue (Miller et al., 2002). Additionally, investigations of the composition of muscle fiber types indicate that the anterior tongue has predominantly fast contracting fibers (type II) for low force tasks (small diameter fibers), and the posterior tongue has slow contracting fibers (type I) for longer duration and greater force (large diameter; Stål et al., 2003). Moreover, studies show that fatigue-resistant muscle fibers are found throughout all tongue regions. These regional differences in lingual muscle fiber types reflect the complexity of tongue function and its multiple roles in speech, swallowing, and breathing. Therefore, both anterior and posterior tongue pressure against the hard palate were measured during NSs and EFSs to account for regional tongue differences that may influence tongue pressure generation.

The experimenter placed the bulb at the desired location and instructed participants to hold it in place with the tongue against the palate before and during each swallow trial. For consistent bulb placement across swallows, a mark was placed on the tongue bulb tubing indicating its depth within the oral cavity. The anterior bulb was placed in the midline between the alveolar ridge (behind the central incisors) and the anterior tongue surface, and participants pressed the bulb with the tip of their tongue. The posterior bulb was placed in the midline between the end of the hard and the tongue dorsum, and participants pressed the bulb with their posterior tongue dorsum. Participants were also instructed to not bite or suck the bulb before, during, and after swallowing.

A portable ultrasound system (GE NextGen LOGIQ eR7, GE Healthcare) was used in the B-mode imaging function with a curved-array transducer (C1-5 MHz) and a liner-array transducer (L4-12 MHz). A liberal amount of ultrasound gel (Parker Aquasonic 100 ultrasound transmission gel) was applied to the transducers before image acquisition. The curved-array transducer was placed under the chin in the right sagittal position to visualize the acoustic shadow of the hyoid bone and the mandible.

The liner-array transducer was placed in the sagittal position, slightly away from the midline, for visualization of the acoustic shadow of the hyoid bone and the thyroid cartilage (Figure 5).

Figure 5: Placement of ultrasound transducers.

Notes: a: curved-array transducer placed in the submental region. b: liner-array transducer placed in the laryngeal region.

Minimal pressure was applied with the transducer to avoid the effects of compression on swallowing biomechanics. Ultrasound parameters (e.g., depth, frequency, and contrast) were adjusted at the start of the experimental recordings for each participant to accommodate individual anatomy and achieve optimal data acquisition, and then held constant for all trials. An ultrasound recording (at a rate of 30 fps) was obtained for each swallow trial of each condition, and the video recordings were de-identified and stored for subsequent analysis.

Participants completed four sets of three normal saliva swallows during data acquisition with a 30 to 45-second rest interval between each trial. Additionally, participants drank a small sip of water before each trial to facilitate their ability to generate saliva swallows. Before each swallow, the researcher instructed participants to gather some saliva. After a 5-second delay to quiet muscle activity, participants were then cued to swallow their saliva. Following each swallow, recordings continued for 5 to 10 seconds for structures and muscle activity to fully return to resting status. Still frame images used for comparison of swallowing to rest position in the ultrasound analysis described below were generated from the rest period that followed each swallow trial to avoid the pre-swallow positioning that occurs when participants gather and hold their saliva before each swallow.

Swallowing tasks were distributed as follows: (1) 3 NSs with the IOPI bulb located in the anterior position with the ultrasound curved-array transducer in the submental region, (2) 3 NSs with the IOPI bulb located in the posterior position with the ultrasound curved-array transducer in the submental region, (3) 3 NSs with the IOPI bulb located in the anterior position with the ultrasound linear-array transducer in the laryngeal region, and (4) 3 NSs with the IOPI bulb located in the posterior position with the ultrasound linear-array transducer in the laryngeal region. Normal swallows were recorded before the training of the EFSs for all participants to avoid potential contamination effects of increased muscle effort from the EFSs to the NSs. The sets of swallows were counterbalanced and randomly assigned to each participant to control for possible order effects.

Next, participants practiced the EFSs using sEMG as biofeedback. For the EFS tasks, participants were instructed: "as you swallow, squeeze hard with your tongue" (EFSt) and "as you swallow, squeeze hard with your throat" (EFSp). After participants achieved criterion level for their EFS performance, they completed four sets of three experimental EFSs with tongue-to-palate emphasis (two for each of the anterior and posterior tongue region measurement locations) and two sets of three experimental EFSs with pharyngeal squeezing emphasis (only targeting the anterior tongue region measurement location). Participants had a resting interval of 45 seconds between EFSs to avoid muscle fatigue and drank a small sip of water between each trial. The researcher visually inspected the submental sEMG peak amplitude after each EFS to ensure correct task performance at or above muscle activation criterion level relative to their NS trials. The sets of swallows were counterbalanced and randomly assigned to each participant to control for possible order effects. During the EFSp, pressure measurements were collected only in the anterior tongue region due to concerns with muscle fatigue in the production of many EFSs. Additionally, this swallowing condition (EFSp) involved emphasis of neck/throat muscles, not tongue muscles (Huckabee & Steele, 2006; Steele & Huckabee, 2007). Thus, the EFSp was not anticipated to be the best maneuver to determine regional differences in tongue pressure.

Although muscle fatigue due to the production of sequential EFSs was not reported in the literature, swallowing-related fatigue may affect tongue pressure generated during swallowing, especially in older adults. In healthy adults, eating a meal reduced maximum anterior isometric tongue pressure (tongue strength) and tongue pressure during swallowing in older adults but not in younger adults (Brates & Molfenter, 2021). However, other swallowing parameters did not change, for example, maximum posterior isometric tongue pressure, tongue endurance, and mastication cycles. After intense endurance exercises to promote tongue fatigue, Brates and Molfenter (2021) found that the only difference in meal consumption (without and with fatigue) was decreased maximum posterior isometric tongue pressure in both younger and older healthy adults. Contrarily, Kays et al. (2010) reported a reduction in both anterior and posterior tongue strength and endurance in younger and older individuals after a meal. The authors assessed if a regular meal, considered an endurance task, would produce muscle fatigue.

Lastly, after each swallowing trial, individuals rated how much perceived muscle effort they used when swallowing their saliva by marking a VAS, consisting of a 100 mm horizontal, undifferentiated line anchored with no effort (0 mm) and maximum effort (100 mm) descriptors. Effort used to swallow can be described as the perceived exertion of an individual to a swallowing task (e.g., NS or EFS). Therefore, swallowing effort is a perceptual parameter experienced by the individual during swallowing rather than a physiological parameter. Each individual can perceive effort used to swallow differently even when completing similar tasks because many factors may influence perception, such as psychosocial, physical, and physiological variables (Baldner et al., 2015; Hunter et al., 2020). This description of swallowing effort is derived from studies addressing perceived vocal effort, which underscores the multidimensional nature of perceived effort measures (Baldner et al., 2015; Hunter et al., 2020).

The VAS is a well-established continuous scale for perceptual measurement of voice quality and effort, showing better validity than ordinal or interval scales (Baldner et al., 2015; Eadie & Doyle, 2002; Kempster et al., 2009). It better represents perceptual judgments due to its flexibility and continuum representation than scales using equal intervals for rating. In swallowing, the VAS has been used to rate patients' perception of swallowing difficulty (Bofill-Soler et al., 2020; Wallace et al., 2000), clinicians' perception of residue severity on instrumental evaluation (Pisegna et al., 2017), and participant's perception of swallowing effort (Bahia & Lowell, 2022; Kays et al., 2010; Matsuyama et al., 2021; Rogus-Pulia et al., 2018). The VAS can be a valid measurement of perceptual effort during swallowing, combining the multifaceted mechanisms involved in effort quantification, such as cognitive-behavioral and physiological influences (Baldner et al., 2015; Hunter et al., 2020). Perceived effort during NSs and EFSst using a VAS was found to be associated with objectively measured swallowing muscle activity (masseter sEMG peak amplitude; Bahia & Lowell, 2022).

5.3 Outcome Measures and Data Analysis

All experimental procedures to determine primary and secondary outcome measures were completed in one 2-hour visit. All ultrasound images and VAS scores were de-identified and randomly coded for subsequent measurement. Two independent evaluators performed ultrasound and VAS measurements, blinded to swallowing conditions (NSs vs. EFSs) and participants. The primary evaluator analyzed 100% of the data, whereas a secondary evaluator analyzed a randomly selected subset of 10% of the data for inter-rater reliability computation. Additionally, 10% of the data were randomized and re-assessed by the primary evaluator for intra-rater reliability.

Tongue-to-palate pressures during swallowing were collected from the numeric output of the IOPI's LCD screen after each swallow during data collection. The maximum isometric tongue pressure ($Tmip$) was the greatest pressure across three elicited trials in each bulb location (Pitts et al., 2018). The following measures were derived:

(i) Maximum isometric tongue pressure ($Tmip$): defined as the greatest pressure exerted on the tongue bulb via tongue-to-palate contact across three trials;

(ii) Peak tongue pressure during swallowing ($Tpeak$): defined as the peak pressure exerted on the tongue bulb during swallowing, and measured for each tongue region (anterior and posterior);

(ii) Percentage of peak tongue pressure ($T\%peak$): calculated as $\left(\frac{Tpeak}{Tmip}\right) x\ 100$, and computed for each tongue region.

For hyolaryngeal displacement measures using ultrasound, built-in software incorporating electronic calipers to generate distance measures in *cm* was used. Sonographic settings include depth measurement, and when computing distance measures as a change from rest position within an individual, no additional systematic calibration methods are required. The video recordings were reviewed frame by frame to select still frames for subsequent analysis. Still frames that showed appropriate image contrast to identify the shadow of the hyoid and the thyroid cartilage *at rest* were selected from the period after each swallow. Frame by frame inspection of the 4-5 frames representing the period directly before and after the swallow response determined the single frame with *maximum displacement* of the hyoid bone and the thyroid, which were then extracted for further analysis. For measuring the hyoid bone displacement during swallowing, two reference points were identified, (1) the juncture of the acoustic shadow of the mandible (mental spine) and the geniohyoid muscle, and (2) the anterior-superior hypoechoic boundary of the shadow cast by the hyoid bone (Figure 6). Then, the following measures were calculated:

Hyoid bone:

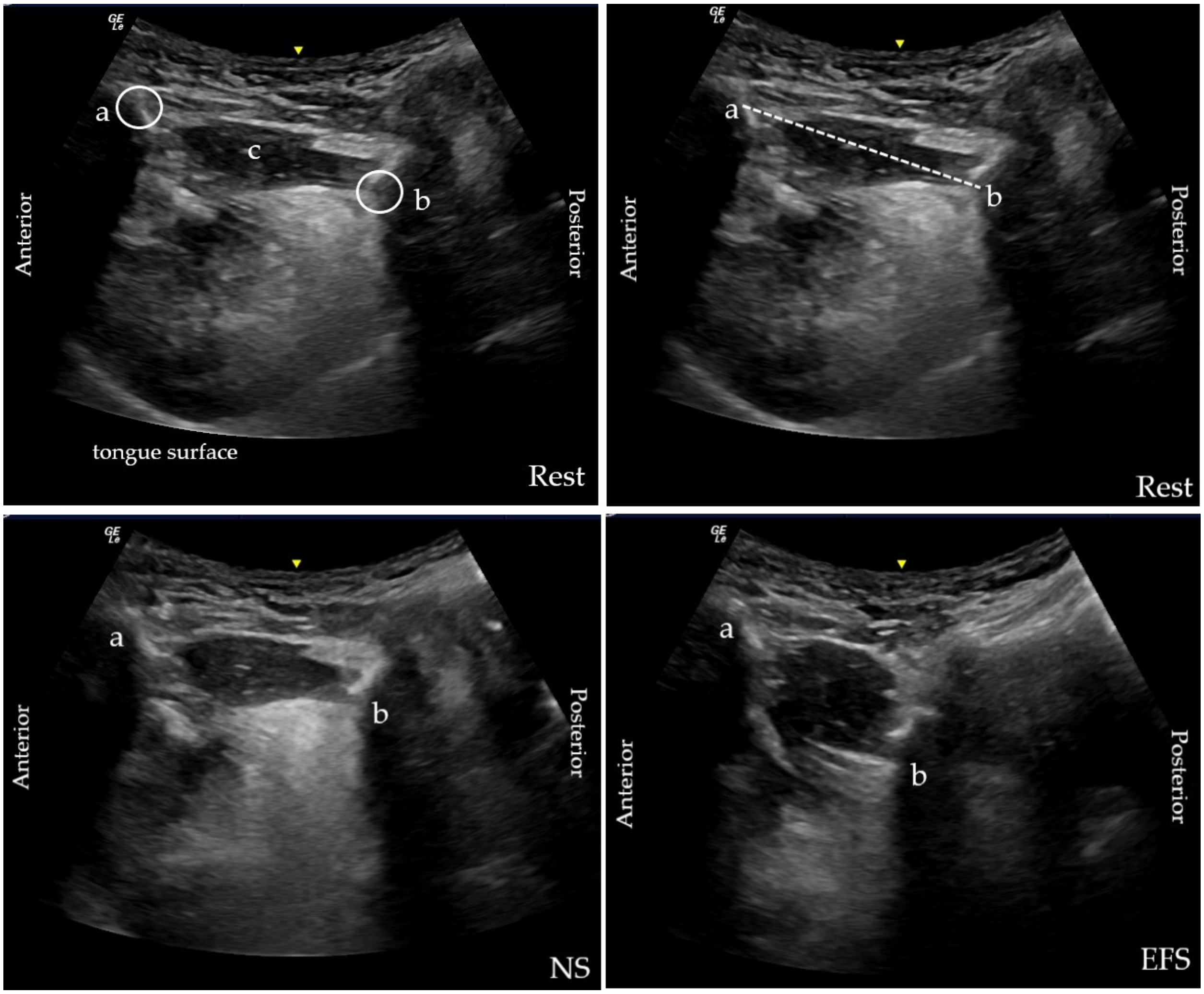
(i) Rest distance ($Hrest$): defined as the rest distance between the mandible and the hyoid bone;

(ii) Swallow distance ($Hswallow$): defined as the distance between the mandible and the hyoid bone during the swallow, and representing the position achieved at maximum hyoid excursion;

(iii) Displacement ($Hchange$): calculated as ($Hrest - Hswallow$);

(iv) Percent change ($H\%change$): calculated as $\left(\frac{Hchange}{Hrest}\right) x\ 100$.

Figure 6: Example of ultrasound still images of hyoid-mandible distance.



Notes: a: the juncture of the acoustic shadow of the mandible and the geniohyoid muscle. b: anterior-superior boundary of the shadow cast by the hyoid bone. c: geniohyoid muscle. Superior panels show the anatomical landmarks for measurement and example of the caliper placements. Inferior panels exemplify a normal swallow (NS) and an effortful swallow (EFS).

For measuring hyoid-larynx approximation, the reference points were (1) the angular, posterior border of the shadow cast by the hyoid bone and (2) the parallel point, determined by a straight horizontal line drawn from the hyoid reference point to the anterior border of the shadow cast by the thyroid cartilage (Figure 7). The following measures were calculated using the electronic ultrasound calipers:

(i) Rest distance ($HLrest$): defined as the rest distance between the hyoid bone and the thyroid cartilage;

(ii) Swallow distance ($HLswallow$): defined as the distance between the hyoid bone and the thyroid cartilage during the swallow, and representing the position achieved at maximum hyoid-larynx approximation;

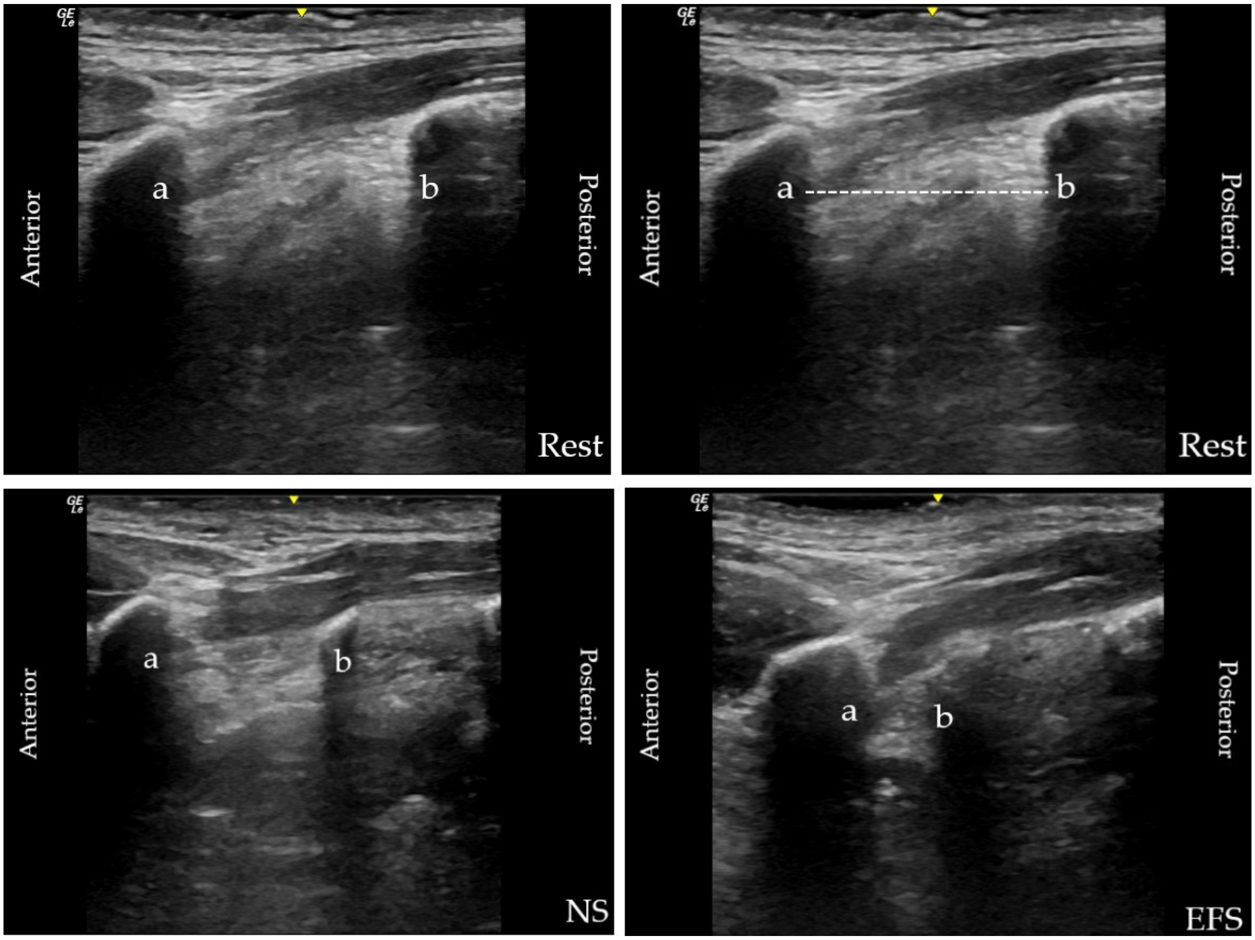
(iii) Approximation ($HLchange$): calculated as ($HLrest - HLswallow$);

(iv) Percentage change ($HL\%change$): calculated as $\left(\frac{HLchange}{HLrest}\right) x\ 100$.

The VAS was used to assess self-perceived effort used to swallow. The evaluators used a ruler to measure where participants marked the effort to swallow from 0 to 100 mm in increments of 0.5 mm. The following formula was used to normalize the VAS measurements:

(i) Normalization of the VAS ($VASnorm$): calculated as $\left(\frac{VASm - VASmin}{VASmax - VASmin}\right) x\ 100$, where $VASm$ is where the participant marked the effort to swallow, $VASmin$ is the minimum effort to swallow marked by the participant across all trials, and $VASmax$ is the maximum effort to swallow marked by the participant across all trials.

Figure 7: Example of ultrasound still images of hyoid-larynx distance.



Notes: a: the angular, posterior border of the shadow cast by the hyoid bone. b: the parallel point from the hyoid bone to the anterior border of the shadow cast by the thyroid cartilage. Superior panels show the anatomical landmarks for measurement and example of the caliper placements. Inferior panels exemplify a normal swallow (NS) and an effortful swallow (EFS).

5.4 Statistical Analysis

Statistical analyses were performed using R statistical package. Means and standard deviations (e.g., age, RTT, and $Tmip$) and percentages (e.g., sex) were calculated to characterize the participants. Mean differences for anterior and posterior $Tmip$ between younger and older groups were investigated using t-tests for independent samples.

Inter- and intra-rater reliability of the swallowing biomechanics ($H\%change$ and $H\%change$) and perceived effort to swallow (absolute VAS) were analyzed using intraclass correlation coefficients (ICCs). Intra-rater reliability was calculated from measures made by the primary investigator during two separate rating occasions, whereas inter-rater reliability was obtained from an independent evaluator.

The hierarchical multivariate regression models presented in this section account for potential dependence of repeated measures within each participant. The individual effect of each participant included in the regression models helps to control for individual characteristics of the participants, such as anatomy and sex differences. Full results of each regression model including all coefficients are available in the Appendices. The individual participant intercepts shown in the tables represent the mean differences between each participant and the reference participant (participant 1 in the older group) under the reference condition. Moreover, the regression coefficients indicate the effect size in the same units as the dependent variables. Finally, regression diagnostics were performed to check the assumptions of normality of the residuals (normal Q-Q plot and kernel density plot) and homoscedasticity (residual vs. fitted plot) for each model. The plots are available in the Appendices. Robust standard error (HC3) calculations were also performed to check for homoscedasticity and to correct the standard errors if heteroscedasticity is present. A reference alpha level of 0.05 was adopted in all multivariate regression models and repeated measures correlations.

5.4.1 Tongue Pressure Generation

5.4.1.1 The effects of the EFS on tongue-to-palate pressure (Objective 1, Hypotheses 1a.1 and 1a.2)

To determine whether EFSst and effortful swallows produced with pharyngeal squeezing (EFSsp) generated greater tongue-to-palate pressure than NSs and whether instructions for the EFSs differently affected tongue-to-palate pressure, a multivariate regression model including the individual effect of each participant was used to estimate the contributions of each type of EFS on tongue pressure. The following regression model [1] was used to fit the data:

$$T\%peak_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \epsilon_{in} \quad [1]$$

where $T\%peak_{in}$ is the dependent variable for each participant (*i*) and swallow (*n*), α_i represents the random effect of each participant, $EFSp_{in}$ and $EFSt_{in}$ are the independent variables for each participant and swallow, β_1 and β_2 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In this model, NS is the reference condition. Therefore, coefficients β_1 and β_2 represent the mean difference in the dependent variable between NSs and EFSsp and EFSst, respectively.

5.4.1.2 The effects of swallowing on anterior and posterior tongue-to-palate pressures (Objective 1, Hypothesis 1a.3)

To determine the contributions of the anterior and posterior tongue regions in pressure generation during NSs and EFSst, two separate and similar multivariate regression models [2] were used for each swallow condition:

$$T\%peak_{in} \; = \alpha_i + \beta_1 Posterior_{in} + \epsilon_{in} \text{ [2]}$$

where $T\%peak_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $Posterior_{in}$ is the independent variable for each participant and swallow, representing pressure generation produced in the posterior tongue region, β_1 is the regression coefficient to be estimated, and ϵ_{in} is the model random error. In this model, pressure generated in the anterior tongue region is the reference condition.

5.4.1.3 Age-related differences in the effects of the EFS on tongue-to-palate pressure (Objective 2, Hypothesis 2)

The last multivariate regression model for tongue-to-palate pressure determined age-related differences in the effects of the EFS on tongue-to-palate pressure during swallowing [3]:

$$T\%peak_{in} \; = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \beta_3 YOUNGER_i$$

$$+(\beta_4 EFSp_{in} \times YOUNGER_i) + (\beta_5 EFSt_{in} \times YOUNGER_i) + \epsilon_{in} \text{ [3]}$$

where $T\%peak_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $EFSp_{in}$ and $EFSt_{in}$ are the independent variables for each participant and swallow, $YOUNGER_i$ is the independent variable for each participant, representing the younger group, $(EFSp_{in} \times YOUNGER_i)$ and $(EFSt_{in} \times YOUNGER_i)$ are the interaction terms of the dummy variable, β_1, β_2, β_3, β_4, and β_5 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In this model, the NS condition and older group are the reference conditions. Therefore, β_1 and β_2 represent the mean difference in the dependent variable between NSs and, EFSsp and EFSst, respectively, for older adults only. Similarly, β_3 represents the mean difference between older and younger adults in NSs only. Coefficients β_4 and β_5 capture interactions between effects and should be interpreted as differences of differences; for instance, β_4 represents the mean difference between older and younger adults in the mean change in the dependent variable when comparing NSs and EFSsp.

5.4.2 Hyolaryngeal Movement

5.4.2.1 The effects of the EFS on hyoid displacement (Objective 1, Hypotheses 2a.1 and 2a.2)

To determine whether EFSst and EFSsp generated greater hyoid displacement and hyoid-larynx approximation than NSs and whether instructions for the EFSs differently affected hyoid displacement and hyoid-larynx approximation, multivariate regression models including the individual effect of each participant were used to estimate the contributions of each type of EFS on hyolaryngeal movement. The following regression models [4] and [5] were used to fit the data:

$$H\%change_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \epsilon_{in} \text{ [4]}$$

$$HL\%change_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \epsilon_{in} \text{ [5]}$$

where $H\%change_{in}$ and $HL\%change_{in}$ are the dependent variables for each participant (i) and swallow (n), α_i represents the random effect of each participant, $EFSp_{in}$ and $EFSt_{in}$ are the independent variables for each participant and swallow, β_1 and β_2 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In these models, NS is the reference condition. Additionally, to determine whether tongue pressure generated in different tongue regions differently affected hyoid displacement and hyoid-larynx approximation during NSs and EFSst, multivariate regression models [6] and [7] were used as follows:

$$H\%change_{in} = \alpha_i + \beta_1 EFSt_{in} + \beta_2 POSTERIOR_{in} + (\beta_3 EFSt_{in} \times POSTERIOR_{in}) + \epsilon_{in} \text{ [6]}$$

$$HL\%change_{in} = \alpha_i + \beta_1 EFSt_{in} + \beta_2 POSTERIOR_{in} + (\beta_3 EFSt_{in} \times POSTERIOR_{in}) + \epsilon_{in} \text{ [7]}$$

where $H\%change_{in}$ and $HL\%change_{in}$ are the dependent variables for each participant (i) and swallow (n), α_i represents the random effect of each participant, $EFSt_{in}$ and $Posterior_{in}$ are the independent variables for each participant and swallow, $(EFSt_{in} \times POSTERIOR_{in})$ is the interaction term of the dummy variable, β_1, β_2, and β_3 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In these models, NS and pressure generated in the anterior tongue region are the reference conditions.

5.4.2.2 Age-related differences in the effects of the EFS on hyoid-larynx approximation (Objective 2, Hypothesis 2)

The last multivariate regression models for hyolaryngeal movement determined age-related differences in the effects of the EFS on hyoid displacement and hyoid-larynx approximation [8] and [9].

$$H\%change_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \beta_3 YOUNGER_i$$

$$+(\beta_4 EFSp_{in} \times YOUNGER_i) + (\beta_5 EFSt_{in} \times YOUNGER_i) + \epsilon_{in} \quad [8]$$

$$HL\%change_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \beta_3 YOUNGER_i$$

$$+(\beta_4 EFSp_{in} \times YOUNGER_i) + (\beta_5 EFSt_{in} \times YOUNGER_i) + \epsilon_{in} \quad [9]$$

where $H\%change_{in}$ and $HL\%change_{in}$ are the dependent variables for each participant (i) and swallow (n), α_i represents the random effect of each participant, $EFSp_{in}$ and

$EFSt_{in}$ are the independent variables for each participant and swallow, $YOUNGER_i$ is the independent variable for each participant, ($EFSp_{in} \times YOUNGER_i$) and ($EFSt_{in} \times YOUNGER_i$) are the interaction terms of the dummy variable, β_1, β_2, β_3, β_4, and β_5 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In these models, the NS condition and older group are the reference conditions.

5.4.3 Perceived Effort to Swallow

A multivariate repression model was also used to determine whether perceived effort to swallow during EFSst and EFSsp was greater than during NSs, as follows [10]:

$$VASnorm_{in} = \alpha_i + \beta_1 EFSp_{in} + \beta_2 EFSt_{in} + \epsilon_{in} \quad [10]$$

where $VASnorm_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $EFSp_{in}$ and $EFSt_{in}$ are the independent variables for each participant and swallow, β_1 and β_2 are the regression coefficients to be estimated, and ϵ_{in} is the model random error. In this model, NS is the reference condition.

5.4.4 Associations

5.4.4.1 Association between tongue pressure and hyoid displacement (Objective 1, Hypothesis 1c)

Repeated measures correlation was used to determine the associations between tongue pressure ($T\%peak$) and hyoid displacement ($H\%change$) during NSs and EFSst. Moreover, a multivariate regression model [11] was used to determine how tongue pressure ($T\%peak$) affects hyoid displacement ($H\%change$) during NSs and EFSst, as follows:

$$T\%peak_{in} = \alpha_i + \beta_1 H\%change_{in} + \epsilon_{in} \quad [11]$$

where $T\%peak_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $H\%change_{in}$ is the independent variable for each participant and swallow, β_1 is the regression coefficient to be estimated, and ϵ_{in} is the model random error.

5.4.4.2 Association between tongue pressure and hyoid-larynx approximation (Objective 1, Hypothesis 1c)

Repeated measures correlation was used to determine the associations between tongue pressure ($T\%peak$) and hyoid-larynx approximation ($HL\%change$) during NSs and EFSst. Additionally, a multivariate regression model [12] was used to determine how tongue pressure ($T\%peak$) affects hyoid-larynx approximation ($HL\%change$) during NSs and EFSst, as follows:

$$T\%peak_{in} = \alpha_i + \beta_1 HL\%change_{in} + \epsilon_{in} \ [12]$$

where $T\%peak_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $HL\%change_{in}$ is the independent variable for each participant and swallow, β_1 is the regression coefficient to be estimated, and ϵ_{in} is the model random error.

5.4.4.3 Association between tongue pressure and perceived effort to swallow (Objective 3, Hypothesis 3)

Repeated measures correlation was used to determine the association between tongue pressure ($T\%peak$) during NSs and EFSst and perceived effort to swallow ($VASnorm$). Moreover, a multivariate regression model [13] was used to determine how tongue pressure ($T\%peak$) affects perceived effort to swallow ($VASnorm$) during NSs and EFSst, as follows:

$$T\%peak_{in} = \alpha_i + \beta_1 VASnorm_{in} + \epsilon_{in} \ [13]$$

where $T\%peak_{in}$ is the dependent variable for each participant (i) and swallow (n), α_i represents the random effect of each participant, $VASnorm_{in}$ is the independent variable for each participant and swallow, β_1 is the regression coefficient to be estimated, and ϵ_{in} is the model random error.

6. RESULTS

6.1 Overview of Participants

A total of 40 healthy adults participated in this study (32 females, 8 males). Participants represented two different groups: a younger age group (n = 20, *Mage* = 21.95 years, *SD* = 4.43, range = 18-36 years) and an older age group (n = 20, *Mage* = 70.10 years, *SD* = 4.30, range = 62-79 years). Per inclusion/exclusion criteria, all participants had normal swallowing skills as evidenced on a swallowing screening test, were eating a normal diet (FOIS maximum score of 7), had normal anterior tongue strength (*Tmip*) per IOPI screening, showed normal oral structure and function as determined by an oral mechanism screening, were in good general health, and had normal auditory comprehension skills (RTT test). Baseline performance group means for the two screening measures that involved quantitative scores beyond pass/fail are summarized in Table 3. Similar auditory comprehension scores in the RTT (subtests I and II) and posterior *Tmip* were demonstrated between groups. However, significantly higher anterior *Tmip* was found in the younger group compared to the older group. Anterior *Tmip* ranged from 41 to 91 kPa in younger participants and from 41 to 72 kPa in older adults, whereas posterior *Tmip* varied from 33 to 87 kPa in the younger group and from 28 to 67 kPa in the older group.

Table 3: Characteristics of the participants.

Group (n)	Younger (20) *Mean (SD)*	Older (20) *Mean (SD)*
Age [years]	21.95 (4.43)	70.10* (4.30)
Sex [count]		
Female	18 or 90%	14 or 70%
Male	2 or 10%	6 or 30%
Revised Token Test		
Subtest I	15.00 (0.00)	15.00 (0.00)
Subtest II	15.00 (0.00)	15.00 (0.02)
$Tmip$ [kPa]		
Anterior $Tmip$	64.30 (12.48)	54.05* (8.89)
Posterior $Tmip$	56.90 (15.40)	51.80 (12.18)

n: number of participants. *SD*: standard deviation. $Tmip$: maximum isometric tongue pressure. Notes: Revised Token Test maximum scores for subtests I and II are 15. Anterior $Tmip$ is considered normal above 40 kPa. Significant differences between younger and older groups are indicated by * ($p<0.05$) on t-test for independent samples.

6.2 sEMG Training

All participants accurately performed the EFSs during the training and experimental procedures, achieving the criterion of doubling the FOM sEMG peak amplitude relative to their NSs. In the practice trials, the younger participants needed less training to complete the required three consecutive EFSs for both types of the maneuver (EFSt: with tongue emphasis, EFSp: with pharyngeal squeezing) than the older adults. In the EFSt, ten younger adults completed the three consecutive swallows without any additional practice needed (3 out of 3 trials), six individuals performed up to six practice swallows, and four completed more than six practice swallows (up to 14 swallows) to reach the three consecutive swallows' criterion. In the EFSp, ten younger participants completed the three consecutive swallows without any additional practice needed (3 out of 3 trials), four individuals performed up to six practice swallows, and six completed more than six practice swallows (up to 12 swallows). In the older group, the three consecutive EFSs produced with tongue emphasis (EFSst) were achieved in the first attempt (3 out of 3 trials) by five individuals, seven participants completed up to six practice swallows, and eight performed more than six practice swallows (up to 19 swallows). In the EFSp, five older individuals completed the three consecutive swallows without any additional practice needed (3 out of 3 trials), seven participants performed up to six practice swallows, and eight completed more than six practice swallows (up to 23 swallows).

6.3 Reliability

Intraclass correlation coefficients for intra-rater reliability were excellent (Koo & Li, 2016) for perceived swallowing effort (absolute VAS) measures, $H\%change$, and $HL\%change$. Inter-rater reliability coefficients were excellent for the absolute VAS measurements, good for the $H\%change$, and moderate for $HL\%change$ (Koo & Li, 2016; Table 4).

Table 4: Intra- and inter-rater reliability for perceived effort to swallow and ultrasound measures.

Variables	Intra-rater Reliability			Inter-rater Reliability		
	ICC	p-value	95% CI	ICC	p-value	95% CI
VAS	0.997	<0.001	0.98-1.0	0.999	<0.001	0.98-1.0
$H\%change$	0.981	<0.001	0.97-0.99	0.861	<0.001	0.84-0.93
$HL\%change$	0.998	<0.001	0.98-1.0	0.746	<0.001	0.67-0.87

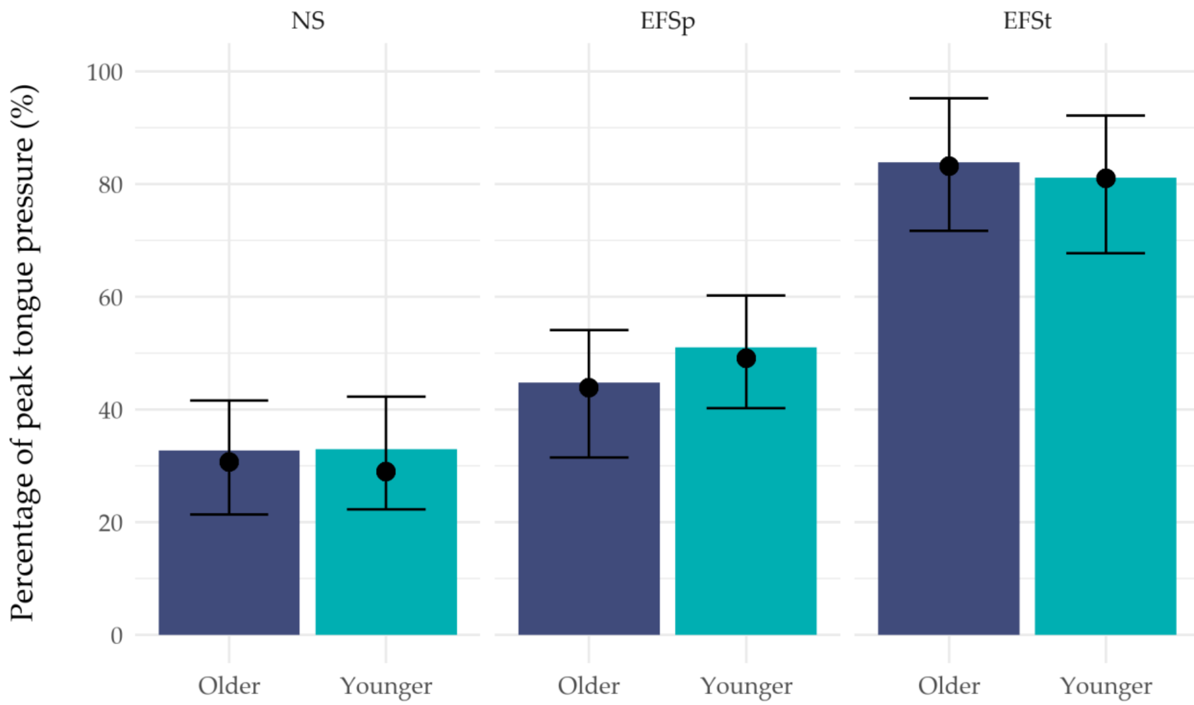
ICC: intraclass correlation coefficient. CI: confidence interval. VAS: visual analog scale. $H\%change$: percent change of hyoid displacement. $HL\%change$: percent change of hyoid-larynx approximation.

6.4 Tongue Pressure Generation

6.4.1 The Effects of the EFS on Tongue-to-Palate Pressure (Objective 1, Hypotheses 1a.1 and 1a.2)

For all analyses including tongue-to-palate pressure, a total of 1200 swallows were used. Aggregating anterior and posterior tongue regions, $Tpeak$ (peak tongue pressure during swallowing) ranged from 2 to 46 kPa (*M* = 18.28 kPa, *SD* = 8.29) for NSs, from 5 to 61 kPa (*M* = 28.55 kPa, *SD* = 11.66) for EFSsp (effortful swallows produced with pharyngeal squeezing), and from 19 to 82 kPa (*M* = 46.22 kPa, *SD* = 12.66) for EFSst (effortful swallows produced with tongue emphasis). The aggregated $T\%peak$ (percentage of peak tongue pressure during swallowing) ranged from 4.88 to 84.21% (*M* = 32.90%, *SD* = 14.86) for NSs, from 9.26 to 90.74% (*M* = 9.26%, *SD* = 16.35) for EFSsp, and from 40.70 to 148.65% (*M* = 82.51%, *SD* = 18.39) for EFSst. The comparison of mean $T\%peak$ between younger and older participants is presented in Figure 8.

Figure 8: Mean percentage of peak tongue pressure ($T\%peak$) by swallowing condition and group.



	NS Older	NS Younger	EFSp Older	EFSp Younger	EFSt Older	EFSt Younger
Mean	32.8	33.0	44.8	51.1	83.8	81.2
Median	30.7	29.0	43.8	49.1	83.2	81.0
Min	4.9	10.4	9.3	19.4	42.0	40.7
Max	78.4	84.2	79.7	90.7	148.6	129.5

Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Mean $T\%peak$, aggregating anterior and posterior tongue regions, was greater during EFSst and EFSsp than NSs (Objective 1a, hypothesis 1a.1; Table 5). Regression coefficient estimates (regression model [1]) showed that $T\%peak$ values during EFSst were on average 49.6 percentage points greater than the average $T\%peak$ of NSs. Similarly, mean $T\%peak$ values during EFSsp were on average 15.0 percentage points greater than the average $T\%peak$ of NSs (R^2 = 0.78; p<0.001). Additionally, the $T\%peak$ values during EFSst were on average 34.6 percentage points greater than the average $T\%peak$ of EFSsp (t = 25.63; p<0.001; Objective 1a, hypothesis 1a.2).

Table 5: Regression results of the percentage of peak tongue pressure ($T\%peak$) by swallowing condition.

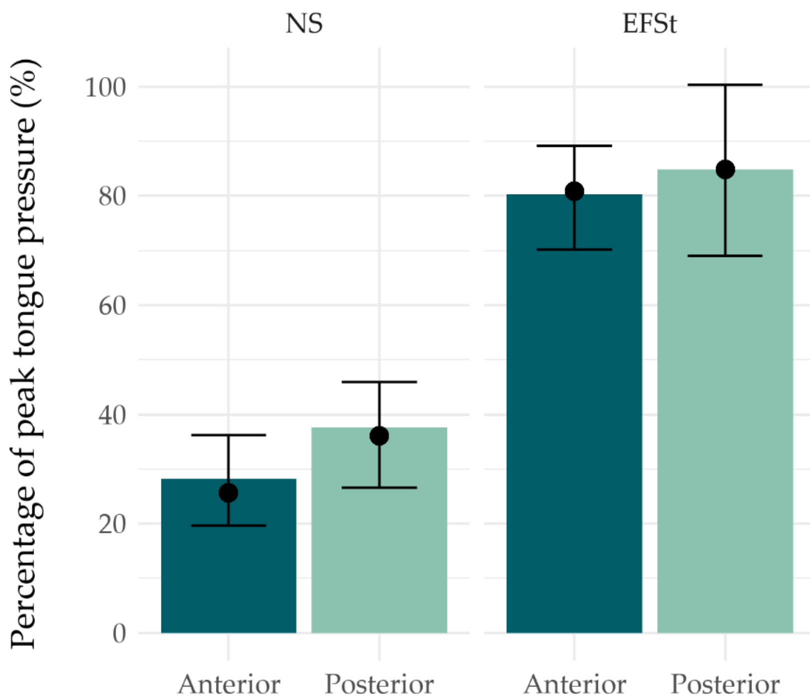
Coefficients	Estimate	SE	t value	p-value
EFSp	15.051	1.052	14.31	<0.001
EFSt	49.609	0.859	57.77	<0.001
R^2		0.782		
Adjusted R^2		0.774		
Observations		1200		

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix B (Table B.3).

6.4.2 The Effects of Swallowing on Anterior and Posterior Tongue-to-Palate Pressures (Objective 1, Hypothesis 1a.3)

The posterior oral tongue region generated more pressure during NSs and EFSst, as shown in Figure 9 (Objective 1a, hypothesis 1a.3). Anterior $T\%peak$ ranged from 4.88 to 70.73% for NSs and from 44.18 to 120.37% for EFSst, whereas posterior $T\%peak$ ranged from 7.41 to 84.21% for NSs and from 40.70 to 148.65% for EFSst. The regression coefficient estimate (regression model [2]) showed that, *during NSs*, the posterior tongue region $T\%peak$ values were on average 9.3 percentage points greater than those of the anterior tongue region (R^2=0.64; p<0.001). Similarly, the regression coefficient estimate showed that, *during EFSst*, *T%peak* values of the posterior tongue were on average 4.55 percentage points greater than those of the anterior tongue (R^2=0.55; p<0.001; Table 6).

Figure 9: Mean percentage of peak tongue pressure (*T%peak*) by swallowing condition and tongue region



Mean	28.3	37.5	80.2	84.8
Median	25.6	36.0	80.8	84.8
Min	4.9	7.4	44.2	40.7
Max	70.7	84.2	120.4	148.6

Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with tongue emphasis (EFSt).

Table 6: Regression results of the percentage of peak tongue pressure ($T\%peak$) by tongue region.

Coefficients	Normal Swallow				Effortful Swallow			
	Estimate	SE	t value	p-value	Estimate	SE	t value	p-value
Posterior	9.293	0.844	11.00	<0.001	4.554	1.170	3.90	<0.001
R^2	0.645				0.555			
Adj. R^2	0.613				0.514			
Obs.	480				480			

SE: standard error. Adj. R^2: adjusted R-squared. Obs.: observations. Note: Regression models include individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix B (Tables B.4 and B.5).

6.4.3 Age-related Differences in the Effects of the EFS on Tongue-to-Palate Pressure (Objective 2, Hypothesis 2)

Age-related analysis indicated a significant interaction effect between $T\%peak$ in the EFSp. Overall, regression coefficient estimates (regression model [3]) showed that the increase in $T\%peak$ during EFSp relative to NS was on average 6.0 percentage points greater for younger participants ($R^2 = 0.78$; $p = 0.004$; Table 7). However, the mean difference between groups during EFSt relative to NS was not statistically significant (Objective 2, hypothesis 2).

Table 7: Regression results of the percentage of peak tongue pressure ($T\%peak$) by swallowing condition and group.

Coefficients	Estimate	SE	t value	p-value
EFSp	12.054	1.477	8.16	<0.001
EFSt	51.043	1.206	42.32	<0.001
Younger	-15.056	3.537	-4.26	<0.001
EFSp*Younger	5.995	2.089	2.87	0.004
EFSt*Younger	-2.868	1.706	-1.68	0.093
R^2			0.785	
Adjusted R^2			0.777	
Observations			1200	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix B (Table B.6).

6.5 Hyoid Displacement

A total of 93 out of 600 swallows (15.5%) were excluded when the video recordings were reviewed frame by frame to select still frames at rest and maximum hyoid displacement during swallowing due to insufficient quality of imaging acquisition. From the excluded swallows, 19.17% were NSs, 12.08% were EFSst, and 15% were EFSsp. Reported data analyses were based on 507 swallows (NSs = 194, EFSst = 211, and EFSsp = 102). EFSsp included fewer trials than EFSst and NSs because tongue-to-palate pressure was measured only in the anterior tongue region.

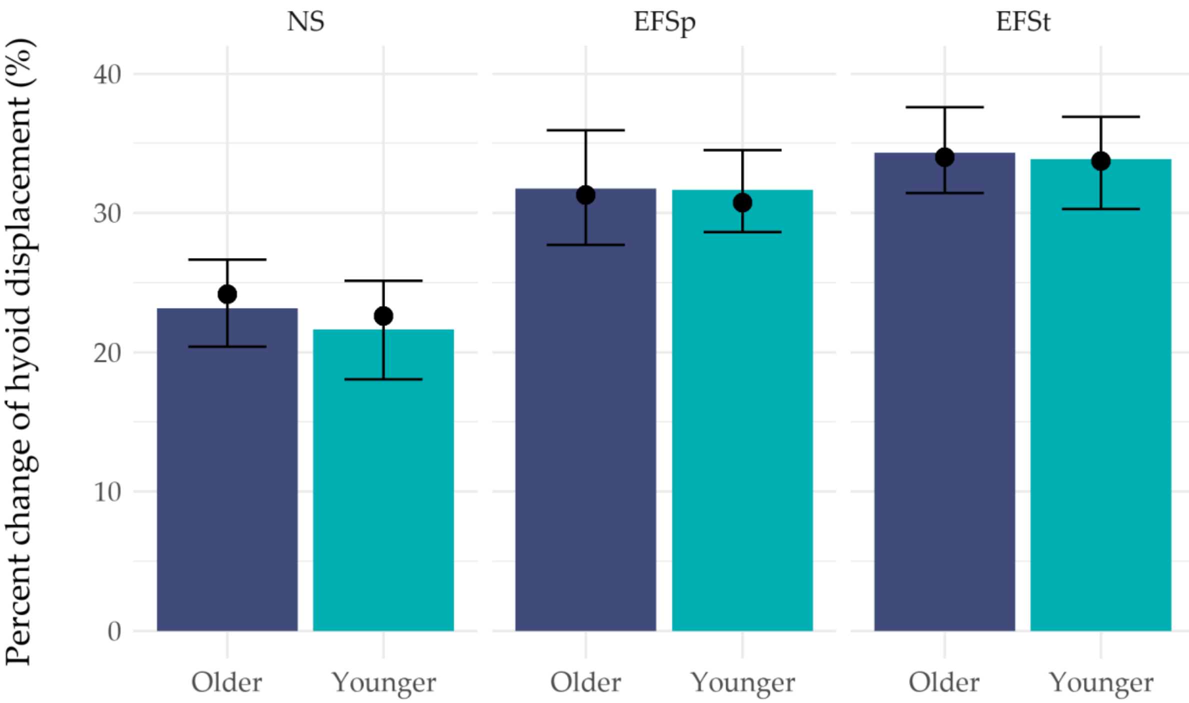
6.5.1 The Effects of the EFS on Hyoid Displacement (Objective 1, Hypotheses 1b.1 and 1b.2)

The $Hrest$ (hyoid resting distance relative to the mandible) varied from 3.43 to 6.16 cm (M = 4.82 cm, SD = 0.54) for NSs, from 3.7 to 6.31 cm (M = 4.92 cm, SD = 0.55) for EFSsp, and from 3.77 to 6.48 cm (M = 4.9 cm, SD = 0.57) for EFSst. The $Hswallow$ (hyoid swallowing distance relative to the mandible) for NSs varied from 2.27 to 5.02 cm (M = 3.74 cm, SD = 0.51), for EFSsp ranged from 2.02 to 4.92 cm (M = 3.38 cm, SD = 0.58), and for EFSst varied from 2.05 to 4.71 cm (M = 3.24 cm, SD = 0.56). These distances represent a $H\%change$ (relative change of hyoid displacement) of 4 to 33.82% (M = 22.43%, SD = 5.41) during NSs, 17.86 to 49.5% (M = 31.7%, SD = 5.52) during EFSsp, and 22.76 to 48.75% (M = 34.12%, SD = 5.15) for EFSst. Figure 10 shows the comparison between the mean percent change of hyoid displacement ($H\%change$) by swallowing condition and group.

Mean $H\%change$ was greater during EFSs than NSs (Objective 1b, hypothesis 1b.1; Table 8). Regression coefficient estimates (regression model [4]) showed that $H\%change$ values during EFSst were on average 11.69 percentage points greater than values of $H\%change$ during NSs. Similarly, $H\%change$ during EFSsp was on average 9.25 percentage points greater than $H\%change$ during NSs ($R^2 = 0.67$; $p<0.001$). Additionally, $H\%change$ values during EFSst were on average 2.4 percentage points greater than the average $H\%change$ during EFSsp (Objective 1b, hypothesis 1b.2; t = 3.72; $p<0.001$).

Regression coefficient estimates (regression model [6]) showed that there was no statistically significant interaction between $H\%change$ by swallowing condition and pressure generated by different tongue regions (Table 9).

Figure 10: Mean percent change of hyoid displacement ($H\%change$) by swallowing condition and group.



	NS Older	NS Younger	EFSp Older	EFSp Younger	EFSt Older	EFSt Younger
Mean	23.2	21.6	31.7	31.7	34.3	33.9
Median	24.2	22.6	31.3	30.7	34.0	33.7
Min	4.0	9.0	17.9	23.8	22.8	24.5
Max	33.8	30.5	49.5	46.9	46.5	48.7

Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Table 8: Regression results of the percent change of hyoid displacement ($H\%change$) by swallowing condition.

Coefficients	Estimate	SE	*t* value	*p*-value
EFSp	9.252	0.553	16.74	<0.001
EFSt	11.687	0.450	25.97	<0.001
R^2			0.675	
Adjusted R^2			0.645	
Observations			507	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix C (Table C.3).

Table 9: Regression results of the percentage change of hyoid displacement ($H\%change$) by swallowing condition and tongue region.

Coefficients	Estimate	SE	*t* value	*p*-value
EFSt	11.751	0.646	18.19	<0.001
Posterior	0.268	0.655	0.41	0.683
EFSt*Posterior	-0.102	0.905	-0.11	0.910
R^2			0.704	
Adjusted R^2			0.670	
Observations			405	

SE: standard error. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix C (Table C.4).

6.5.2 Age-related Differences in the Effects of the EFS on Hyoid Displacement (Objective 2, Hypothesis 2)

Regression coefficient estimates (regression model [8]) showed that there was no statistically significant interaction between $H\%change$ by swallowing condition and group (Objective 2, hypothesis 2; Table 10).

Table 10: Regression results of the percent change of hyoid displacement ($H\%change$) by swallowing condition and group.

Coefficients	Estimate	SE	t value	p-value
EFSp	8.718	0.773	11.27	<0.001
EFSt	11.202	0.619	18.10	<0.001
Younger	-1.307	1.870	-0.70	0.484
EFSp*Younger	1.110	1.106	1.00	0.316
EFSt*Younger	1.032	0.902	1.14	0.253
R^2			0.676	
Adjusted R^2			0.646	
Observations			507	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix C (Table C.5).

6.6 Hyoid-Larynx Approximation

A total of 138 out of 600 swallows (23%) were excluded when the video recordings were reviewed frame by frame to select still frames at rest and maximum hyoid-larynx distance during swallowing due to insufficient quality of imaging acquisition. From the excluded swallows, 25.42% were NSs, 22.5% were EFSst, and

19.17% were EFSsp. Reported data analyses were based on 462 swallows (NSs = 179, EFSst = 186, and EFSsp = 97). EFSsp included fewer trials than EFSst and NSs because tongue-to-palate pressure was measured only in the anterior tongue region.

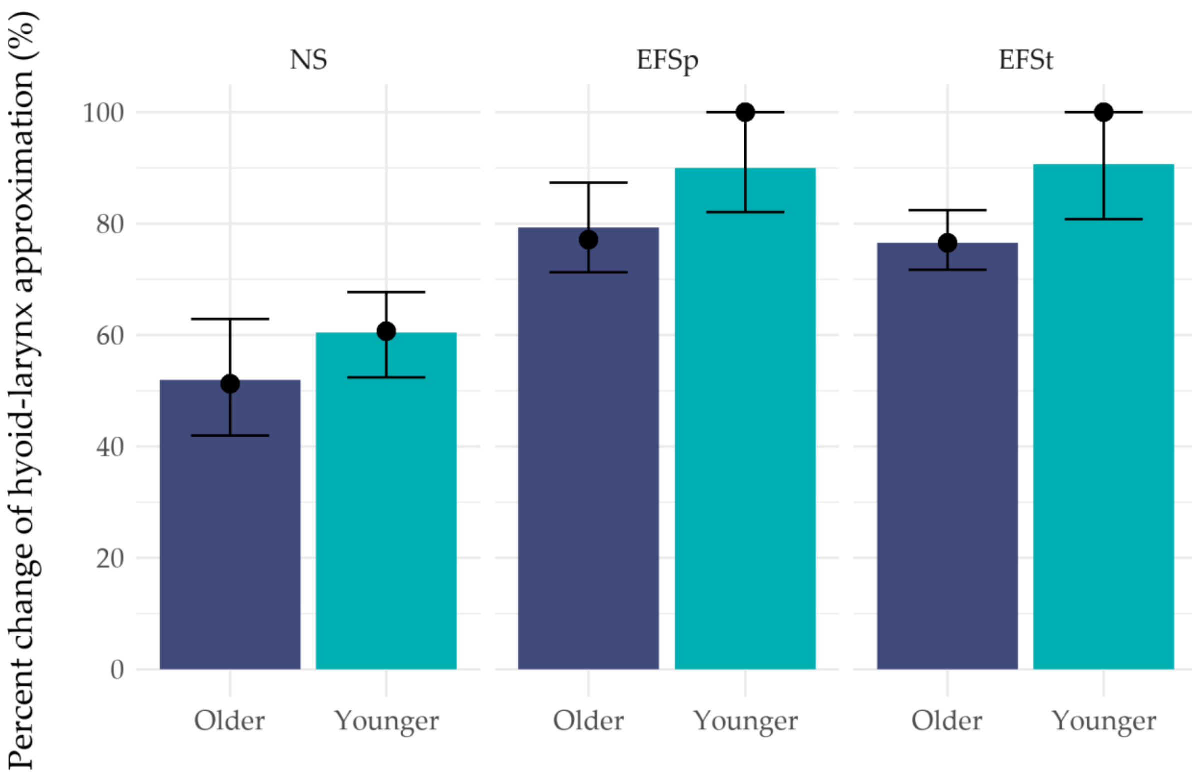
6.6.1 The Effects of the EFS on Hyoid-Larynx Approximation (Objective 1, Hypotheses 1b.1 and 1b.2)

The $HLrest$ (hyoid-larynx resting distance) varied from 0.75 to 2.98 cm (M = 1.71 cm, SD = 0.44) for NSs, from 0.93 to 2.74 cm (M = 1.72 cm, SD = 0.45) for EFSsp, and from 0.73 to 2.83 cm (M = 1.76 cm, SD = 0.43) for EFSst. The $HLswallow$ (hyoid-larynx swallowing distance) for NSs varied from 0 to 1.73 cm (M = 0.78 cm, SD = 0.37), for EFSsp ranged from 0 to 0.92 cm (M = 0.3 cm, SD = 0.28), and for EFSst varied from 0 to 1.17 cm (M = 0.32 cm, SD = 0.28). These distances represent a $HL\%change$ (relative change of hyoid-larynx approximation) of 21.68 to 100% (M = 56.15%, SD = 14.05) during NSs, 58.13 to 100% (M = 84.65%, SD = 13.16) during EFSsp, and 54.3 to 100% (M = 83.26%, SD = 12.7) for EFSst. Figure 11 shows the comparison between the mean $HL\%change$ by swallowing condition and group.

Mean $HL\%change$ was greater during EFSs than NSs (Objective 1b, hypothesis 1b.1; Table 11). Regression coefficient estimates (regression model [5]) showed that $HL\%change$ values during EFSst were on average 27.56 percentage points greater than values of $HL\%change$ during NSs. Similarly, $HL\%change$ during EFSsp was on average 28.0 percentage points greater than $HL\%change$ during NSs ($R^2 = 0.76$; $p < 0.001$).

However, a t-test showed that mean differences in $HL\%change$ between the two instructional types of EFSs was not statistically significant (Objective 1b, hypothesis 1b.2; t = -0.85; p = 0.40).

Figure 11: Mean percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition and group.



	NS Older	NS Younger	EFSp Older	EFSp Younger	EFSt Older	EFSt Younger
Mean	52.0	60.5	79.3	89.9	76.5	90.6
Median	51.2	60.6	77.0	100.0	76.6	100.0
Min	23.2	21.7	58.7	58.1	54.3	58.0
Max	80.9	100.0	100.0	100.0	100.0	100.0

Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Table 11: Regression results of the percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition.

Coefficients	Estimate	SE	t value	p-value
EFSp	27.998	1.239	22.60	<0.001
EFSt	27.565	1.028	26.81	<0.001
R^2			0.758	
Adjusted R^2			0.734	
Observations			462	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix D (Table D.3).

Finally, regression coefficient estimates (regression model [7]) showed that there was no statistically significant interaction between $HL\%change$ by swallowing condition and pressure generated by different tongue regions (Table 12).

Table 12: Regression results of the percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition and tongue region.

Coefficients	Estimate	SE	t value	p-value
EFSt	27.256	1.444	18.88	<0.001
Posterior	0.407	1.475	0.27	0.782
EFSt*Posterior	0.531	2.065	0.26	0.797
R^2			0.766	
Adjusted R^2			0.736	
Observations			365	

SE: standard error. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix D (Table D.4).

6.6.2 Age-related Differences in the Effects of the EFS on Hyoid-Larynx Approximation (Objective 2, Hypothesis 2)

Age-related analysis indicated a significant interaction effect between $HL\%change$ in the EFSt. Overall, regression coefficient estimates (regression model [9]) showed that the increase in $HL\%change$ during EFSt relative to NS was on average 6.0 percentage points greater for younger participants (R^2 = 0.76; p = 0.003; Table 13). However, the mean difference between groups during EFSp relative to NS was not statistically significant (Objective 2, hypothesis 2).

Table 13: Regression results of the percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition and group.

Coefficients	Estimate	SE	t value	p-value
EFSp	26.542	1.742	15.24	<0.001
EFSt	24.657	1.424	17.31	<0.001
Younger	-12.657	4.034	4.72	0.001
EFSp*Younger	2.950	3.809	1.99	0.231
EFSt*Younger	5.977	2.041	2.93	0.003
R^2			0.763	
Adjusted R^2			0.738	
Observations			462	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix D (Table D.5).

6.7 Perceived Effort to Swallow

For the analysis addressing perceived effort to swallow, a total of 1200 VAS measurements (one for each swallow) were used. Overall, perceived effort used to swallow ($VASnorm$) varied from 0 to 100% in all swallowing conditions. Nevertheless, mean differences were observed between NSs and EFSs as shown in Figure 12.

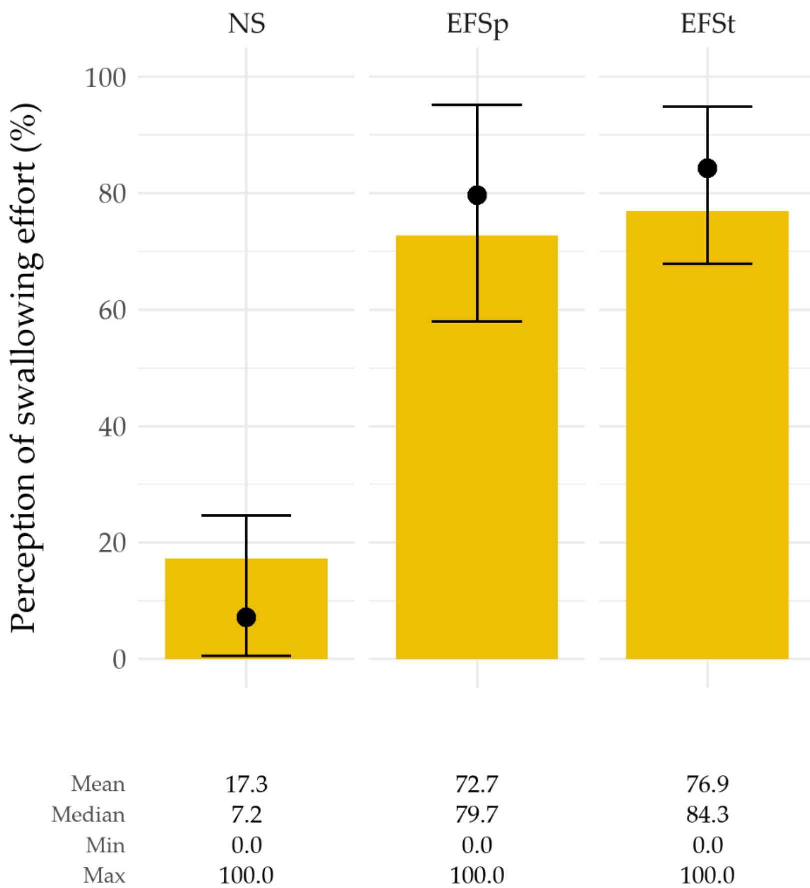
Mean perceived effort to swallow was associated with swallowing condition (Table 14). Regression coefficient estimates (regression model [10]) showed that, on average, perceived swallowing effort increased 59.67 percentage points with EFSst, and 55.45 percentage points with the EFSsp (R^2=0.61; p<0.001). Moreover, mean differences in effort to swallow between the two instructional types of EFSs was statistically significant (t = -2.07; p = 0.038). Perceived effort to swallow for EFSt was on average 4.22 percentage points greater than for EFSp.

Table 14: Regression results of perceived effort used to swallow ($VASnorm$) by swallowing condition.

Coefficients	Estimate	SE	t value	p-value
EFSp	55.448	1.884	29.42	<0.001
EFSt	59.668	1.538	38.78	<0.001
R^2			0.612	
Adjusted R^2			0.598	
Observations			1200	

SE: standard error. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Note: Regression model includes individual participant intercepts. This table only reports the coefficients of interest for the present discussion. Full results including all coefficients are available in Appendix E (Table E.3).

Figure 12: Mean perceived effort to swallow ($VASnorm$) by swallowing condition.



Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

6.7 Associations

6.7.1 Association Between Tongue Pressure and Hyoid Displacement (Objective 1, Hypothesis 1c)

Repeated measures correlation showed a moderate, positive association between $T\%peak$ values during NSs and EFSst, in all tongue regions, and $H\%change$ (r = 0.71; 95% CI = 0.65 to 0.76; p<0.001; Figures 13 and 14; Objective 1c, hypothesis 1c).

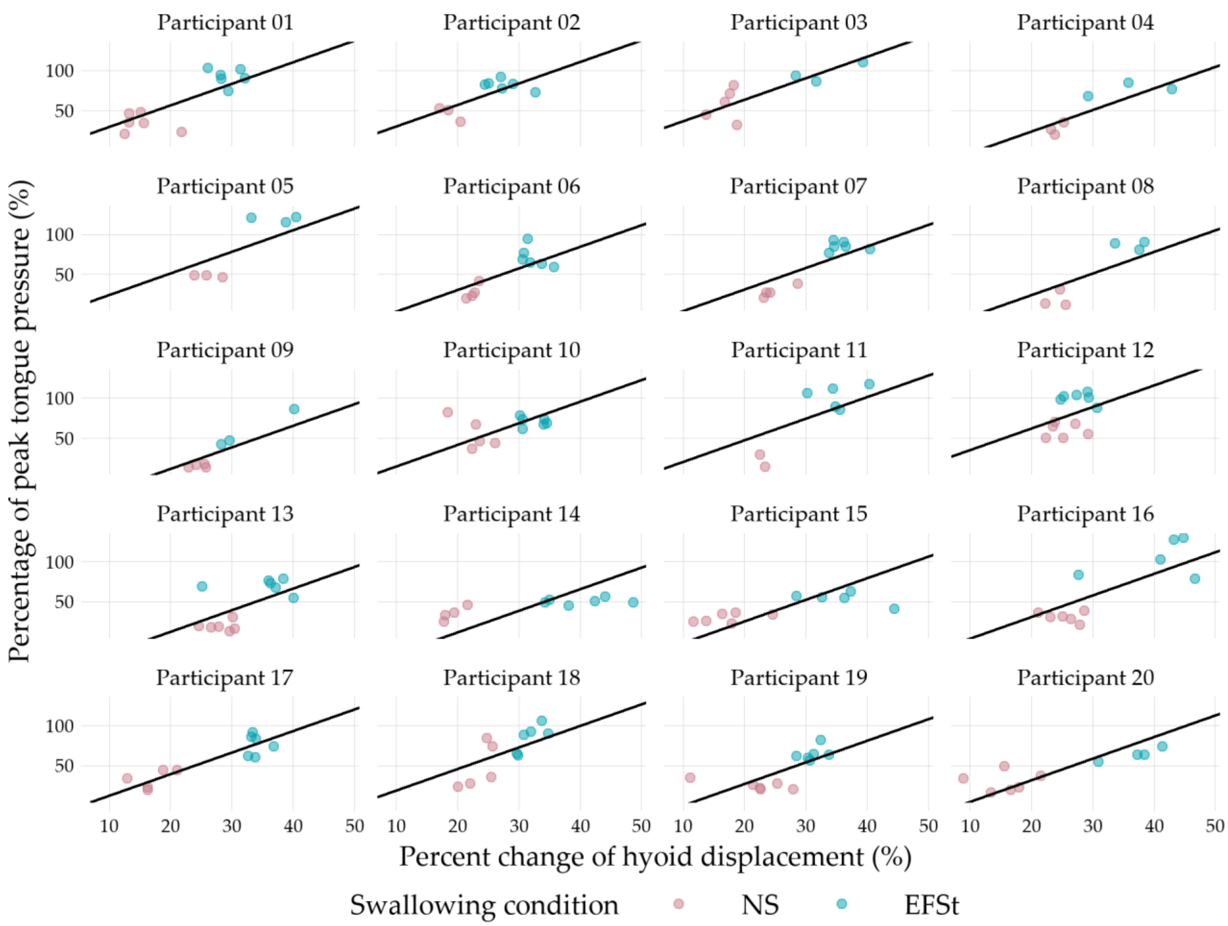
Additionally, the regression coefficient estimate (regression model [11]) showed that for each percentage point change in $T\%peak$, the $H\%change$ increased by 2.69 percentage points ($R^2 = 0.58$; $p<0.001$; Table 15).

Table 15: Regression results of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid displacement ($H\%change$).

Coefficients	Estimate	SE	t value	p-value
$H\%change$	2.691	0.140	19.21	<0.001
R^2		0.586		
Adjusted R^2		0.540		
Observations		405		

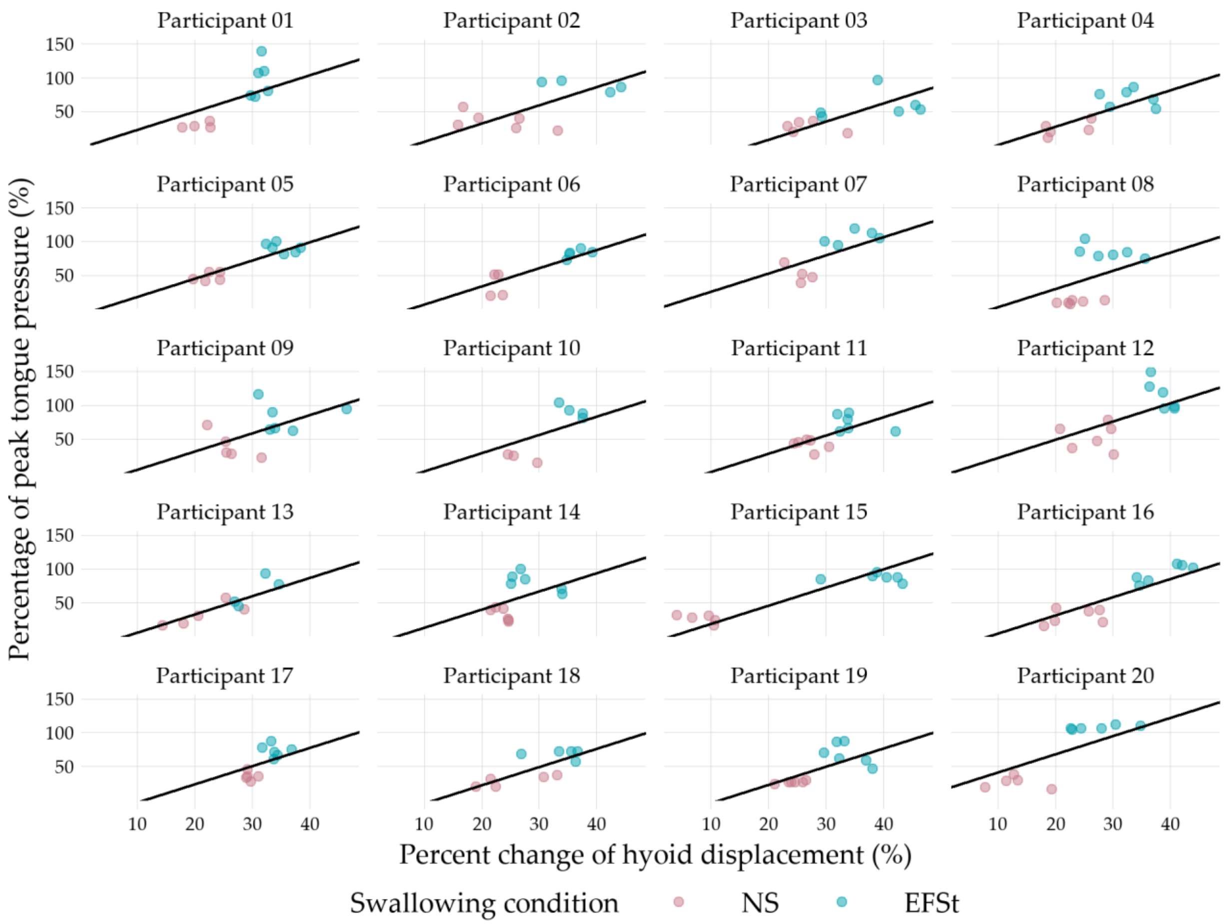
SE: standard error. $H\%change$: percentage change of hyoid displacement. Note: Regression model includes individual participant intercepts. This table only reports the coefficient of interest for the present discussion. Full results including all coefficients are available in Appendix F (Table F.1).

Figure 13: Individual measurements of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid displacement ($H\%change$) in younger participants.



Notes: Dots represent swallow events at which tongue pressure and hyoid displacement were recorded. Black lines represent estimated regression coefficients: intercepts reflect participant-specific means and the slope (common to all participants) reflects the average effect of $T\%peak$ on $H\%change$.

Figure 14: Individual measurements of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid displacement ($H\%change$) in older participants.



Notes: Dots represent swallow events at which tongue pressure and hyoid displacement were recorded. Black lines represent estimated regression coefficients: intercepts reflect participant-specific means and the slope (common to all participants) reflects the average effect of $T\%peak$ on $H\%change$.

6.7.2 Association Between Tongue Pressure and Hyoid-Larynx Approximation (Objective 1, Hypothesis 1c)

Repeated measures correlation showed a moderate, positive association between $T\%peak$ values during NSs and EFSst, in all tongue regions, and $HL\%change$ (*r* = 0.74; 95% CI = 0.68 to 0.78; *p*<0.001; Figures 15 and 16; Objective 1c, hypothesis 1c).

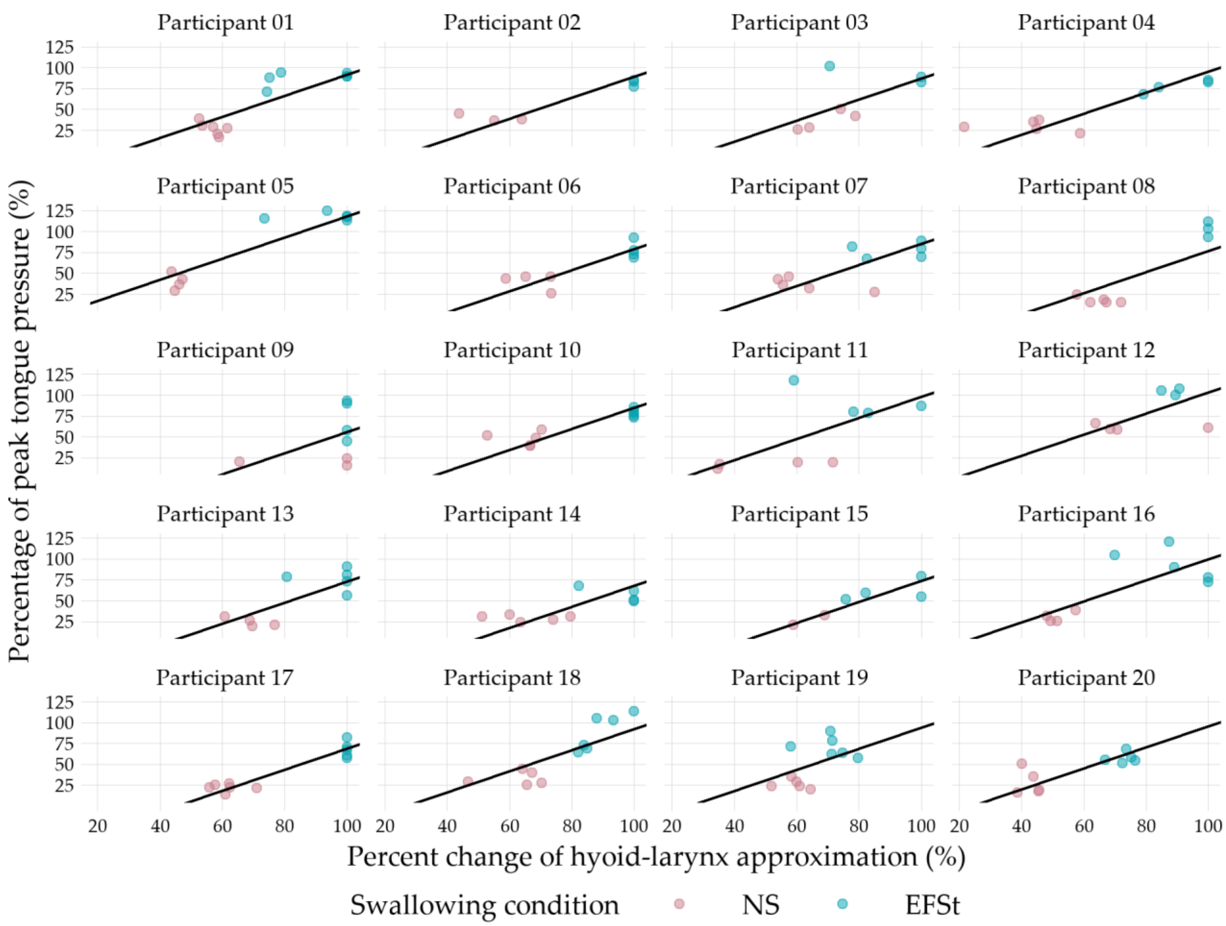
Additionally, the regression coefficient estimate (regression model [12]) showed that for each percentage point change in $T\%peak$, the $HL\%change$ increased by 1.26 percentage points ($R^2 = 0.59$; $p<0.001$; Table 16).

Table 16: Regression results of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid-larynx approximation ($HL\%change$).

Coefficients	Estimate	SE	t value	p-value
$HL\%change$	1.264	0.064	19.80	<0.001
R^2		0.593		
Adjusted R^2		0.543		
Observations		365		

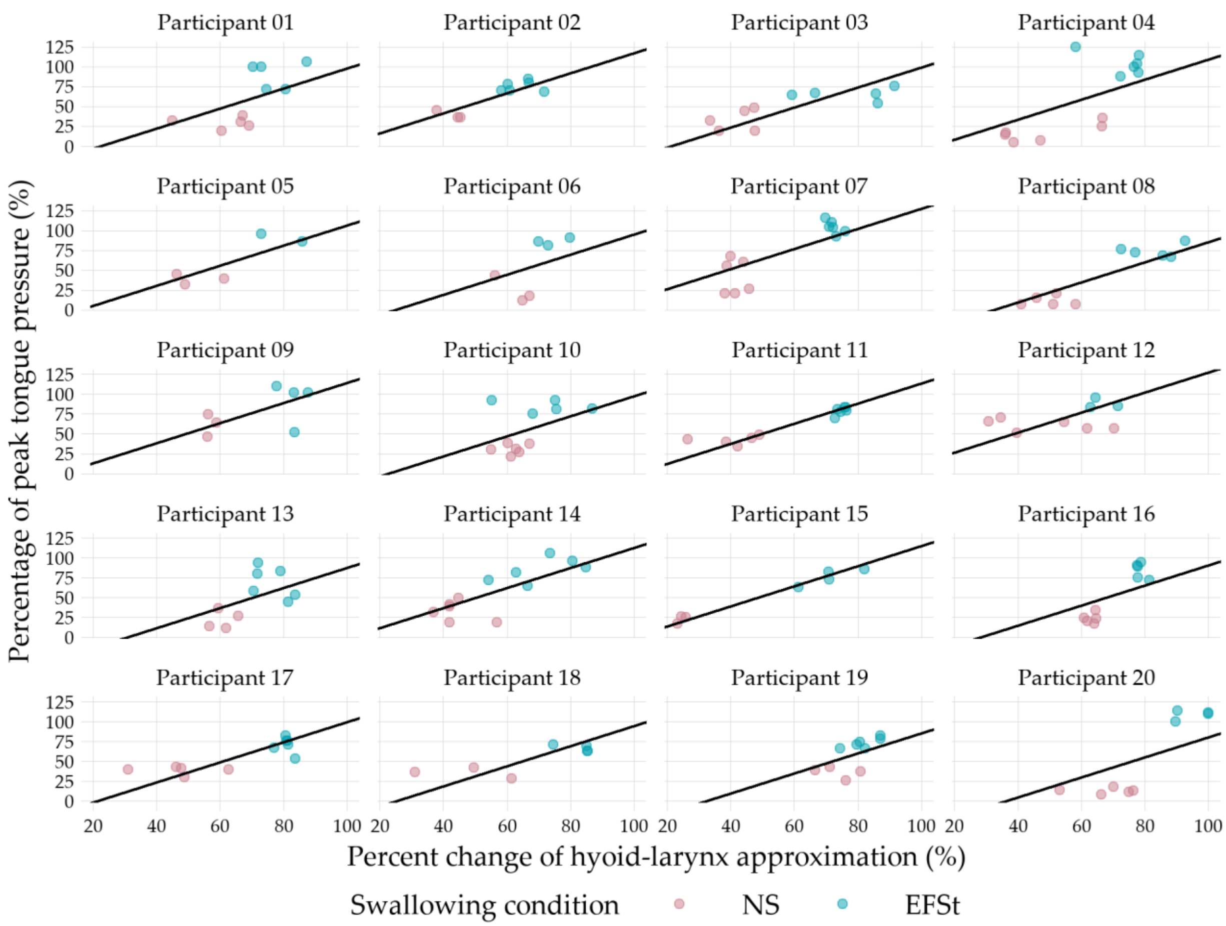
SE: standard error. $HL\%change$: percentage change of hyoid-larynx approximation. Note: Regression model includes individual participant intercepts. This table only reports the coefficient of interest for the present discussion. Full results including all coefficients are available in Appendix F (Table F.2).

Figure 15: Individual measurements of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid-larynx approximation ($HL\%change$) in younger participants.



Notes: Dots represent swallow events at which tongue pressure and hyoid displacement were recorded. Black lines represent estimated regression coefficients: intercepts reflect participant-specific means and the slope (common to all participants) reflects the average effect of $T\%peak$ on $HL\%change$.

Figure 16: Individual measurements of the percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid-larynx approximation ($HL\%change$) in older participants.



Notes: Dots represent swallow events at which tongue pressure and hyoid displacement were recorded. Black lines represent estimated regression coefficients: intercepts reflect participant-specific means and the slope (common to all participants) reflects the average effect of $T\%peak$ on $HL\%change$.

6.7.3 Association Between Tongue Pressure and Perceived Effort to Swallow (Objective 3, Hypothesis 3)

The association between tongue pressure and perceived effort used to swallow helps demonstrate how perceived effort used to swallow is associated with objectively determined physiological measurement of muscle effort. Repeated measures correlation, considering NSs and EFSst, showed a moderate, positive association between $T\%peak$ values during NSs and EFSst, in all tongue regions, and $VASnorm$ (r = 0.75; 95% CI = 0.72 to 0.77; p<0.001; Objective 3, hypothesis 3). The regression coefficient estimate (regression model [13]) showed that for each percentage point change in $T\%peak$, perceived swallowing effort ($VASnorm$) increased by 0.56 percentage points (R^2 = 0.61; p<0.001; Table 17).

Table 17: Regression results of the percentage of peak tongue pressure ($T\%peak$) by perceived effort used to swallow ($VASnorm$).

Coefficients	Estimate	SE	t value	p-value
$VASnorm$	0.558	0.016	34.09	<0.001
R^2		0.607		
Adjusted R^2		0.590		
Observations		960		

SE: standard error. $VASnorm$: normalized visual analog scale. Note: Regression model includes individual participant intercepts. This table only reports the coefficient of interest for the present discussion. Full results including all coefficients are available in Appendix F (Table F.3).

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7. DISCUSSION

A unique characteristic of this study was the simultaneous assessment of tongue-to-palate pressure, hyolaryngeal movement, suprahyoid muscle activity, and perception of swallowing effort during NSs and EFSs. Simultaneous data acquisition allowed direct comparison between different swallowing events. Moreover, this was the first study to compare hyolaryngeal motion during EFSs under two different instructions (EFSt and EFSp). Previous research analyzed differences between differing EFS instructional conditions for pressure measurement (oral and pharyngeal) and submental sEMG (Huckabee & Steele, 2006; Steele & Huckabee, 2007). Finally, this was the first study to compare physiological swallowing differences between NSs and EFSs using ultrasound. Ultrasound has been used to determine hyolaryngeal excursion during NSs in healthy and disordered populations (Feng et al., 2015; Hsiao et al., 2012; Huang et al., 2009; Kuhl et al., 2003; Kwak et al., 2018; Lee et al., 2016; Oh et al., 2016; Yabunaka et al., 2011).

The overall purposes of this investigation were to determine the effects of the EFS maneuver under two different instructions (tongue emphasis and pharyngeal squeezing) on tongue pressure generation and swallowing biomechanics (hyolaryngeal displacement), determining age-related differences in those parameters in a sample of healthy younger and older adults. Additionally, this study also examined the association between perceived swallowing effort and tongue pressure during swallowing. The hypotheses were that tongue pressure and hyolaryngeal movement would be greater during EFSs (EFSt and EFSp) than NSs and greater in the EFSt than the EFSp. Moreover, these measures would be greater in younger than older individuals. Finally, perceived effort to complete NSs and EFSs would positively correlate with tongue pressure during swallowing. Findings from this study partially support these hypotheses.

7.1 Tongue Pressure Generation

The results showed that mean $T\%peak$ values during EFSs (EFSt and EFSp) were greater than during NSs, supporting hypothesis 1a.1. Furthermore, a significant difference was also identified between EFSs conditions, with greater mean $T\%peak$ values demonstrated during the EFSt than the EFSp. Therefore, these findings support hypothesis 1a.2. Adequate tongue pressure generation during swallowing is critical for driving the bolus towards the pharynx, assisting with oral and pharyngeal clearance. During EFSst, the increased contact between the tongue and the hard palate subsequently generates increased pressure. Previous research consistently reported greater tongue pressure across the oral tongue region during EFSs than NSs (Fukuoka et al., 2013; Hind et al., 2001; Huckabee & Steele, 2006; Yeates et al., 2010). Only one of these investigations (Hind et al., 2001) recommended a general instruction to swallow hard for the EFS, whereas the others instructed participants to produce the EFS using tongue/mouth muscles.

The difference in pressure generation between EFS instructions in the present study highlights that participants completed the two different EFS conditions accurately. During training, the participants were instructed to produce (i) EFSs emphasizing the contact between the tongue and the hard palate (EFSt) and (ii) EFSs emphasizing neck muscles (EFSp). These instructions were informed by previous research by Huckabee & Steele (2006), who found that the EFS completed with tongue-to-palate emphasis produced greater oral pressures than the EFS produced with neck muscle emphasis while restricting tongue-to-palate contact. However, unlike the Huckabee & Steele (2006) instructions, in the present study participants were *not* explicitly instructed to restrict the tongue-to-palate contact during the EFSp but to focus their muscle effort on the neck/throat region and not in the mouth/tongue. Nevertheless, tongue pressures during the EFSp in the present study were also greater than during NSs, but to a much smaller degree than the EFSt. This finding suggests that individuals slightly increased the contact between the tongue and the hard palate while recruiting pharyngeal muscles to complete the EFSp.

This research also investigated the contributions of the anterior and posterior oral tongue portions in pressure generation during swallowing and found that the posterior tongue generated greater pressure than the anterior tongue in both NSs and

EFSst, contrary to hypothesis 1a.3. These results suggest that both tongue portions contribute to pressure generation during swallowing, but the posterior region plays a more important function in oral pressure generation during swallowing. A possible explanation for this finding is that the anterior tongue works as a first pressure point due to its initial contact with the alveolar ridge region of the hard palate (major contraction of the superior longitudinal muscle). Then, in a progressive stripping action to move the bolus posteriorly, the posterior oral tongue contacts the hard palate and exerts greater pressure than the initial anterior tongue actions (contraction of the superior longitudinal and extrinsic tongue muscles). This second pressure point is critical for driving the bolus into the pharynx, which may explain the greater pressure that was evidenced in this tongue region. During the entire oral transport process, the anterior tongue remains in contact with the alveolar ridge (Logemann, 1998). This stationary and prolonged positioning of the anterior tongue may partially explain its lower pressure generation than the posterior tongue; lack of movement and prolonged contact may necessitate lower pressures relative to the rolling action of the posterior tongue during this phase of swallowing. Additionally, regional lingual differences in muscle fibers, movement, and cortical neural control may also explain the distinct contributions of the anterior and posterior tongue in pressure generation during swallowing (Cullins & Connor, 2017; Malandraki et al., 2009; Miller et al., 2002; Stål et al., 2003).

Different findings regarding the comparative oral pressure contributions of the anterior and posterior tongue were found by Fukuoka et al. (2013), who evaluated tongue-to-palate pressure patterns during NSs and EFSst. These researchers noted that the *timing* of pressure generation began with anterior region activity and then moved posteriorly. However, the anterior sensor generated more pressure than the posterior sensor during EFSst (water trials), although no difference was found between sensors during NS trials involving saliva or water. The results reported in our study and by Fukuoka et al. (2013) may indicate that individuals can emphasize different tongue portions during swallowing, especially when completing an EFSt, and that material swallowed (saliva versus water) may impact anterior versus posterior tongue contributions. Nevertheless, it is important to further investigate whether these differences affect the subsequent physiological events of the swallowing process and their consequences relative to oral and pharyngeal residues which are important to swallow safety. Further studies to clarify the differential roles of the anterior and posterior tongue may also help researchers and clinicians improve instructions for optimally performing an EFSt by clearly specifying the region of the tongue that should be emphasized.

Finally, the findings indicated limited age-related differences in tongue pressure generation. Younger adults showed higher anterior $Tmip$ than older adults but not posterior $Tmip$. Although all participants in this study had normal anterior tongue strength (above 40 kPa) as an inclusion criterion, it is possible that the difference in the anterior *Tmip* indicates some age-related decline in the tongue muscles. This decline was only evident in the anterior versus posterior tongue, corroborating the aging literature that shows more changes in muscle fiber size and type in the intrinsic, anterior tongue muscles (Cullins & Connor 2017; Miller et al., 2002; Stål et al., 2003). Studies using pressure-sensitive electrodes attached to the hard palate reported greater anterior *Tmip* in younger than older adults (Nicosia et al., 2000; Robbins et al., 2016; Tamine et al., 2010; Todd et al., 2013; Yeates et al., 2010). However, some of these studies also reported greater posterior *Tmip* in younger than older adults (Nicosia et al., 2000; Robbins et al., 2016). Differences in methods between studies may explain the mixed results, including age of participants, instrumentation used for measuring tongue pressure, and bolus characteristics. Nicosia et al. (2000) included participants ages 48 to 55 years old in the younger group and 69 to 91 years old in the older group. Moreover, pressures were compared between varied swallow trials of semisolid and liquid (3ml and 10 ml). Robbins et al. (2016) included participants ages 21 to 40 years old in the younger group and 61 to 82 years old in the older group. Additionally, tongue-to-palate pressures were generated during thin liquid trials (5 ml and 10 ml). Both studies used a sensor sheet attached to the hard palate. However, the Nicosia et al. (2000) study used three sensors, while Robbins et al. (2016) study used five sensors. In the present study, participants in the younger and older group were ages 18 to 36 years old and 62 to 79 years old respectively, and two sensors (IOPI bulbs) were used to determine anterior and posterior tongue pressures. The only study that investigated age effects on posterior $Tmip$ using the IOPI did not find differences between younger and older adults (Pitts et al., 2017).

Age-related differences were not observed in $T\%peak$ during NSs and EFSst conditions, thus, not supporting hypothesis 2. These findings suggest that individuals only use a percentage of their pressure capacity to normally swallow, allowing older healthy adults to achieve similar swallowing functionality relative to oral pressures as those who are substantially younger. The findings regarding tongue pressure during NSs were mixed in studies using pressure-sensitive electrodes attached to the hard palate (Nicosia et al., 2000; Robbins et al., 2016; Tamine et al., 2010; Todd et al., 2013; Yeates et al., 2010). Although some studies reported a decline in tongue pressure functional reserve ($Tmip$ – maximum tongue pressure during swallowing) due to decreased $Tmip$ (Nicosia et al., 2000; Todd et al., 2013), when the functional reserve was reported as a percentage of maximum tongue pressure to normalize tongue pressure across individuals, age-related differences were not evident (Steele, 2013; Youmans et al., 2009).

In this study, mean $T\%peak$ was only greater for younger versus older adults during the EFSp condition, suggesting that older participants performed the EFSp condition while recruiting less tongue-to-palate contact than younger adults. The fact that differences in mean $T\%peak$ did not occur across all swallowing conditions indicates that overall age-related differences in tongue-to-palate pressure during swallowing were not evident for the participants in this study. Yeates et al. (2010) introduced a new concept called swallowing reserve, which they defined as pressure differences between NSs and EFSs. As with our present study, older adults in the Yeates et al. (2010) study were able to generate enough tongue pressure to produce adequate EFSst despite declines in $Tmip$, corroborating our finding that pressure-generating functionality and the ability to adjust pressures for a swallowing maneuver (the EFS) are preserved with aging. This ability to voluntarily modulate tongue pressure across varied conditions may decrease the risk of older individuals for developing swallowing disorders. Another explanation for this outcome relates to our finding that the posterior tongue contributes more significantly to swallowing than the anterior tongue. In our age group comparisons, posterior $Tmip$ was similar in younger and older adults, whereas $Tmip$ in the anterior tongue differed between groups. Given the greater involvement of the posterior tongue in generating oral swallowing pressures, a decline in the anterior $Tmip$ would not substantially affect performance of EFSst, thus potentially explaining the lack of age-related differences in the NS and EFSt conditions.

7.2 Hyolaryngeal Movement

The findings of this study provide new insights regarding the physiological effects of the EFS maneuver on hyolaryngeal displacement, showing that the EFS increases both hyoid displacement and hyoid-larynx approximation, supporting hypothesis 1b.1. The results indicate that tongue and neck muscles contribute to hyolaryngeal movement, as both the EFSt and EFSp conditions increased hyoid displacement and hyoid-larynx approximation. However, the EFSt improved hyoid movement to a greater degree than the EFSp, suggesting that tongue-to-palate pressure (an early swallowing event) primes subsequent motor events in swallowing, such as BOT retraction and hyolaryngeal elevation. This finding partially supports hypothesis 1b.2. This potential priming effect of tongue-to-palate pressure is also supported by the positive correlation between $T\%peak$ and $H\%change$ (hypothesis 1c). A difference between EFSt and EFSp was not observed for hyoid-larynx approximation; thus, not supporting hypothesis 1b.2.

Previous studies investigating hyolaryngeal movement during the EFS have shown inconsistent results (Bülow et al., 1999; Hind et al., 2001; Jang et al., 2015; Wheeler-Hegland et al., 2008). These investigations lacked objective training and verification of the EFS, thus individuals may have failed to appropriately increase muscle effort during the EFS to move the hyoid bone and the larynx. The present study showed that training with biofeedback was critical for learning the EFSs, as only 38% of the participants mastered their execution in the first attempt. Moreover, 30% of the participants had difficulty mastering the EFSt and 35%, the EFSp. During experimental measures, accurate execution of the EFSs was verified and participants repeated the trials in which the specific criterion of EFSs was not achieved. Another difference between this research and earlier investigations is that results were reported as relative change in hyoid displacement ($H\%change$) and hyoid-larynx approximation ($HL\%change$) rather than as absolute change in movement ($Hrest - Hswallow$ and $HLrest - HLswallow$). In this study, the changes in hyoid and larynx movements are presented as a fraction of the baseline distance ($Hrest$ and $HLrest$), thus normalizing and standardizing the measurements for all participants. This method accounts for anatomical differences across individual participants. Variation in hyolaryngeal movement between and within individuals has been demonstrated due to multiple factors including height and other structural differences, bolus volume and consistency, sex, and anatomical landmarks used for measurements (Brates et al., 2020; Feng et al., 2015; Molfenter & Steele, 2011). Thus, outcome measures that reflect relative change in hyoid and larynx movements are better for comparing swallowing conditions and participants.

Our investigation measured total displacement of the hyoid and the larynx, considering both superior and anterior movements together. Previous studies analyzed elevation and anterior movement separately, with some studies showing that hyoid elevation increased but not its anterior movement, whereas both superior and anterior laryngeal movement increased during the EFS (Hind et al., 2001; Jang et al., 2015). Hyoid superior movement is important for airway protection, while the anterior displacement is critical for UES opening. Therefore, differences between hyoid superior and anterior movements should be confirmed in future studies to better evaluate hyoid displacement during EFSs. Yabunaka et al. (2011) used automated software to track hyoid bone movement during NSs recorded using ultrasound, capturing superior and anterior motion of the hyoid separately. However, no ultrasound studies to date have addressed both superior and anterior movement of the larynx separately.

During the oral transport phase of swallowing, contraction of the superior longitudinal muscle and extrinsic tongue muscles (e.g., genioglossus, styloglossus, and hyoglossus) facilitate the tongue-to-palate contact needed to drive the bolus in an antero-posterior wave-like motion (Matsuo & Palmer, 2008; Shaw & Martino, 2013). Furthermore, contractions of the mandibular elevators (e.g., masseter, temporalis, and medial pterygoid) provide structural assistance for tongue-to-palate contact, and contraction of the mylohyoid muscle helps the elevation of the FOM muscles and tongue. Thus, anatomical connections between the tongue and the hyoid bone, through extrinsic tongue muscles and submental muscles, may explain the contributions of the tongue to hyoid displacement during the EFSt. Greater tongue-to-palate contact and submental muscle activation during the EFS have been observed in prior research (Huckabee & Steele, 2006), findings that are consistent with an anatomical connectivity explanation for the greater movement of the hyoid bone that we found. The upward and forward movement of the hyoid subsequently increases hyoid-larynx approximation, as these structures are connected via the thyrohyoid muscle, membrane, and ligaments. The EFSp may also contribute to hyoid bone displacement and subsequent hyoid-larynx approximation due to greater contraction of the FOM muscles, which show increased activation during the EFSp as measured with submental sEMG (Huckabee et al., 2006).

Interestingly, in the present study, although a positive correlation between $T\%peak$ and $H\%change$ was found (hypothesis 1c), $HL\%change$ was not different between EFS conditions. The positive association between $T\%peak$and $HL\%change$ suggests that tongue-to-palate pressure may contribute to increasing hyoid-larynx approximation, but the lack of difference between EFS conditions indicates that other mechanisms are also important to hyolaryngeal movement during EFSs. Although there are many muscles involved in hyoid movement, including the suprahyoid and pharyngeal elevator muscles (e.g., stylopharyngeus, salpingopharyngeus, and palatopharyngeus), the movement of the larynx is mostly influenced by the movement of the hyoid bone along with contraction of the thyrohyoid muscle, as there are no direct connections between the larynx and the suprahyoid muscles (Robbins et al., 2006; Pearson et al., 2012). Therefore, a possible explanation for the lack of difference between $HL\%change$ across EFS conditions is the lack of direct muscle connections between the tongue/pharyngeal muscles and the larynx. The extra lingual muscle force associated with increased tongue-to-palate pressure, which may facilitate hyoid bone movement due to direct tongue to hyoid muscle connections, would not be translated to hyoid-larynx approximation.

An interaction between $H\%change$ or $HL\%change$ with pressure generated by different tongue regions was not observed. Although the posterior tongue contributed more to $T\%peak$ than the anterior tongue during NSs and EFSst, this difference did not seem to affect hyolaryngeal movement. However, it is important to note that fewer swallows in each separate tongue region were available for these analyses, as many swallows were excluded due to poor ultrasound imaging acquisition (93 out of 600 for hyoid displacement and 138 out of 600 for hyoid-larynx approximation). Thus, it is possible that the analyses had insufficient measures. Future investigations should elucidate whether pressures generated in different lingual regions influence hyolaryngeal movement during the EFSt.

Finally, age-related analyses showed an interaction between $HL\%change$ and EFSt, indicating that younger adults had greater $HL\%change$ than older adults, supporting hypothesis 2. However, a similar pattern was not observed for $H\%change$, thus, contrary to hypothesis 2. Previous research comparing NSs and EFSs did not use robust models to evaluate age differences in the EFS and hyolaryngeal movement. Jang et al. (2015) compared younger and older adults across NSs and EFSst using pairwise comparisons. Their results indicated that greater differences across swallowing conditions were found in the younger group, but the differences between NSs and EFSst in the older group did not reach significance. The only reported difference that reached statistical significance was greater hyoid elevation in younger participants between NSs and EFSs, whereas our results highlighted age differences in hyoid-larynx approximation. Other investigations analyzing age-related differences in hyolaryngeal excursion showed mixed results. While Brates et al. (2020) and Yabunaka et al. (2011) reported that hyoid excursion during NS was greater in healthy younger adults than older adults, Mancopes et al. (2011) and Nishkbo et al. (2015) did not find differences across age groups. Nishikbo et al. (2015) and Wang et al. (2015) also did not show age-related differences in the anterior and superior movement of the larynx. Methodological differences may explain the variability in results, such as the use of different instrumentations for measuring hyolaryngeal displacement (e.g., VFSS, ultrasound, and piezoelectric sensor), bolus characteristics (e.g., volume and consistencies), anatomical reference points and reported measurements (e.g., absolute vs. relative), and participant characteristics (e.g., age, sex, and inclusion criteria for determining healthy participants).

7.3 Perceived Effort to Swallow

The findings indicated that perceived muscle effort to swallow was greater during both types of EFSs (on average, more than 55 percentage points greater) than NSs and that participants also perceived different levels of muscle effort when producing the two types of EFSs. Overall, mean perceived effort to swallow for EFSt was greater than for EFSp. These results suggest that healthy adults are aware of muscle effort used to swallow (e.g., in the tongue and neck muscles) when practicing swallowing strategies in a therapeutic setting. In general, most people swallow without conscious awareness of the events and structures involved in the swallowing process. Therefore, the VAS provides a method to facilitate people's ability to attend to and rate subjective swallowing parameters such as muscle effort. This increased attention may help individuals modulate these parameters as required for different conditions (e.g., NSs and EFSs). This result is consistent with previous research showing that healthy younger adults perceived greater muscle effort to swallow during EFSst (on average, 63.5 mm more) as compared to NSs (Bahia & Lowell, 2022).

The VAS is a widely accessible method for rating perception, including perceived pain, effort, and fatigue (Baldner et al., 2014; Kays et al., 2010; Matsuyama et al., 2021), thus providing a means of tracking changes over time or differences between conditions. In the current study, the VAS determined how much perceived muscle effort participants used to produce NSs and EFSst. The positive, significant association between perceived muscle effort used to swallow and the objectively determined physiological measurement of tongue pressure ($T\%peak$) supported hypothesis 3, and suggests that the VAS may be a useful method when practicing EFSs to differentiated them from NSs. The utility of the VAS for practicing the EFS is twofold: it rates physical effort (e.g., tongue press or neck squeezing to swallow) *and* perceived exertion (e.g., subjective individual characteristics), capturing effort at the specific moment of swallowing (Baldner et al., 2015; Hunter et al., 2020). Therefore, VAS measurement offers an appropriate estimation of how hard individuals are swallowing when performing an EFS based on their physical sensations, helping them to adjust their level of exertion during swallowing. Furthermore, our results suggest that swallowing muscles, such as the tongue, play an important role in the perception of muscle effort used to swallow. Tongue-to-palate pressure is the initial driving force for propelling the bolus backward into the pharynx. In this study, participants were instructed to perform the EFSt; thus, increasing the contact of the tongue and the hard palate during swallowing.

Previous studies also showed that the use of a VAS for tracking perception of swallowing correlated with objective measures of swallowing physiology. Bahia & Lowell (2022), for example, found a positive correlation between perceived muscle effort (VAS measurement) and masseter sEMG peak amplitude during NSs and EFSst. Matsuyama et al. (2021) reported that perception of effort required to swallow gel-type food with varied deformation characteristics correlated well with submental sEMG amplitudes, tongue pressure measurements, and swallowing duration. In contrast, Kays et al. (2010) did not find a significant association between the perception of swallowing effort related to muscle fatigue and tongue endurance measures before and after a meal that was considered to be an endurance task. However, the authors pointed out that individuals who reported the greatest levels of perceived fatigue (swallowing effort) after a meal using a VAS also showed signs of swallowing difficulties and decreased tongue strength and endurance measurements.

7.4 Limitations of this Study

This study has several limitations, including participant recruitment and characteristics, swallowing tasks, and feasibility of ultrasound imaging acquisition. The sample was obtained from a convenience sample of healthy younger adults, mostly formed by college students, and healthy older adults from the community. The oldest participant was 79 years, with no participants in the age range of 80 and older. There is a lack of studies investigating age-related changes in swallowing in healthy individuals over the age of 80 (Jardine et al., 2020). Additionally, more prominent swallowing physiological changes may arise in the oldest segment of older individuals. Another limitation in the sample selection for the present study was sex. Few male individuals were interested in participating in this study (8 out of 40: 2 in the younger group and 6 in the older group). Despite the fact that all physiological measurements were normalized across participants to control for possible differences, including sex differences, the inclusion of more male participants would better represent the population. Although the literature consistently reports greater anterior maximum isometric tongue pressure in males than females, sex differences in tongue pressure *during swallowing* are not evident (Stierwalt & Youmans, 2007; Youmans & Stierwalt, 2006; Youmans et al., 2009). Brates et al. (2020) did not find sex-related differences in hyoid displacement during swallowing for the relative (scaled) measures of movement. Sex differences were only evident for the absolute measurements of hyoid displacement (Brates et al., 2020). Finally, Wheeler-Hegland et al. (2008) did not find any sex differences in hyolaryngeal excursion during NSs and EFSs. Another limitation in our study was the inclusion of individuals showing tongue strength above 40 kPa. This selection criterion may have limited the identification of age-related differences. Nevertheless, this criterion was important for excluding participants with possible pathological oral phase dysphagia.

Limitations regarding the swallowing tasks included lack of data of posterior $T\%peak$ in the EFSp condition. Only measurements of oral pressure in the anterior tongue-to-palate region were completed because participants were instructed to focus on generating pressure on the neck/throat and not in the mouth/tongue. It was anticipated that participants would not over-recruit tongue muscle in the EFSp condition. Thus, the EFSp swallowing condition was not optimal for analyzing tongue region differences. Moreover, concerns about fatigue arose due to the completion of many sequential EFSs, especially in the older group. The literature reports fatigue effects in both tongue strength and endurance (Kays et al., 2010). Therefore, fatigue could have affected data acquisition and correct production of EFSs. The completion of EFSp with anterior tongue pressure measurements only decreased the total number of experimental EFS trials (18 trials instead of 24).

In this study, participants performed only saliva swallows; bolus trials were not tested. It is known that swallowing events, such as tongue pressure, adjust to bolus conditions (e.g., volume and consistency). Thus, comparing NSs and EFSs with varied boluses may add new information beyond the data generated in this study.

Finally, some ultrasound video recordings were discarded after data collection due to insufficient quality of imaging acquisition. During ultrasound, appropriate contact between the transducer and the skin is necessary for good visualization of the anatomical landmarks used for measurement. However, increasing pressure between the transducer and the skin for better contact may cause deformation of muscles (e.g., the geniohyoid), limit the movement of structures, and cause discomfort in the participants. Because swallowing involves active movement of many structures, imaging acquisition can be challenging, especially for hyoid-larynx approximation, as both structures move during swallowing. Therefore, due to the exclusion of some video recordings, fewer measurements of hyolaryngeal displacement were acquired. Consequently, data for some analyses were limited, including the contributions of anterior and posterior tongue pressure in hyoid excursion and hyoid-larynx approximation.

8. CONCLUSIONS AND FUTURE DIRECTIONS

8.1 Conclusions

This study advanced the clinical understanding of the physiological effects of the EFS maneuver on tongue-to-palate pressure and hyolaryngeal excursion in healthy individuals across the life span. Findings highlighted differences between EFS instructions, providing support for the potential need to individualize the training and execution of the EFS based on the physiological swallowing deficits of each patient. Although both types of EFSs increased relative maximum tongue pressure during swallowing and relative hyoid displacement change as compared to NSs, the EFS produced with tongue emphasis (EFSt) had a more robust impact on those measures. In addition, the EFSt and EFSp increased relative hyoid-larynx approximation as compared to the NS. Identifying physiological effects of the EFS maneuver may guide treatment decisions in SLP, improving rehabilitation. Furthermore, improvements in hyolaryngeal displacement may contribute to UES opening and laryngeal vestibule closure.

Study findings also indicated that relative peak tongue pressure during swallowing (NSs and EFSst) correlated with hyolaryngeal excursion, emphasizing the critical role of the tongue in swallowing biomechanics. The results of this study determined regional tongue differences in pressure generation during swallowing, underscoring the contributions of the posterior oral tongue during NSs and EFSs. This finding provides further insights into how clinicians may train swallowing during rehabilitation, for example, by emphasizing posterior tongue-to-palate contact and adapting EFS instructions to optimize posterior tongue emphasis rather than the anterior region. Therefore, individuals with tongue weakness and swallowing disorders may benefit from exercises targeting posterior tongue strength during swallowing to optimize pressure generation.

This research also aimed to expand the knowledge of age-related differences in the execution of the EFS, documenting differences in tongue-to-palate pressure and hyolaryngeal excursion. Both younger and older participants were able to complete both types of EFSs. However, older participants needed more training to master the strategies. This is a relevant finding as most patients with dysphagia are in the older age range. Thus, patients may need additional instructions and training during the therapeutic process. Age-related differences were not evident in relative peak tongue pressure during swallowing and in relative hyoid displacement change. Although anterior maximum isometric tongue pressure was lower in older than younger adults, age-related changes in anatomy and physiology did not seem to decrease tongue-to-palate pressure during swallowing. The lack of decline in tongue-to-palate pressure in older adults, despite known changes in muscle mass and strength at older ages, may be helpful for decreasing the risk for swallowing disorders. Therefore, clinical evaluation of swallowing should include not only measurements of isometric tongue pressure but also pressure generated *during swallowing* as a better indicator for dysphagia risk. Aging effects were not apparent in hyoid excursion, but older adults showed less hyoid-larynx approximation during the EFS produced with tongue emphasis as compared to younger adults. Older individuals with dysphagia may show similar patterns during rehabilitation. Thus, clinicians should always monitor patients' progress and add additional strategies to target patient-specific physiological deficits.

Finally, study findings indicated that participants perceived changes in swallowing effort between NSs and EFSs and that relative peak tongue pressure during swallowing (NSs and EFSst) correlated well with perceived effort used to swallow. For clinical practice, these findings provide support for using the VAS as an adjunctive tool in rehabilitation to gauge EFS performance. The VAS may be a useful tool for increasing awareness of swallowing effort to produce EFSs during the rehabilitation process.

8.2 Future Directions

Future studies should focus on evaluating the effects of the EFS in disordered individuals, as they are the target population for the use of this swallowing maneuver, while considering the complexity of patients' medical diagnoses and their ability to appropriately perform this swallowing strategy. Additionally, the investigation of the physiological effects of a treatment approach in a disordered population supports its potential generalizability. Swallowing biomechanics may differ in those experiencing a disorder and multiple co-occurring disorders can add to overall swallowing impairment.

Individual contributions of the EFS to anterior and superior hyolaryngeal movements may elucidate the impact of the EFS on UES opening and airway protection as direct conclusions cannot be made from this study. Specific investigations of the contributions of the EFS to UES opening diameter and laryngeal vestibule closure secondary to improvements in hyolaryngeal excursion are a critical next step. As the current literature lacks evidence addressing the benefits of the EFS in swallowing efficiency and safety, further studies are needed to determine functional swallowing outcomes, specially assessing changes in the occurrence and severity of post-swallow residue, penetration, and aspiration. Additionally, future studies should investigate whether the EFS maneuver improves swallowing coordination and the timing of biomechanical events, specifically addressing the coordination and timing of tongue-to-palate pressure and hyolaryngeal movement.

Previous studies have emphasized the immediate effects of the EFS. Thus, long-term effects of the EFS on swallowing physiology are critical to assess its restorative role. Future treatment studies that involve the training and execution of EFSs following a systematic and hierarchical approach are needed to elucidate its potential utility as a swallowing exercise. A rehabilitation program using the EFS might improve muscle strength and coordination due to motor and neuroplasticity principles. Future investigations can determine whether an EFS therapeutic program drives post-therapy cortical reorganization.

APPENDICES

Appendix A: Health Questionnaire

Identification		
ID #:	Date: ____/____/_________	
DOB: ____/____/_________	Age: _____ years _____ month(s)	Sex: □ Female □ Male

Medical History
Current or prior history of neurologic disorders (e.g., stroke, TBI, PD, etc.): □ Yes □ No
Current history of respiratory problems (e.g., COPD, pneumonia): □ Yes □ No
Current or prior history of gastrointestinal disorders (e.g., cancer): □ Yes □ No
Current or prior history of head and neck cancer: □ Yes □ No
Current history of structural abnormalities in the head and neck (e.g., cleft palate): □ Yes □ No
Current or prior history of head and neck surgery: □ Yes □ No
Other major medical diseases (e.g., autoimmune diseases): □ Yes □ No

Swallowing History
Current diet level: FOIS ____
Current or prior history of swallowing difficulties: □ Yes □ No
Vocal fold paresis or paralysis: □ Yes □ No
Severe voice disorders: □ Yes □ No

Appendix B: Tongue Pressure Generation

Table B.1 summarizes the *raw data* for peak tongue pressure during swallowing ($Tpeak$) by swallowing condition, group, and tongue region.

Table B.1: Mean peak tongue pressure during swallowing ($Tpeak$) by swallowing condition, group, and tongue region.

Group	Tongue region	NS	EFSt	EFSp
		Mean (*SD*) Min-Max	*Mean* (*SD*) Min-Max	*Mean* (*SD*) Min-Max
Younger	Anterior	18.12 (7.67) 7.00-37.00	50.87 (13.63) 25.00-80.00	32.69 (11.48) 12.00-61.00
	Posterior	20.57 (8.71) 7.00-46.00	46.11 (13.44) 22.00-82.00	
Older	Anterior	14.94 (6.59) 2.00-32.00	44.12 (11.17) 19.00-71.00	24.42 (10.34) 5.00-54.00
	Posterior	19.50 (8.96) 3.00-40.00	43.80 (11.04) 21.00-69.00	

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Tongue pressure measurement is in kPa.

Similarly, Table B.2 summarizes the *raw data* for percentage of peak tongue pressure ($T\%peak$) by swallowing condition, group, and tongue region.

Table B.2: Mean percentage of peak tongue pressure ($T\%peak$) by swallowing condition, group, and tongue region.

Group	Tongue region	NS *Mean* (*SD*) Min-Max	EFSt *Mean* (*SD*) Min-Max	EFSp *Mean* (*SD*) Min-Max
Younger	Anterior	28.84 (12.90) 10.45-69.81	79.23 (16.16) 44.78-120.37	51.05 (16.05) 19.40-90.74
	Posterior	37.17 (15.20) 12.94-84.21	83.13 (21.47) 40.70-129.54	-
Older	Anterior	27.66 (12.13) 4.88-70.73	81.23 (15.35) 44.19-116.00	44.85 (16.11) 9.26-79.69
	Posterior	37.92 (16.00) 7.41-78.38	86.44 (19.37) 42.00-148.65	-

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Tongue pressure measurement is in %.

Table B.3 presents the full results of the regression model of $T\%peak$ by swallowing condition as shown in Table 5. In this table (B.3), all regression coefficient estimates are provided including individual participant effects. Similarly, Tables B.4, B.5, and B.6 display the full results of the regression models showed in Tables 6 and 7, respectively, including all regression coefficient estimates.

Figures B.1 and B.2 show the relative percentage of peak tongue pressure ($T\%peak$) by swallowing condition for each participant.

Table B.3: Regression results of percentage of peak tongue pressure ($T\%peak$) by swallowing condition including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	36.026	2.474	14.56	<0.001	P20_O	-0.192	3.435	-0.05	0.955
EFSp	15.051	1.052	14.31	<0.001	P01_Y	2.618	3.435	0.76	0.446
EFSt	49.609	0.859	57.77	<0.001	P02_Y	-0.607	3.435	-0.17	0.859
P02_O	1.015	3.435	0.296	0.767	P03_Y	7.272	3.435	2.12	0.034
P03_O	-15.420	3.435	-4.49	<0.001	P04_Y	-6.906	3.435	-2.01	0.044
P04_O	-8.816	3.435	-2.57	0.010	P05_Y	22.304	3.435	6.49	<0.001
P05_O	9.339	3.435	2.72	0.006	P06_Y	-4.317	3.435	-1.26	0.209
P06_O	-5.205	3.435	-1.51	0.129	P07_Y	-2.864	3.435	-0.83	0.404
P07_O	15.526	3.435	4.52	<0.001	P08_Y	.6.604	3.435	-1.92	0.054
P08_O	-15.115	3.435	-4.40	<0.001	P09_Y	-15.852	3.435	-4.61	<0.001
P09_O	7.582	3.435	2.21	0.027	P10_Y	0.760	3.435	0.22	0.824
P10_O	-3.935	3.435	-1.14	0.252	P11_Y	-0.578	3.435	-0.17	0.866
P11_O	-2.559	3.435	-0.74	0.456	P12_Y	22.677	3.435	6.60	<0.001
P12_O	18.467	3.435	5.37	<0.001	P13_Y	-13.020	3.435	-3.79	<0.001
P13_O	-13.146	3.435	-3.83	<0.001	P14_Y	-19.699	3.435	-5.73	<0.001
P14_O	-8.542	3.435	-2.49	0.013	P15_Y	-8.095	3.435	-2.35	0.018
P15_O	12.187	3.435	-3.55	<0.001	P16_Y	1.586	3.435	0.46	0.644
P16_O	-5.598	3.435	-1.63	0.103	P17_Y	-8.882	3.435	-2.58	0.009
P17_O	-6.326	3.435	-1.84	0.065	P18_Y	1.130	3.435	0.33	0.742
P18_O	-10.328	3.435	-3.01	0.002	P19_Y	-15.877	3.435	-4.62	<0.001
P19_O	-9.780	3.435	-2.85	0.004	P20_Y	-15.005	3.435	-4.37	<0.001
R^2					0.782				
Adjusted R^2					0.774				
Observations					1200				

Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. O: older participants. Y: younger participants.

Table B.4: Regression results of percentage of peak tongue pressure ($T\%peak$) during normal swallows by tongue region including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	27.483	2.703	10.17	<0.001	P01_Y	-1.296	3.776	-0.34	0.731
Post.	9.239	0.844	11.00	<0.001	P02_Y	9.282	3.776	2.46	0.014
P02_O	4.199	3.776	1.12	0.266	P03_Y	14.501	3.776	3.84	<0.001
P03_O	-1.939	3.776	-0.51	0.607	P04_Y	-3.422	3.776	-0.90	0.365
P04_O	-11.608	3.776	-3.07	0.002	P05_Y	12.790	3.776	3.39	<0.001
P05_O	14.999	3.776	3.97	<0.001	P06_Y	-0.011	3.776	-0.00	0.997
P06_O	-1.116	3.776	-0.29	0.767	P07_Y	-0.426	3.776	-0.11	0.910
P07_O	12.339	3.776	3.27	0.001	P08_Y	-14.880	3.776	-3.94	<0.001
P08_O	-21.481	3.776	-5.69	<0.001	P09_Y	-14.216	3.776	-3.76	<0.001
P09_O	18.264	3.776	4.38	<0.001	P10_Y	18.413	3.776	4.88	<0.001
P10_O	-6.305	3.776	-1.67	0.095	P11_Y	-12.602	3.776	-3.34	<0.001
P11_O	9.056	3.776	2.40	0.016	P12_Y	28.211	3.776	7.47	<0.001
P12_O	24.874	3.776	6.59	<0.001	P13_Y	-10.022	3.776	-2.65	0.008
P13_O	-4.268	3.776	-1.13	0.258	P14_Y	-2.019	3.776	-0.53	0.593
P14_O	0.677	3.776	0.18	0.857	P15_Y	-1.448	3.776	-0.38	0.701
P15_O	-8.607	3.776	-2.28	0.023	P16_Y	-1.136	3.776	-0.30	0.763
P16_O	-6.193	3.776	-1.64	0.101	P17_Y	-3.700	3.776	-0.98	0.327
P17_O	5.298	3.776	1.40	0.161	P18_Y	9.559	3.776	2.53	0.011
P18_O	-1.149	3.776	-0.30	0.761	P19_Y	-6.408	3.776	-1.70	0.090
P19_O	-1.504	3.776	-0.40	0.690	P20_Y	-3.703	3.776	-0.98	0.327
P20_O	-12.300	3.776	-3.26	0.001					
R^2					0.645				
Adjusted R^2					0.613				
Observations					480				

Coef.: coefficients. β: estimate. SE: standard error. *t:* *t* value. *p:* *p*-value. Post.: posterior tongue region. P: participant. O: older participants. Y: younger participants.

Table B.5: Regression results of percentage of peak tongue pressure ($T\%peak$) during effortful swallow produced with tongue emphasis (EFSt) by tongue region including individual participant effects.

Coef.	β	SE	*t*	*p*	Coef.	β	SE	*t*	*p*
Intercept	90.150	3.747	24.06	<0.001	P01_Y	-2.618	5.234	-0.50	0.617
Post.	4.554	1.170	3.90	<0.001	P02_Y	-10.226	5.234	-1.95	0.051
P02_O	-10.786	5.234	-2.06	0.039	P03_Y	-1.146	5.234	-0.22	0.826
P03_O	-30.434	5.234	-5.81	<0.001	P04_Y	-15.007	5.234	-2.87	0.004
P04_O	-5.674	5.234	-1.08	0.278	P05_Y	23.641	5.234	4.52	<0.001
P05_O	-3.973	5.234	-0.76	0.448	P06_Y	-16.732	5.234	-3.20	0.001
P06_O	-6.637	5.234	-1.27	0.205	P07_Y	-8.949	5.234	-1.71	0.087
P07_O	11.867	5.234	2.27	0.023	P08_Y	0.492	5.234	0.09	0.925
P08_O	-10.945	5.234	-2.10	0.037	P09_Y	-25.984	5.234	-4.96	<0.001
P09_O	-5.831	5.234	-1.11	0.268	P10_Y	-18.868	5.234	-3.60	<0.001
P10_O	-7.822	5.234	-1.49	0.135	P11_Y	3.625	5.234	0.69	0.488
P11_O	-16.079	5.234	-3.07	0.002	P12_Y	9.618	5.234	1.84	0.066
P12_O	10.809	5.234	2.06	0.039	P13_Y	-21.388	5.234	-4.09	<0.001
P13_O	-21.264	5.234	-4.06	<0.001	P14_Y	-38.265	5.234	-7.31	<0.001
P14_O	-9.728	5.234	-1.86	0.063	P15_Y	-28.290	5.234	-5.41	<0.001
P15_O	-11.518	5.234	-2.20	0.028	P16_Y	4.623	5.234	0.88	0.377
P16_O	-3.396	5.234	-0.65	0.516	P17_Y	-18.514	5.234	-3.54	<0.001
P17_O	-20.427	5.234	-3.90	<0.001	P18_Y	-6.638	5.234	-1.27	0.205
P18_O	-23.092	5.234	-4.41	<0.001	P19_Y	-25.033	5.234	-4.78	<0.001
P19_O	-21.879	5.234	-4.18	<0.001	P20_Y	-29.309	5.234	-5.60	<0.001
P20_O	14.967	5.234	2.86	0.004					
R^2					0.555				
Adjusted R^2					0.514				
Observations					480				

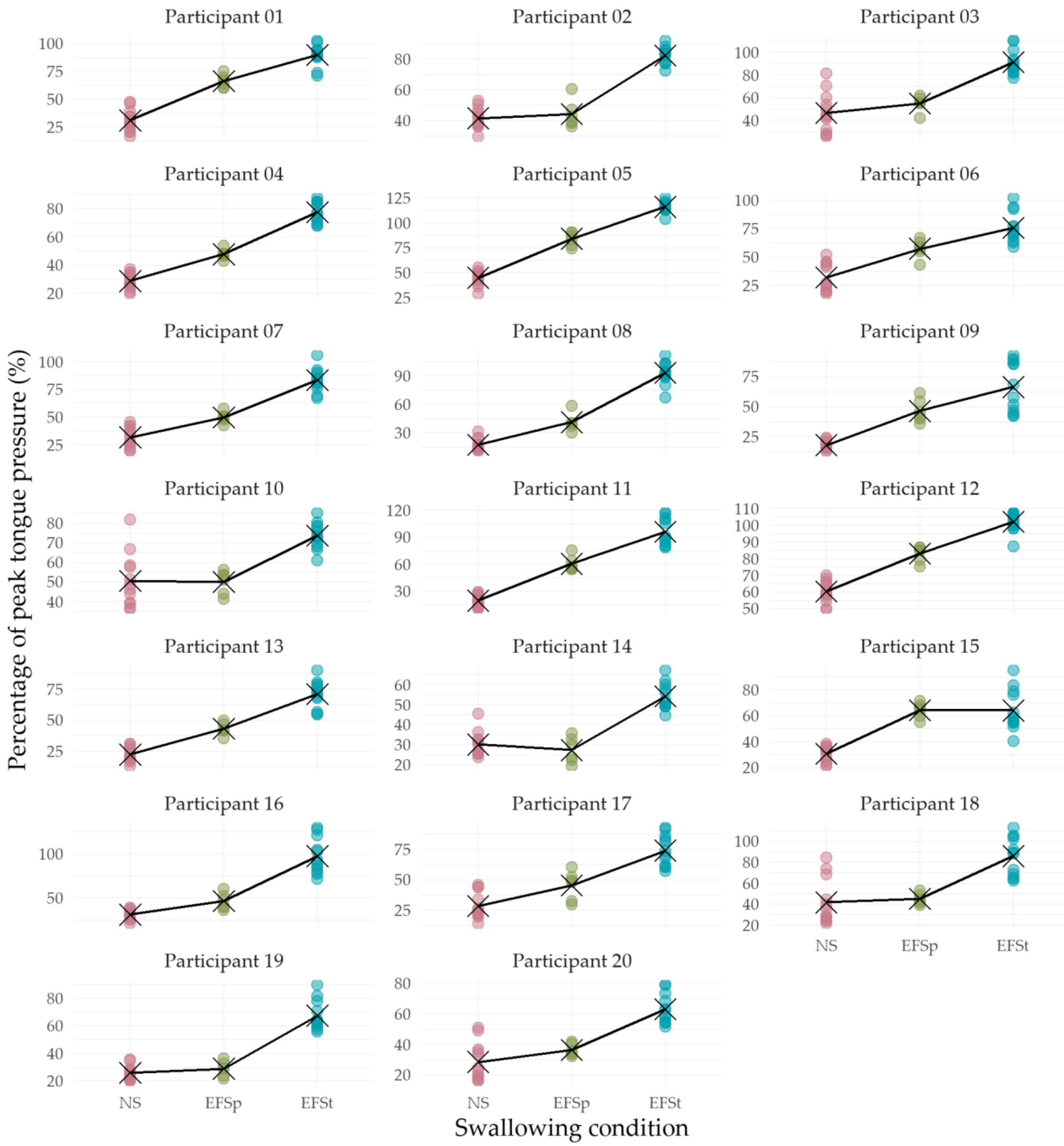
Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. Post.: posterior tongue region. P: participant. O: older participants. Y: younger participants.

Table B.6: Regression results of percentage of peak tongue pressure ($T\%peak$) by swallowing condition and group including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	36.052	2.501	14.41	<0.001	P18_O	-10.328	3.411	-3.03	0.002
EFSp	12.054	1.477	8.16	<0.001	P19_O	-9.780	3.411	-2.87	0.004
EFSt	51.043	1.206	42.32	<0.001	P20_O	-0.192	3.411	-0.05	0.955
Younger	-15.056	3.537	-4.26	<0.001	P01_Y	17.623	3.411	5.16	<0.001
EFSp*Y	5.994	2.089	2.87	0.004	P02_Y	14.397	3.411	4.22	<0.001
EFSt*Y	-2.867	1.706	-1.68	0.093	P03_Y	22.246	3.411	6.53	<0.001
P02_O	1.015	3.411	0.30	0.766	P04_Y	8.099	3.411	2.37	0.017
P03_O	-15.420	3.411	-4.52	<0.001	P05_Y	37.309	3.411	10.93	<0.001
P04_O	-8.816	3.411	-2.58	0.009	P06_Y	10.687	3.411	3.13	0.001
P05_O	9.339	3.411	2.74	0.006	P07_Y	12.140	3.411	3.56	<0.001
P06_O	-5.205	3.411	-1.52	0.127	P08_Y	8.400	3.411	2.46	0.013
P07_O	15.526	3.411	4.55	<0.001	P09_Y	-0.848	3.411	-0.25	0.803
P08_O	-15.115	3.411	-4.43	<0.001	P10_Y	15.764	3.411	4.62	<0.001
P09_O	7.582	3.411	2.22	0.026	P11_Y	14.426	3.411	4.23	<0.001
P10_O	-3.935	3.411	-1.15	0.248	P12_Y	37.682	3.411	11.04	<0.001
P11_O	-2.559	3.411	-0.75	0.453	P13_Y	1.984	3.411	0.58	0.561
P12_O	18.467	3.411	5.41	<0.001	P14_Y	-4.694	3.411	-1.37	0.169
P13_O	-13.146	3.411	-3.85	<0.001	P15_Y	6.914	3.411	2.03	0.043
P14_O	-8.542	3.411	-2.50	0.012	P16_Y	16.590	3.411	4.86	<0.001
P15_O	-12.187	3.411	-3.57	<0.001	P17_Y	6.122	3.411	1.79	0.073
P16_O	-5.598	3.411	-1.64	0.101	P18_Y	16.134	3.411	4.73	<0.001
P17_O	-6.326	3.411	-1.85	0.063	P19_Y	-0.872	3.411	-0.25	0.798
R^2					0.785				
Adjusted R^2					0.777				
Observations					1200				

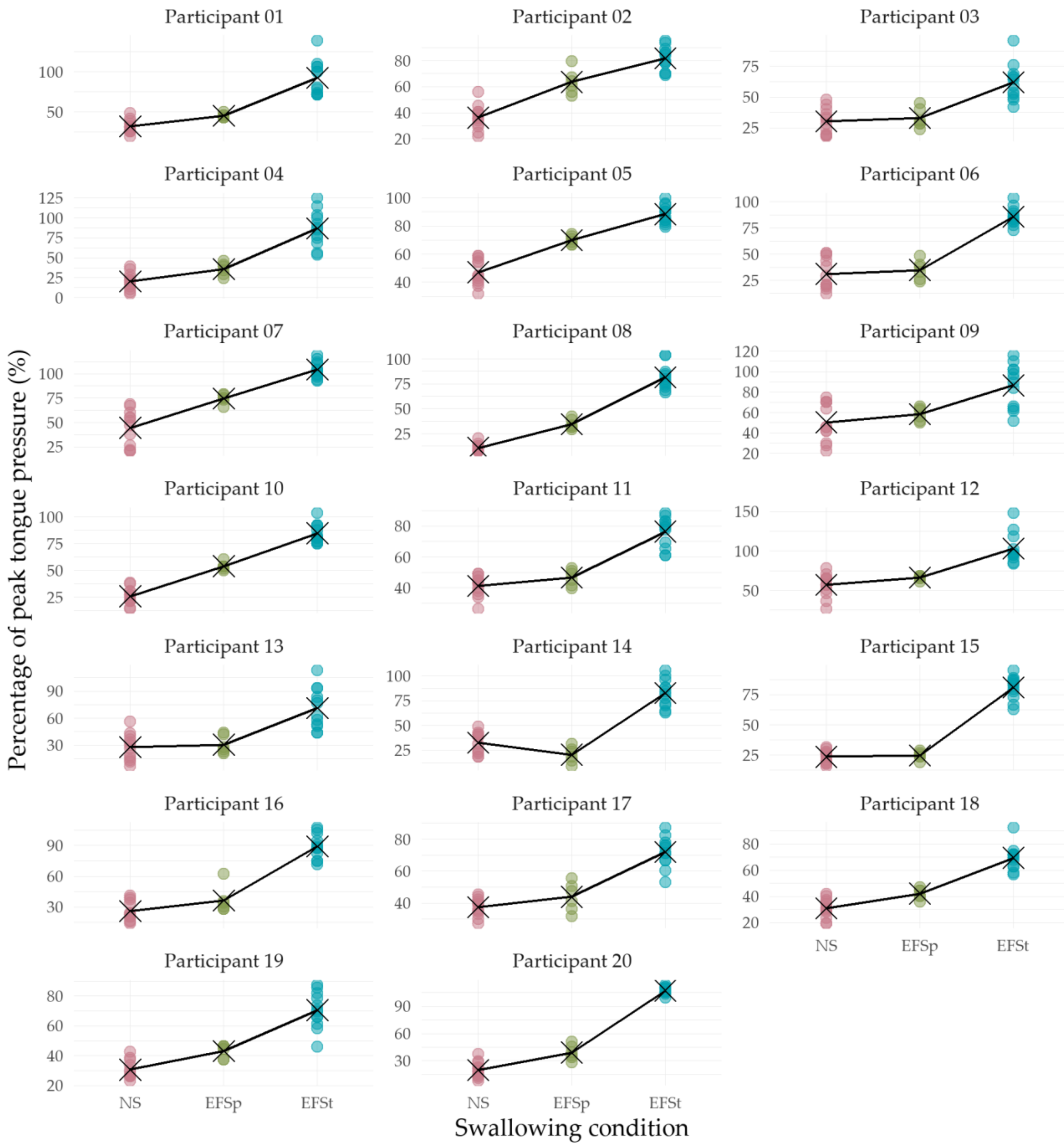
Coef.: coefficients. β: estimate. SE: standard error. *t*: *t* value. *p*: *p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. Y: younger participants. O: older participants.

Figure B.1: Individual relative percentage of peak tongue pressure ($T\%peak$) by swallowing condition in younger participants.



Notes: Dots represent swallow events at which tongue pressures were recorded (30 swallows per participant). Black crosses in each swallowing condition indicate mean $T\%peak$. Black lines connect mean $T\%peak$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figure B.2: Individual relative percentage of peak tongue pressure ($T\%peak$) across swallowing condition in older participants.



Notes: Dots represent swallow events at which tongue pressures were recorded (30 swallows per participant). Black crosses in each swallowing condition indicate mean $T\%peak$. Black lines connect mean $T\%peak$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figures B.3, B.4, and B.5 show the regression diagnostics for the regression models [1], [2], and [3], respectively.

Figure B.3: Regression diagnostics for the regression model [1].

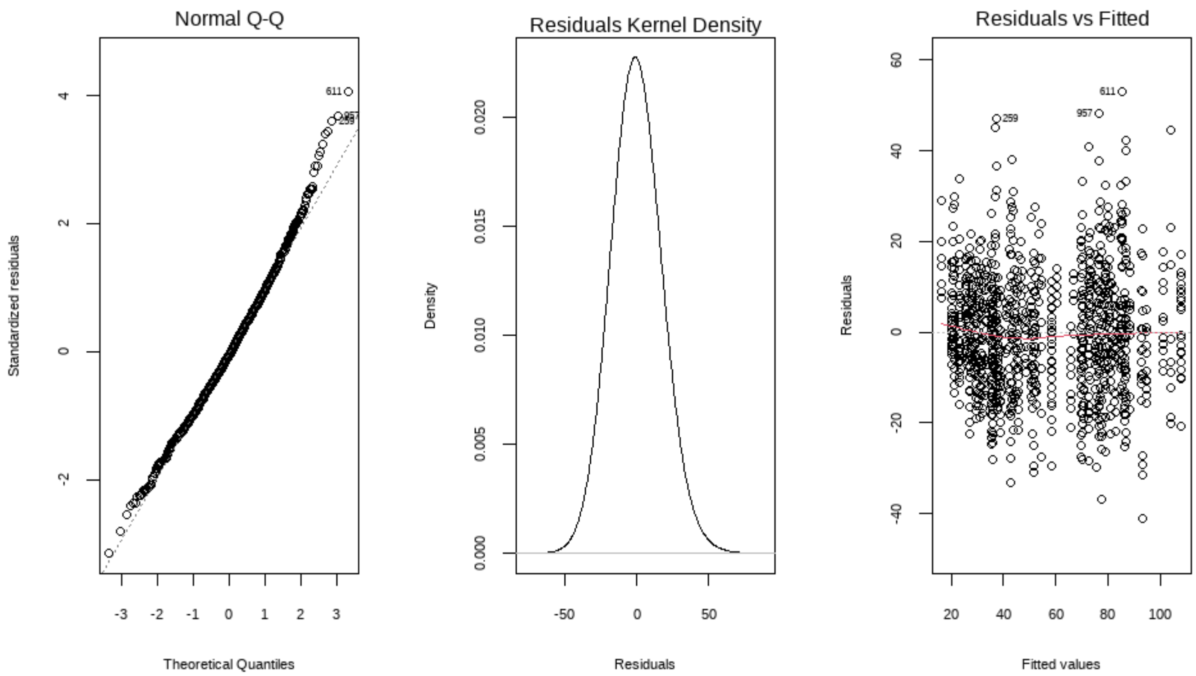


Figure B.4: Regression diagnostics for the regression model [2].

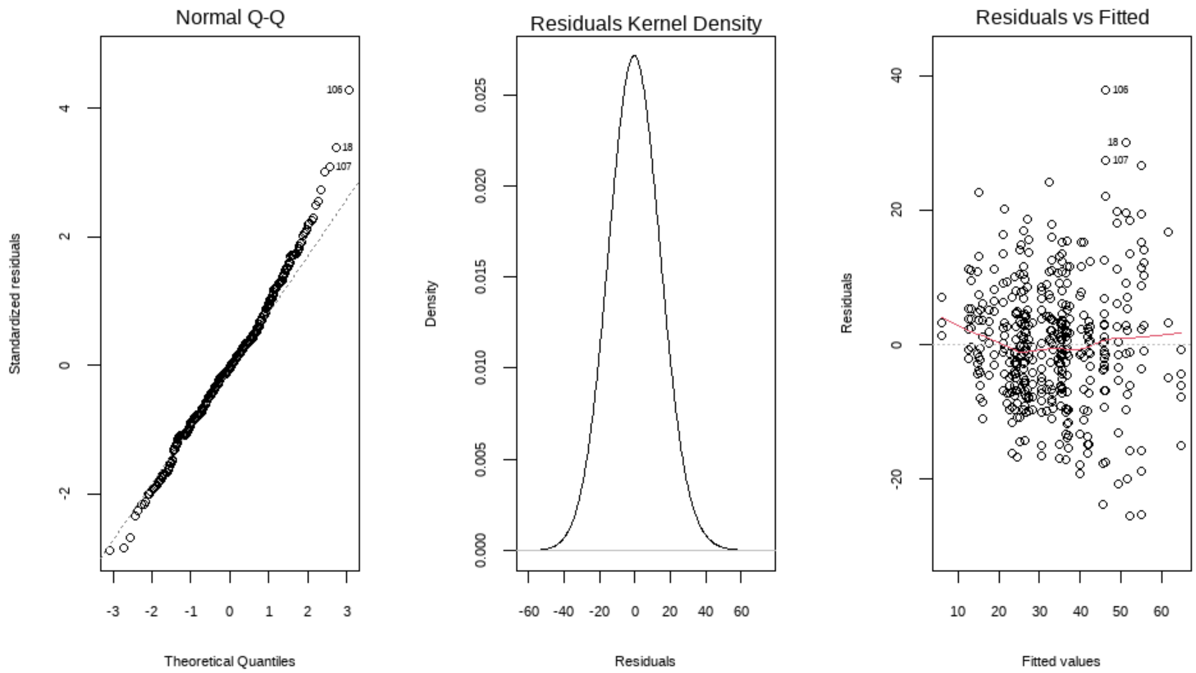
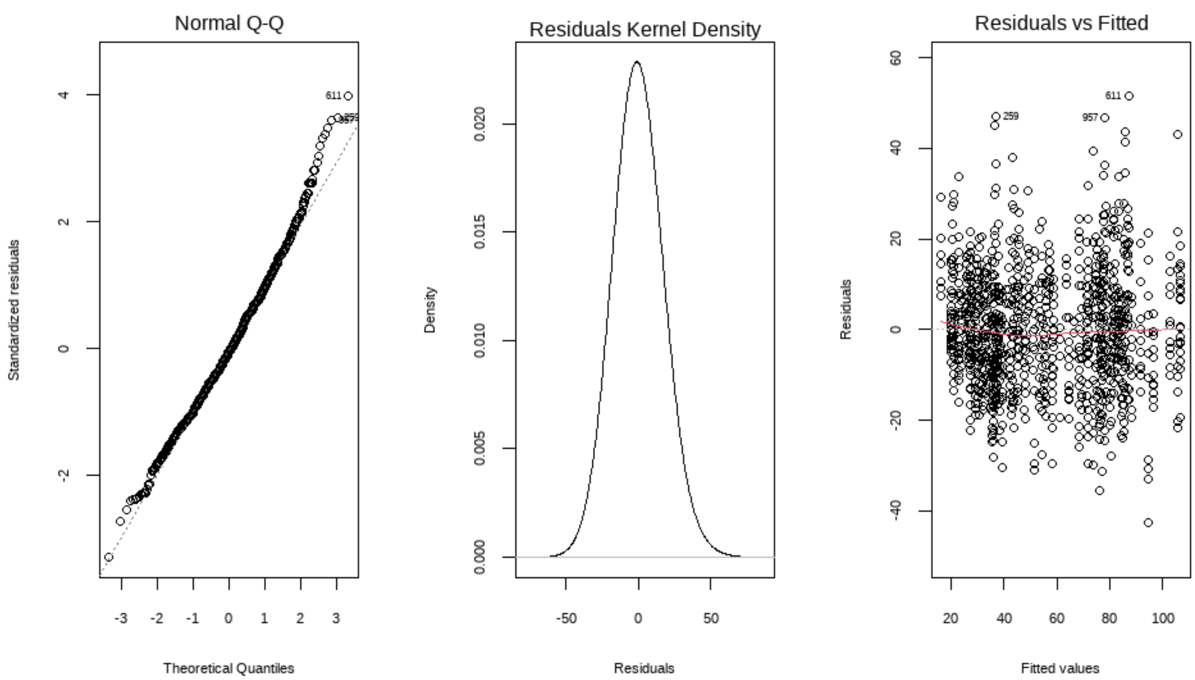


Figure B.5: Regression diagnostics for the regression model [3].



Appendix C: Hyoid Displacement

Tables C.1 and C.2 summarize the *raw data* for the hyoid-mandible resting distance ($Hrest$) and hyoid-mandible swallowing distance ($Hswallow$) by swallowing condition and group.

Table C.1: Mean hyoid-mandible resting distance ($Hrest$) by swallowing condition and group.

Group	NS	EFSt	EFSp
	Mean (*SD*) Min-Max	*Mean* (*SD*) Min-Max	*Mean* (*SD*) Min-Max
Younger	4.89 (0.52) 3.83-6.16	4.93 (0.58) 3.77-6.48	4.93 (0.54) 4.04-6.31
Older	4.75 (0.55) 3.43-6.07	4.86 (0.55) 3.83-6.41	4.91 (0.57) 3.70-6.13

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Hyoid measurement is in cm.

Table C.2: Mean hyoid-mandible swallowing distance ($Hswallow$) by swallowing condition and group.

Group	NS	EFSt	EFSp
	Mean (*SD*) Min-Max	*Mean* (*SD*) Min-Max	*Mean* (*SD*) Min-Max
Younger	3.83 (0.46) 2.85-5.02	3.28 (0.57) 2.22-4.71	3.38 (0.54) 2.37-4.74
Older	3.66 (0.55) 2.27-4.87	3.21 (0.55) 2.05-4.53	3.37 (0.61) 2.02-4.92

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Hyoid measurement is in cm.

Table C.3 presents the full results of the regression model of $H\%change$ by swallowing condition as shown in Table 8. In this table (C.3) all regression coefficient estimates are provided including individual participant effects. Similarly, Tables C.4 and C.5 display the full results of the regression models showed in Tables 9 and 10, respectively, including all regression coefficient estimates.

Figures C.1 and C.2 display the relative $H\%change$ by swallowing condition of for participant.

Table C.3: Regression results of percent change in hyoid displacement ($H\%change$) by swallowing condition including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	20.951	1.327	15.78	<0.001	P20_O	-6.963	1.769	-3.93	<0.001
EFSp	9.252	0.553	16.74	<0.001	P01_Y	-4.399	1.770	-2.48	0.013
EFSt	11.687	0.450	25.97	<0.001	P02_Y	-4.518	1.837	-2.46	0.014
P02_O	4.563	1.802	2.53	0.011	P03_Y	-2.553	1.927	-1.32	0.186
P03_O	6.499	1.800	3.61	<0.001	P04_Y	3.040	2.053	1.48	0.139
P04_O	1.106	1.800	0.61	0.539	P05_Y	3.957	2.053	1.93	0.054
P05_O	1.747	1.800	0.97	0.332	P06_Y	0.200	1.801	0.11	0.911
P06_O	3.337	1.877	1.77	0.076	P07_Y	4.140	1.801	2.30	0.021
P07_O	4.124	1.926	2.14	0.032	P08_Y	3.643	2.053	1.77	0.076
P08_O	-1.517	1.742	-0.87	0.384	P09_Y	1.565	1.928	0.81	0.417
P09_O	3.365	1.769	1.90	0.058	P10_Y	1.423	1.800	0.79	0.429
P10_O	5.521	1.983	2.78	0.005	P11_Y	1.492	1.984	0.75	0.452
P11_O	3.355	1.742	1.92	0.054	P12_Y	-0.252	1.770	-0.14	0.886
P12_O	5.165	1.742	2.96	0.003	P13_Y	5.712	1.742	3.23	0.001
P13_O	-1.456	1.837	-0.79	0.428	P14_Y	5.735	1.801	3.18	0.001
P14_O	-0.792	1.742	-0.45	0.649	P15_Y	-0.029	1.801	-0.01	0.987
P15_O	-0.149	1.769	-0.08	0.933	P16_Y	5.800	1.770	3.27	0.001
P16_O	2.863	1.742	1.64	0.100	P17_Y	-0.941	1.769	-0.53	0.595
P17_O	4.077	1.769	2.30	0.021	P18_Y	0.516	1.769	0.29	0.770
P18_O	2.466	1.801	1.37	0.171	P19_Y	-0.749	1.742	-0.43	0.667
P19_O	2.110	1.770	1.19	0.233	P20_Y	-0.675	1.802	-0.37	0.708
R^2					0.675				
Adjusted R^2					0.646				
Observations					507				

Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. O: older participants. Y: younger participants.

Table C.4: Regression results of percent change in hyoid displacement ($H\%change$) by swallowing condition and tongue region including individual participant effects.

Coef.	β	SE	*t*	*p*	Coef.	β	SE	*t*	*p*
Intercept	20.029	1.479	13.55	<0.001	P20_O	-5.757	1.976	-2.91	0.003
EFSt	11.751	0.646	18.19	<0.001	P01_Y	-3.715	1.937	-1.92	0.055
Post.	0.268	0.655	0.41	0.683	P02_Y	-3.307	2.080	-1.59	0.112
EFSt*Post	-0.102	0.905	-0.11	0.910	P03_Y	-1.458	2.150	-0.68	0.497
P02_O	4.104	2.025	2.01	0.043	P04_Y	4.091	2.339	1.75	0.081
P03_O	6.791	1.978	1.98	<0.001	P05_Y	5.840	2.336	2.50	0.012
P04_O	1.283	1.978	1.98	0.516	P06_Y	1.302	2.023	0.64	0.520
P05_O	3.024	1.976	1.97	0.126	P07_Y	4.468	2.022	2.21	0.027
P06_O	3.630	2.079	2.08	0.081	P08_Y	4.372	2.339	1.87	0.062
P07_O	4.041	2.079	2.08	0.052	P09_Y	2.914	2.231	1.30	0.192
P08_O	0.382	1.937	1.93	0.843	P10_Y	1.451	1.978	0.73	0.463
P09_O	4.988	1.976	2.52	0.012	P11_Y	3.126	2.230	1.40	0.161
P10_O	5.130	2.231	2.30	0.022	P12_Y	0.532	1.937	0.27	0.783
P11_O	4.876	1.937	2.52	0.012	P13_Y	5.885	1.937	3.04	0.002
P12_O	6.683	1.937	3.45	<0.001	P14_Y	4.780	2.026	2.36	0.018
P13_O	0.098	2.079	0.05	0.962	P15_Y	0.187	1.978	0.09	0.924
P14_O	0.223	1.937	0.11	0.908	P16_Y	6.901	1.978	3.49	<0.001
P15_O	-1.609	1.976	-0.81	0.416	P17_Y	-0.225	1.976	-0.11	0.909
P16_O	5.013	1.937	2.59	0.010	P18_Y	1.610	1.976	0.81	0.415
P17_O	5.508	1.978	2.78	0.005	P19_Y	0.529	1.937	0.27	0.785
P18_O	3.625	2.025	1.79	0.074	P20_Y	-0.608	2.026	-0.30	0.764
P19_O	3.004	1.937	1.55	0.121					
R^2					0.704				
Adjusted R^2					0.670				
Observations					405				

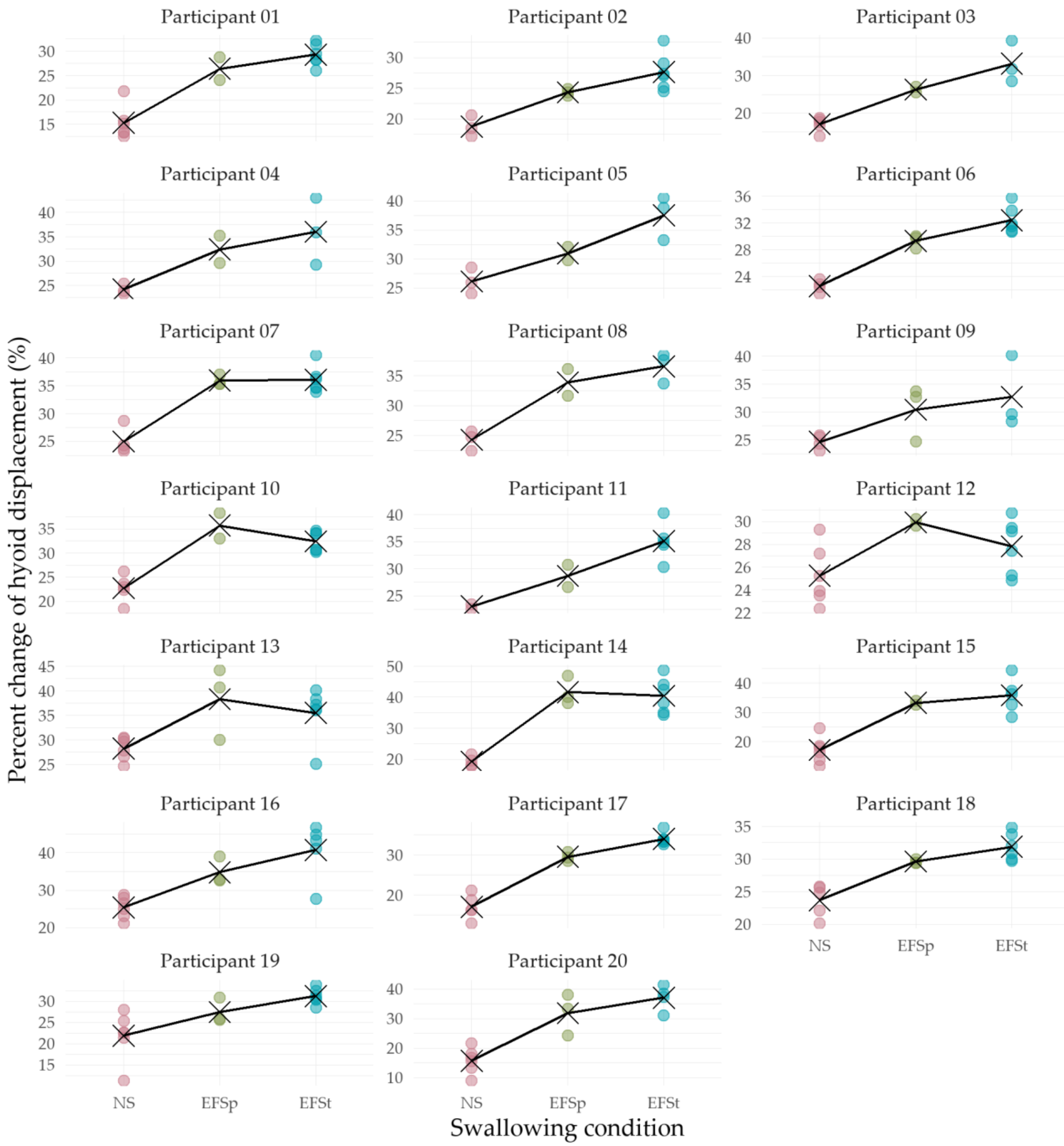
Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSt: effortful swallow produced with tongue emphasis. Post.: posterior tongue region. P: participant. O: older participants. Y: younger participants.

Table C.5: Regression results of percent change in hyoid displacement ($H\%change$) by swallowing condition and group including individual participant effects.

Coef.	β	SE	*t*	*p*	Coef.	β	SE	*t*	*p*
Intercept	21.282	1.354	15.72	<0.001	P18_O	2.445	1.802	1.35	0.175
EFSp	8.718	0.773	11.27	<0.001	P19_O	2.063	1.771	1.16	0.244
EFSt	11.202	0.619	18.10	<0.001	P20_O	-6.972	1.770	-3.94	<0.001
Younger	-1.307	1.870	-0.70	0.484	P01_Y	-3.740	1.735	-2.15	0.031
EFSp*Y	1.110	1.106	1.00	0.316	P02_Y	-3.959	1.806	-2.19	0.028
EFSt*Y	1.032	0.902	1.14	0.253	P03_Y	-1.856	1.893	-0.98	0.327
P02_O	4.504	1.804	2.49	0.012	P04_Y	3.667	2.022	1.81	0.070
P03_O	6.474	1.801	3.59	<0.001	P05_Y	4.584	2.022	2.27	0.023
P04_O	1.080	1.801	0.60	0.548	P06_Y	0.791	1.768	0.45	0.654
P05_O	1.721	1.801	0.95	0.339	P07_Y	4.731	1.768	2.67	0.007
P06_O	3.323	1.878	1.77	0.077	P08_Y	4.270	2.022	2.11	0.035
P07_O	4.089	1.927	2.12	0.034	P09_Y	2.204	1.893	1.16	0.244
P08_O	-1.548	1.743	-0.88	0.374	P10_Y	2.058	1.767	1.16	0.244
P09_O	3.356	1.770	1.89	0.058	P11_Y	2.036	1.957	1.04	0.298
P10_O	5.523	1.984	2.78	0.005	P12_Y	0.407	1.735	0.23	0.814
P11_O	3.324	1.743	1.91	0.057	P13_Y	6.353	1.706	3.72	<0.001
P12_O	5.134	1.743	2.94	0.003	P14_Y	6.326	1.768	3.58	<0.001
P13_O	-1.492	1.839	-0.81	0.417	P15_Y	0.648	1.766	0.37	0.713
P14_O	-0.823	1.743	-0.47	0.637	P16_Y	6.457	1.733	3.72	<0.001
P15_O	-0.158	1.770	-0.09	0.929	P17_Y	-0.323	1.734	-0.18	0.852
P16_O	2.832	1.743	1.62	0.104	P18_Y	1.135	1.734	0.65	0.513
P17_O	4.067	1.770	2.30	0.022	P19_Y	-0.107	1.706	-0.06	0.950
R^2					0.676				
Adjusted R^2					0.646				
Observations					507				

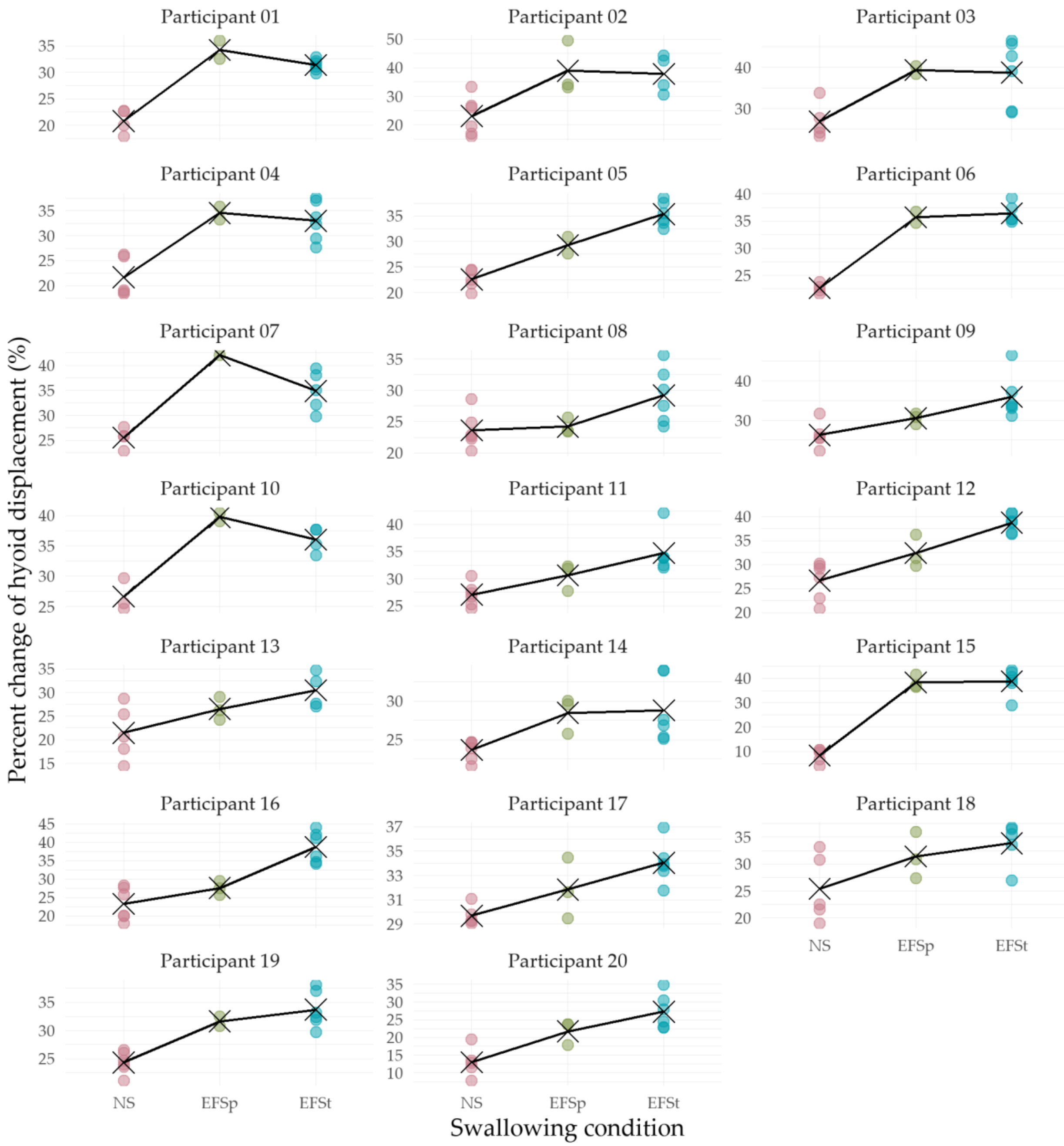
Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Y: younger participants. P: participant. O: older participants.

Figure C.1: Individual relative percent change of hyoid displacement ($H\%change$) by swallowing condition and group in younger participants.



Notes: Dots represent swallow events at which hyoid displacement were recorded. Black crosses in each swallowing condition indicate mean $H\%change$. Black lines connect mean $H\%change$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figure C.2: Individual relative percent change of hyoid displacement ($H\%change$) by swallowing condition and group in older participants.



Notes: Dots represent swallow events at which hyoid displacement were recorded. Black crosses in each swallowing condition indicate mean $H\%change$. Black lines connect mean $H\%change$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figures C.3, C.4, and C.5 show the regression diagnostics for the regression models [4], [6], and [8], respectively.

Figure C.3: Regression diagnostics for the regression model [4].

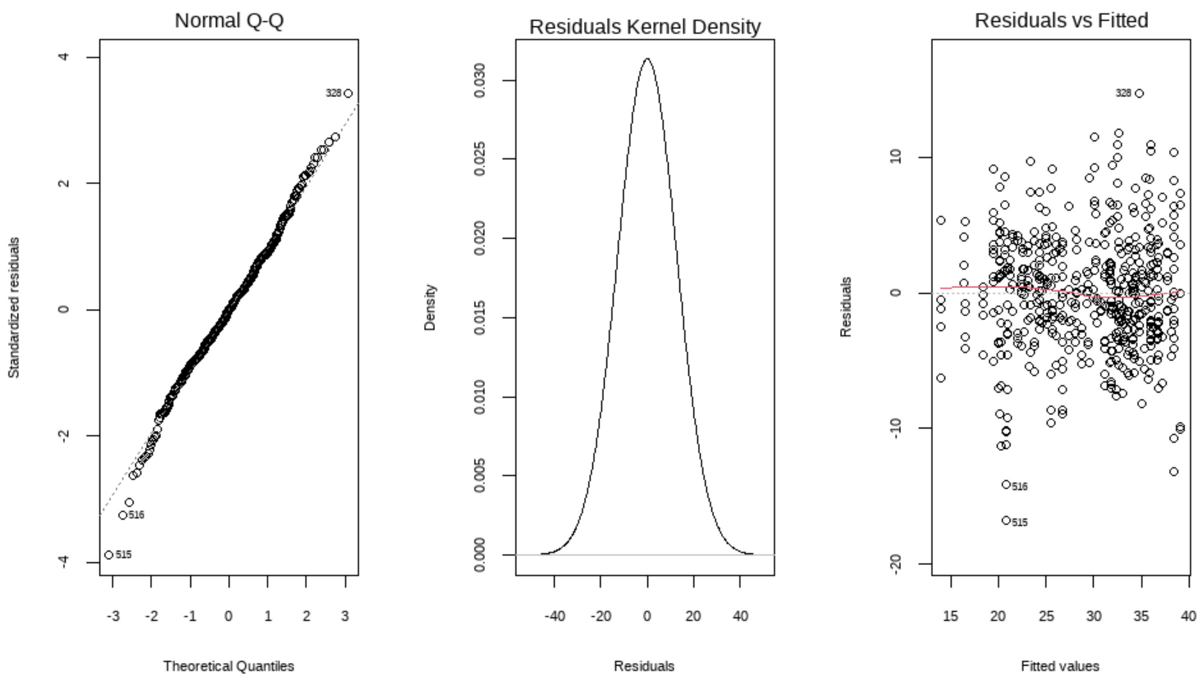


Figure C.4: Regression diagnostics for the regression model [6].

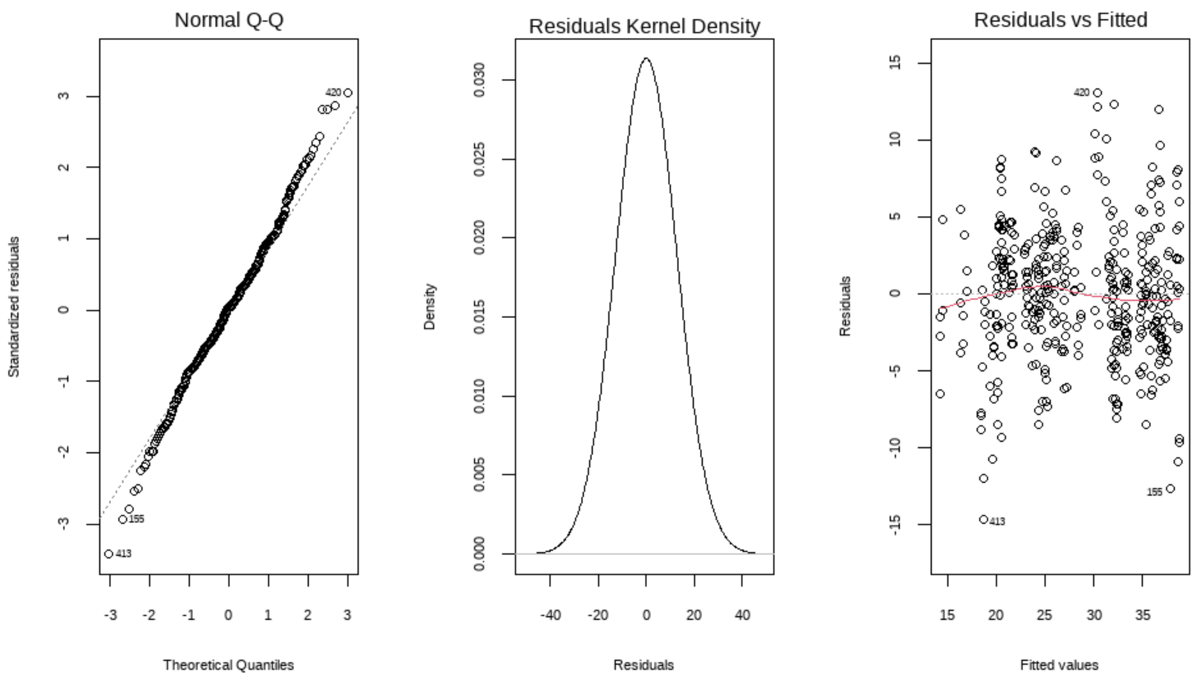
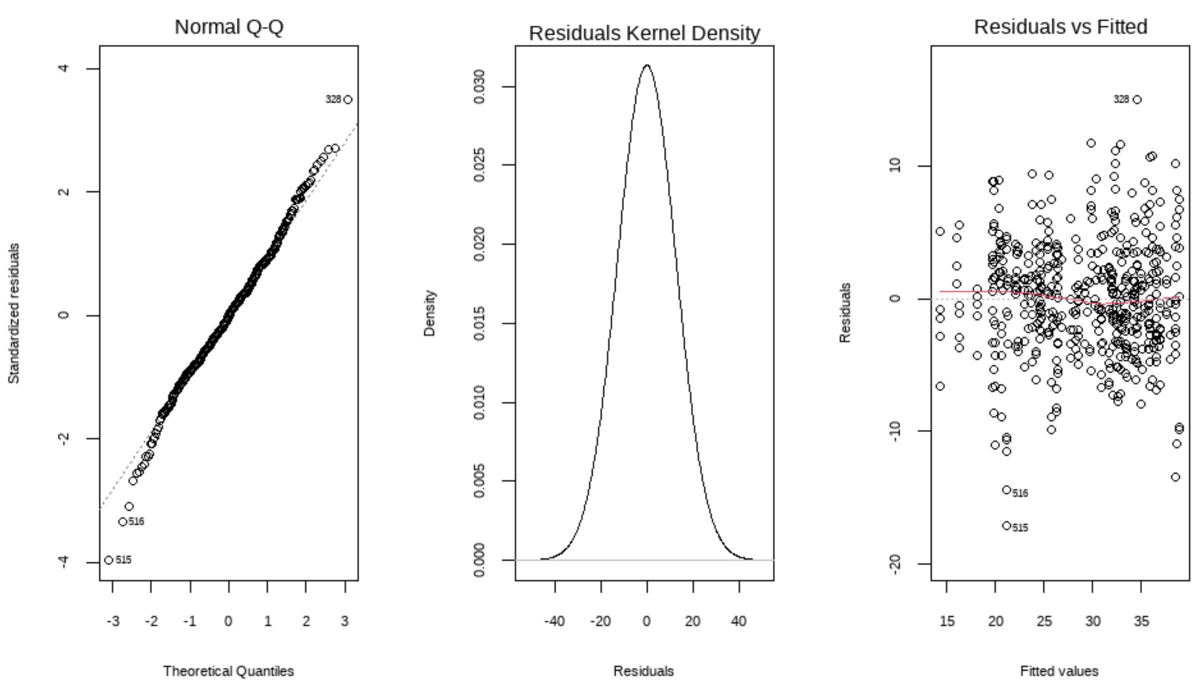


Figure C.5: Regression diagnostics for the regression model [8].



Appendix D: Hyoid-Larynx Approximation

Tables D.1 and D.2 summarize the *raw data* for hyoid-larynx resting distance ($HLrest$) and hyoid-larynx swallowing distance ($HLswallow$) by swallowing condition and group.

Table D.1: Mean hyoid-larynx resting distance ($HLrest$) by swallowing condition and group.

Group	NS *Mean* (*SD*) Min-Max	EFSt *Mean* (*SD*) Min-Max	EFSp *Mean* (*SD*) Min-Max
Younger	1.64 (0.36) 0.76-2.54	1.61 (0.35) 0.73-2.34	1.61 (0.41) 0.93-2.54
Older	1.78 (0.50) 0.75-2.98	1.89 (0.46) 1.06-2.83	1.82 (0.46) 1.08-2.74

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Hyoid-larynx measurement is in cm.

Table D.2: Mean hyoid-larynx swallow distance ($HLswallow$) by swallowing condition and group.

Group	NS	EFSt	EFSp
	Mean (*SD*) Min-Max	*Mean* (*SD*) Min-Max	*Mean* (*SD*) Min-Max
Younger	0.67 (0.31) 0.00-1.40	0.17 (0.23) 0.00-0.81	0.20 (0.28) 0.00-0.89
Older	0.88 (0.40) 0.27-1.73	0.46 (0.25) 0.00-1.17	0.39 (0.24) 0.00-0.92

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Hyoid-larynx measurement is in cm.

Table D.3 presents the full results of the regression model of $HL\%change$ by swallowing condition as shown in Table 11. In this table (D.3) all regression coefficient estimates are provided including individual participant effects. Similarly, Tables D.4 and D.5 show the full results of the regression models showed in Tables 12 and 13, respectively, including all regression coefficient estimates.

Figures D.1 and D.2 show the relative $HL\%change$ by swallowing condition for each participant.

Table D.3: Regression results of percent change in hyoid-larynx approximation displacement ($HL\%change$) by swallowing condition including individual participant effects.

Coef.	β	SE	*t*	*p*	Coef.	β	SE	*t*	*p*
Intercept	56.342	2.767	20.36	<0.001	P20_O	11.726	3.906	3.00	0.002
EFSp	27.998	1.239	22.60	<0.001	P01_Y	-0.713	3.697	0.19	0.847
EFSt	27.565	1.028	26.81	<0.001	P02_Y	9.201	4.384	2.10	0.036
P02_O	-16.473	3.999	-4.12	<0.001	P03_Y	10.828	4.386	2.47	0.013
P03_O	-8.09	3.826	-2.11	0.035	P04_Y	-0.698	3.997	-0.17	0.861
P04_O	-9.304	3.759	-2.47	0.013	P05_Y	-4.457	3.906	1-1.4	0.254
P05_O	-7.668	4.575	-1.67	0.094	P06_Y	11.258	4.104	2.74	0.006
P06_O	-2.8	4.384	-0.64	0.523	P07_Y	9.413	3.826	2.46	0.014
P07_O	-12.584	3.759	-3.35	<0.001	P08_Y	11.858	3.998	2.96	0.003
P08_O	-5.758	3.906	-1.48	0.141	P09_Y	21.354	4.231	5.05	<0.001
P09_O	0.433	4.231	0.10	0.918	P10_Y	12.934	3.906	3.31	0.001
P10_O	-4.249	3.758	-1.13	0.258	P11_Y	-0.713	4.104	-0.17	0.862
P11_O	-12.935	3.758	-3.44	<0.001	P12_Y	13.799	4.104	3.36	<0.001
P12_O	-10.903	4.109	-2.65	0.008	P13_Y	10.546	3.997	2.64	0.008
P13_O	-5.461	3.827	-1.43	0.154	P14_Y	11.371	3.997	2.84	0.004
P14_O	-12.471	3.697	-3.37	<0.001	P15_Y	3.589	4.233	0.85	0.397
P15_O	-18.428	4.231	-4.35	<0.001	P16_Y	2.634	3.906	0.67	0.500
P16_O	-0.246	3.906	-0.06	0.949	P17_Y	10.533	3.758	2.80	0.005
P17_O	-5.184	3.828	-1.35	0.176	P18_Y	6.511	3.758	1.73	0.083
P18_O	-2.547	4.105	-0.62	0.535	P19_Y	-8.759	3.758	-2.33	0.020
P19_O	8.032	3.827	2.10	0.036	P20_Y	-9.882	3.906	-2.53	0.011
R^2					0.758				
Adjusted R^2					0.734				
Observations					462				

Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. O: older participants. Y: younger participants.

Table D.4: Regression results of percent change in hyoid-larynx approximation ($HL\%change$) by swallowing condition and tongue region including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	55.514	3.208	17.30	<0.001	P20_O	12.138	4.503	2.70	0.007
EFSt	27.256	1.444	18.88	<0.001	P01_Y	3.092	4.194	0.73	0.461
Post.	0.407	1.475	0.27	0.782	P02_Y	7.650	5.057	1.51	0.131
EFSt*Post.	0.531	2.065	0.26	0.797	P03_Y	10.848	4.830	2.46	0.025
P02_O	-17.137	4.503	-3.80	<0.001	P04_Y	-3.667	4.500	-0.81	0.415
P03_O	-9.628	4.382	-2.20	0.002	P05_Y	1.075	4.500	0.24	0.811
P04_O	-8.486	4.194	-2.02	0.043	P06_Y	14.376	4.646	3.09	0.002
P05_O	-3.504	5.366	-0.65	0.514	P07_Y	8.253	4.382	1.88	0.060
P06_O	-0.879	5.061	-0.17	0.862	P08_Y	12.154	4.647	2.61	0.009
P07_O	-12.640	4.194	-3.04	0.002	P09_Y	23.659	4.827	4.90	<0.001
P08_O	-2.980	4.384	-0.68	0.497	P10_Y	13.103	4.382	2.99	0.003
P09_O	0.484	4.830	0.10	0.920	P11_Y	-4.160	4.646	-0.89	0.371
P10_O	-1.798	4.280	-0.42	0.674	P12_Y	13.712	4.830	2.84	0.004
P11_O	-11.372	4.282	-2.65	0.008	P13_Y	13.141	4.503	2.92	0.003
P12_O	-10.276	4.506	-2.28	0.023	P14_Y	11.040	4.503	2.45	0.014
P13_O	-1.961	4.382	-0.45	0.654	P15_Y	6.890	5.061	1.36	0.174
P14_O	-12.234	4.194	-2.92	0.003	P16_Y	1.556	4.503	0.34	0.729
P15_O	-20.007	4.834	-4.14	<0.001	P17_Y	10.853	4.280	2.53	0.011
P16_O	1.540	4.382	4.40	0.725	P18_Y	6.192	4.282	1.44	0.149
P17_O	-5.050	4.279	4.28	0.238	P19_Y	-5.114	4.282	-1.19	0.233
P18_O	-4.037	4.830	4.83	0.403	P20_Y	-11.639	4.379	-2.66	0.008
P19_O	6.394	4.382	4.38	0.145					
R^2					0.766				
Adjusted R^2					0.736				
Observations					365				

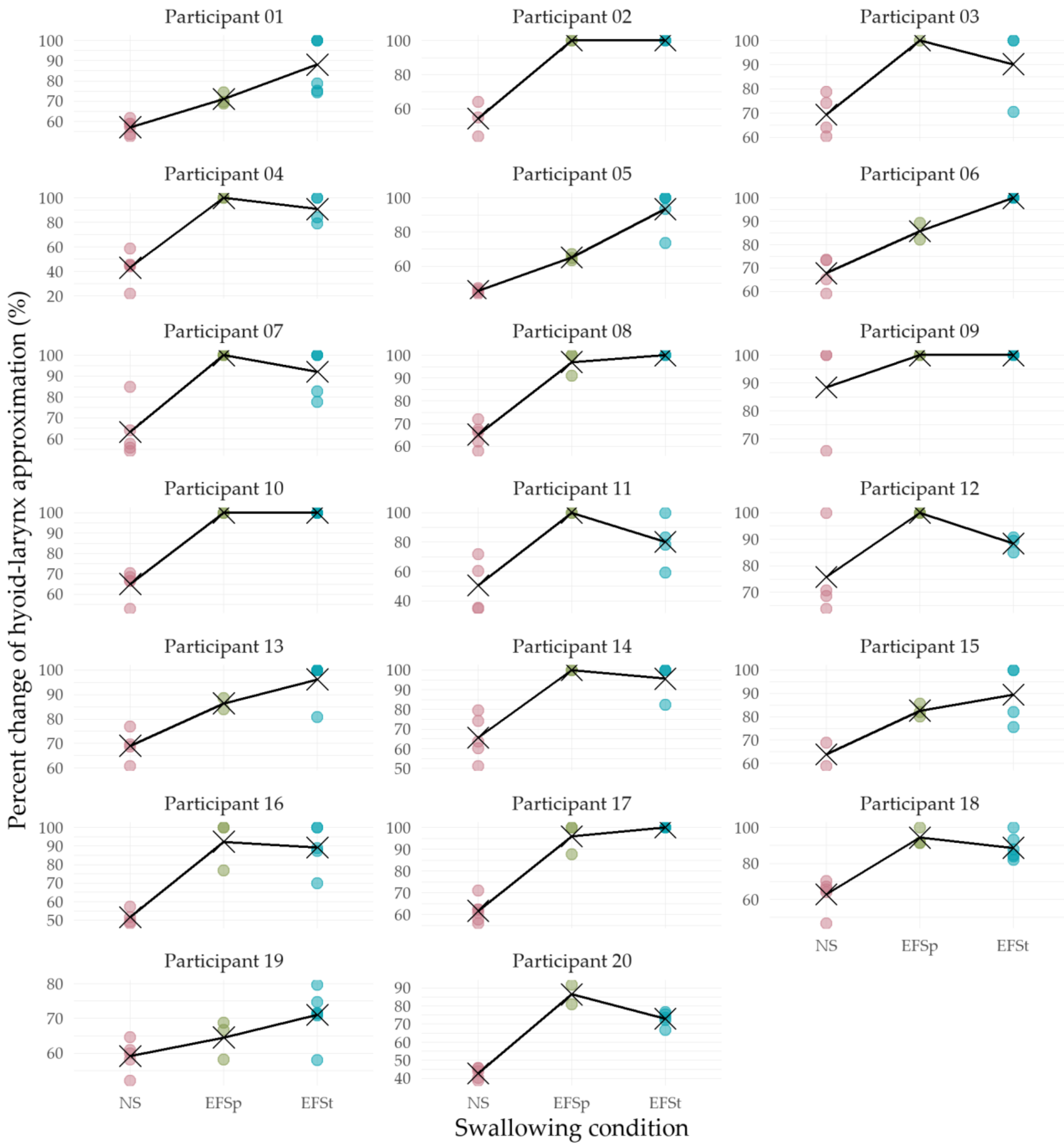
Coef.: coefficients. β: estimate. SE: standard error. *t:* *t* value. *p:* *p*-value. EFSt: effortful swallow produced with tongue emphasis. Post.: posterior tongue region. P: participant participants. O: older. Y: younger participants.

Table D.5: Regression results of percent change in hyoid-larynx approximation ($HL\%change$) by swallowing condition and group including individual participant effects.

Coef.	β	SE	*t*	*p*	Coef.	β	SE	*t*	*p*
Intercept	57.797	2.803	20.62	<0.001	P18_O	-2.402	4.074	-0.59	0.555
EFSp	26.542	1.742	15.24	<0.001	P19_O	8.256	3.798	2.17	0.030
EFSt	24.657	1.424	17.31	<0.001	P20_O	11.605	3.876	2.99	0.002
Younger	-12.657	4.034	-3.20	0.001	P01_Y	9.170	3.749	2.44	0.014
EFSp*Y	2.950	3.809	1.99	0.231	P02_Y	19.085	4.420	4.32	<0.001
EFSt*Y	5.977	2.041	2.93	0.003	P03_Y	20.899	4.420	4.73	<0.001
P02_O	-16.076	3.971	-4.05	<0.001	P04_Y	9.323	4.041	2.31	0.021
P03_O	-8.090	3.797	-2.13	0.033	P05_Y	5.300	3.955	1.34	0.180
P04_O	-9.304	3.731	-2.50	0.013	P06_Y	21.141	4.145	5.10	<0.001
P05_O	-7.876	4.540	-1.73	0.083	P07_Y	19.297	3.876	4.98	<0.001
P06_O	-2.800	4.350	-0.64	0.520	P08_Y	22.022	4.046	5.44	<0.001
P07_O	-12.584	3.731	-3.37	<0.001	P09_Y	31.067	4.270	7.27	<0.001
P08_O	-5.758	3.876	-1.48	0.138	P10_Y	22.816	3.952	5.77	<0.001
P09_O	0.595	4.198	0.14	0.887	P11_Y	9.170	4.145	2.21	0.027
P10_O	-4.353	3.729	-1.17	0.243	P12_Y	23.839	4.151	5.74	<0.001
P11_O	-12.831	3.729	-3.44	<0.001	P13_Y	20.289	4.041	5.02	<0.001
P12_O	-11.340	4.083	-2.78	0.005	P14_Y	21.393	4.041	5.30	<0.001
P13_O	-5.237	3.798	-1.38	0.168	P15_Y	13.136	4.280	3.07	0.002
P14_O	-12.471	3.668	-3.40	<0.001	P16_Y	12.390	3.955	3.13	0.001
P15_O	-18.266	4.198	-4.35	<0.001	P17_Y	20.526	3.809	5.39	<0.001
P16_O	-0.246	3.876	-1.17	0.949	P18_Y	16.285	3.809	4.27	<0.001
P17_O	-5.072	3.799	-0.06	0.182	P19_Y	1.015	3.809	0.27	0.789
R^2					0.763				
Adjusted R^2					0.738				
Observations					462				

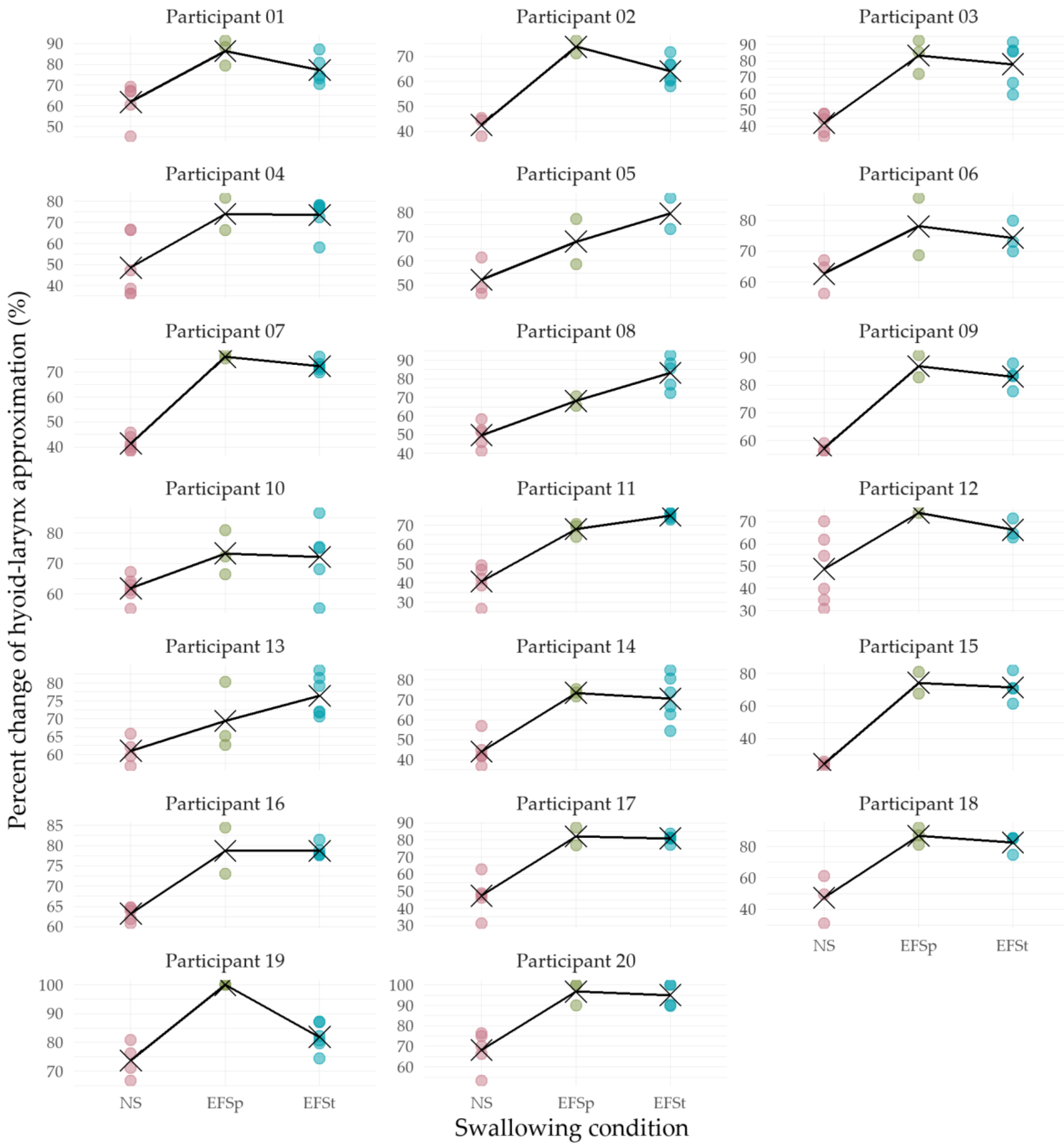
Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. Y: younger. P: participant participants. O: older participants.

Figure D.1: Individual relative percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition in younger participants.



Notes: Dots represent swallow events at which hyoid-larynx approximation were recorded. Black crosses in each swallowing condition indicate mean $HL\%change$. Black lines connect mean $HL\%change$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figure D.2: Individual relative percent change of hyoid-larynx approximation ($HL\%change$) by swallowing condition in older participants.



Notes: Dots represent swallow events at which hyoid-larynx approximation were recorded. Black crosses in each swallowing condition indicate mean $HL\%change$. Black lines connect mean $HL\%change$. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figures D.3, D.4, and D.5 show the regression diagnostics for the regression models [5], [7], and [9], respectively.

Figure D.3: Regression diagnostics for the regression model [5].

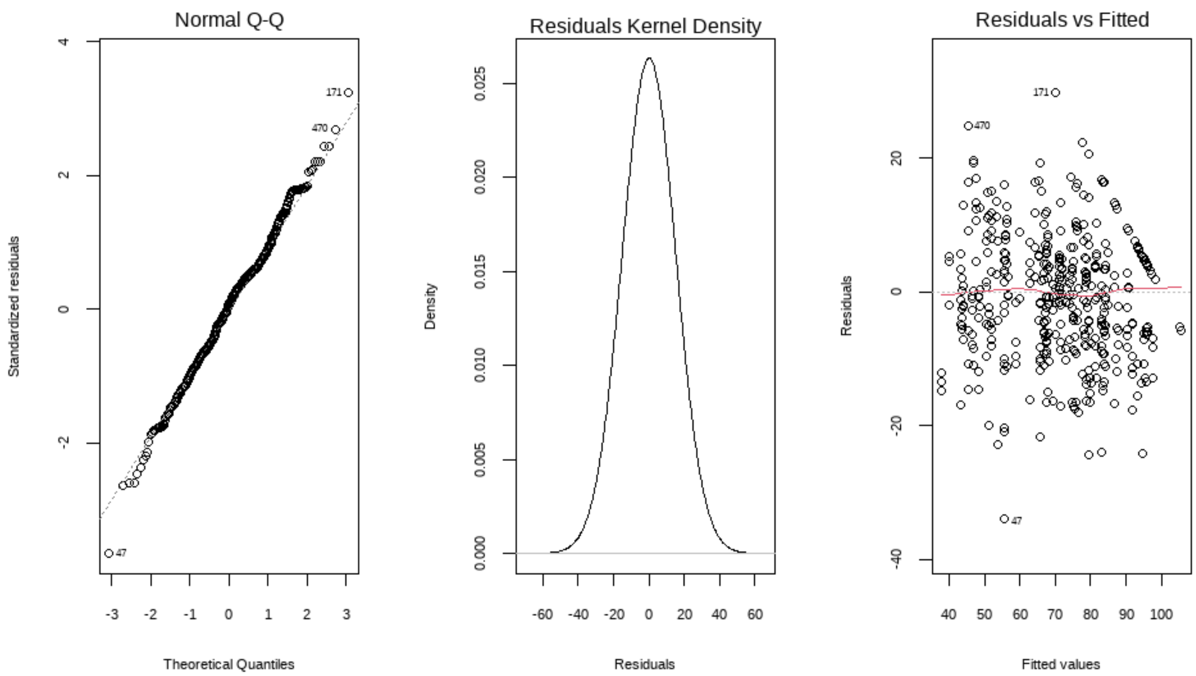


Figure D.4: Regression diagnostics for the regression model [7].

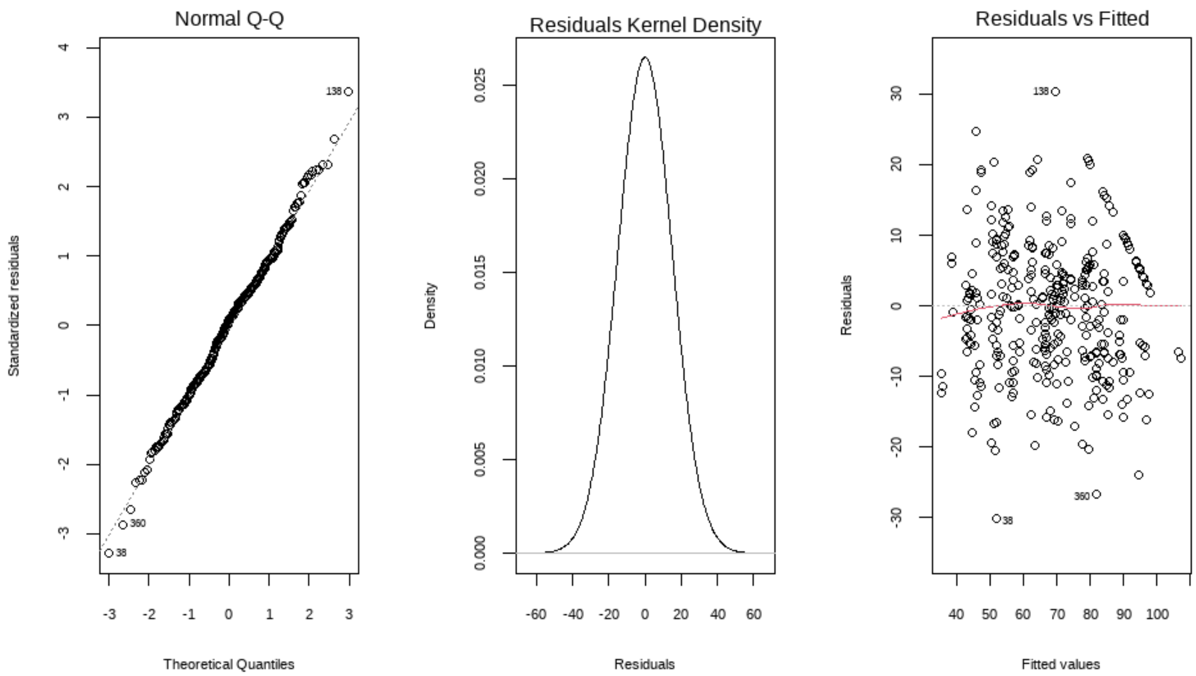
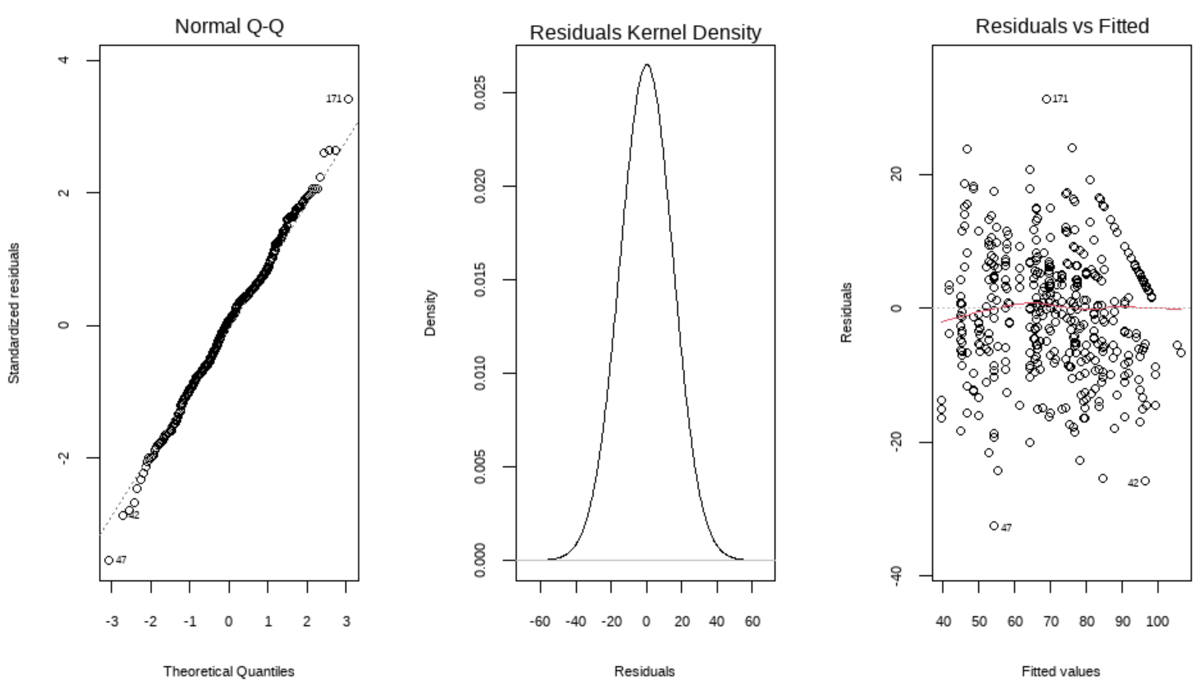


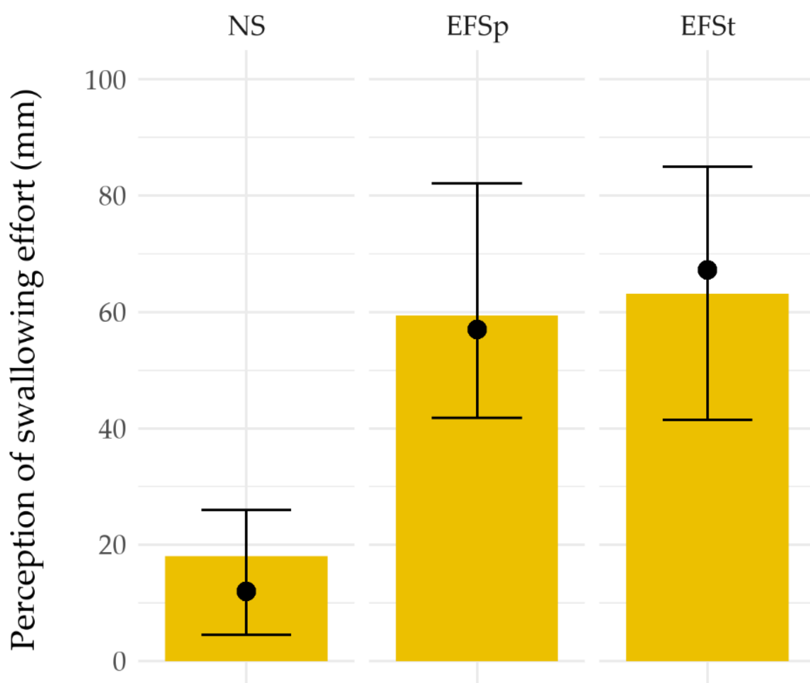
Figure D.5: Regression diagnostics for the regression model [9].



Appendix E: Perceived Effort to Swallow

Figure E.1 presents the *absolute* perceived effort to swallow determined by the visual analog scale (VAS) by swallowing condition, as a supplement to Figure 12. The VAS measurements varied from 0 to 93 mm in the NSs, from 9.5 to 99.5 mm in the EFSsp, and from 8 to 100 mm in the EFSst.

Figure E.1: Mean absolute perceived effort to swallow (VAS) by swallowing condition.



	NS	EFSp	EFSt
Mean	18.1	59.5	63.1
Median	12.0	57.0	67.2
Min	0.0	9.5	8.0
Max	93.0	99.5	100.0

Notes: Column heights indicate means, dots indicate medians, and whiskers represent interquartile ranges. Normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Tables E.1 and E.2 summarize perceived effort used to swallow, absolute (VAS) and normalized values ($VASnorm$), respectively, by swallowing condition, group, and tongue region.

Table E.1: Mean absolute perceived effort used to swallow (VAS) by swallowing condition, group, and tongue region.

Group	Tongue region	NS	EFSt	EFSp
		Mean (*SD*) Min-Max	*Mean* (*SD*) Min-Max	*Mean* (*SD*) Min-Max
Younger	Anterior	11.57 (12.30) 0.00-66.00	65.87 (26.60) 8.00-98.50	67.27 (23.42) 11.00-99.50
	Posterior	25.35 (19.84) 0.00-86.00	71.99 (22.85) 10.50-100.00	
Older	Anterior	12.02 (10.58) 0.00-41.00	54.78 (24.93) 9.50-99.00	51.67 (23.53) 9.50-98.50
	Posterior	23.27 (21.63) 0.00-93.00	59.95 (24.24) 10.50-98.50	

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Perceived effort measurement is in mm.

Table E.2: Mean normalized perceived effort used to swallow ($VASnorm$) by swallowing condition, group, and tongue region.

Group	Tongue region	NS *Mean* (*SD*) Min-Max	EFSt *Mean* (*SD*) Min-Max	EFSp *Mean* (*SD*) Min-Max
Younger	Anterior	6.71 (11.84) 0.00-100.00	74.65 (25.64) 0.00-100.00	78.15 (21.18) 21.71-100.00
	Posterior	27.82 (27.20) 0.00-100.00	84.36 (18.00) 8.62-100.00	
Older	Anterior	8.08 (11.76) 0.00-50.00	70.41 (27.21) 0.00-100	67.27 (30.06) 0.00-100.00
	Posterior	70.41 (29.14) 0.00-100.00	78.32 (22.21) 5.97-100.00	

NS: normal swallow. EFSt: effortful swallow produced with tongue emphasis. EFSp: effortful swallow produced with pharyngeal squeezing. *SD*: standard deviation. Min-Max: minimum-maximum. Note: Perceived effort measurement is in %.

Table E.3 presents the full results of the regression model of $VASnorm$ by swallowing condition as shown in Table 14. In this table (E.3) all regression coefficient estimates are provided including individual participant effects. Moreover, Tables E.4 shows the regression results of the *absolute* perceived effort used to swallow (VAS) by swallowing condition.

Figures E.2 and E.3 display absolute perceived effort to swallow (VAS) by swallowing condition for each participant.

Table E.3: Regression results of normalized perceived effort used to swallow ($VASnorm$) by swallowing condition including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	24.573	4.432	5.54	<0.001	P20_O	-9.911	6.154	-1.61	0.107
EFSp	55.448	1.884	29.42	<0.001	P01_Y	-3.779	6.154	-0.61	0.539
EFSt	59.668	1.538	38.78	<0.001	P02_Y	0.980	6.154	0.16	0.873
P02_O	-2.324	6.154	-0.38	0.705	P03_Y	-2.693	6.154	-0.44	0.661
P03_O	-6.048	6.154	-0.98	0.325	P04_Y	-3.313	6.154	-0.54	0.590
P04_O	-0.125	6.154	-0.02	0.982	P05_Y	-2.605	6.154	-0.42	0.672
P05_O	-4.051	6.154	-0.66	0.510	P06_Y	-13.267	6.154	-2.15	0.031
P06_O	-22.261	6.154	-3.62	<0.001	P07_Y	-1.269	6.154	-0.20	0.836
P07_O	-16.362	6.154	-2.66	0.007	P08_Y	-25.488	6.154	-4.14	<0.001
P08_O	-6.429	6.154	-1.04	0.296	P09_Y	-1.014	6.154	-0.16	0.869
P09_O	-18.859	6.154	-3.06	0.002	P10_Y	-2.978	6.154	-0.48	0.628
P10_O	-3.518	6.154	-0.57	0.567	P11_Y	0.688	6.154	0.11	0.910
P11_O	-12.292	6.154	-2.16	0.030	P12_Y	-14.192	6.154	-2.30	0.021
P12_O	-11.006	6.154	-1.78	0.074	P13_Y	-14.049	6.154	-2.28	0.022
P13_O	-13.042	6.154	-2.12	0.034	P14_Y	0.0251	6.154	0.00	0.996
P14_O	-11.278	6.154	-1.83	0.067	P15_Y	-2.374	6.154	-0.38	0.699
P15_O	-7.995	6.154	-1.23	0.194	P16_Y	0.657	6.154	0.11	0.914
P16_O	-17.397	6.154	-2.82	0.004	P17_Y	1.626	6.154	0.26	0.791
P17_O	-7.592	6.154	-1.23	0.217	P18_Y	-8.375	6.154	-1.36	0.173
P18_O	-3.176	6.154	-0.51	0.605	P19_Y	-4.081	6.154	-0.66	0.507
P19_O	-13.747	6.154	-2.23	0.025	P20_Y	-8.312	6.154	-1.35	0.177
R^2					0.612				
Adjusted R^2					0.598				
Observations					1200				

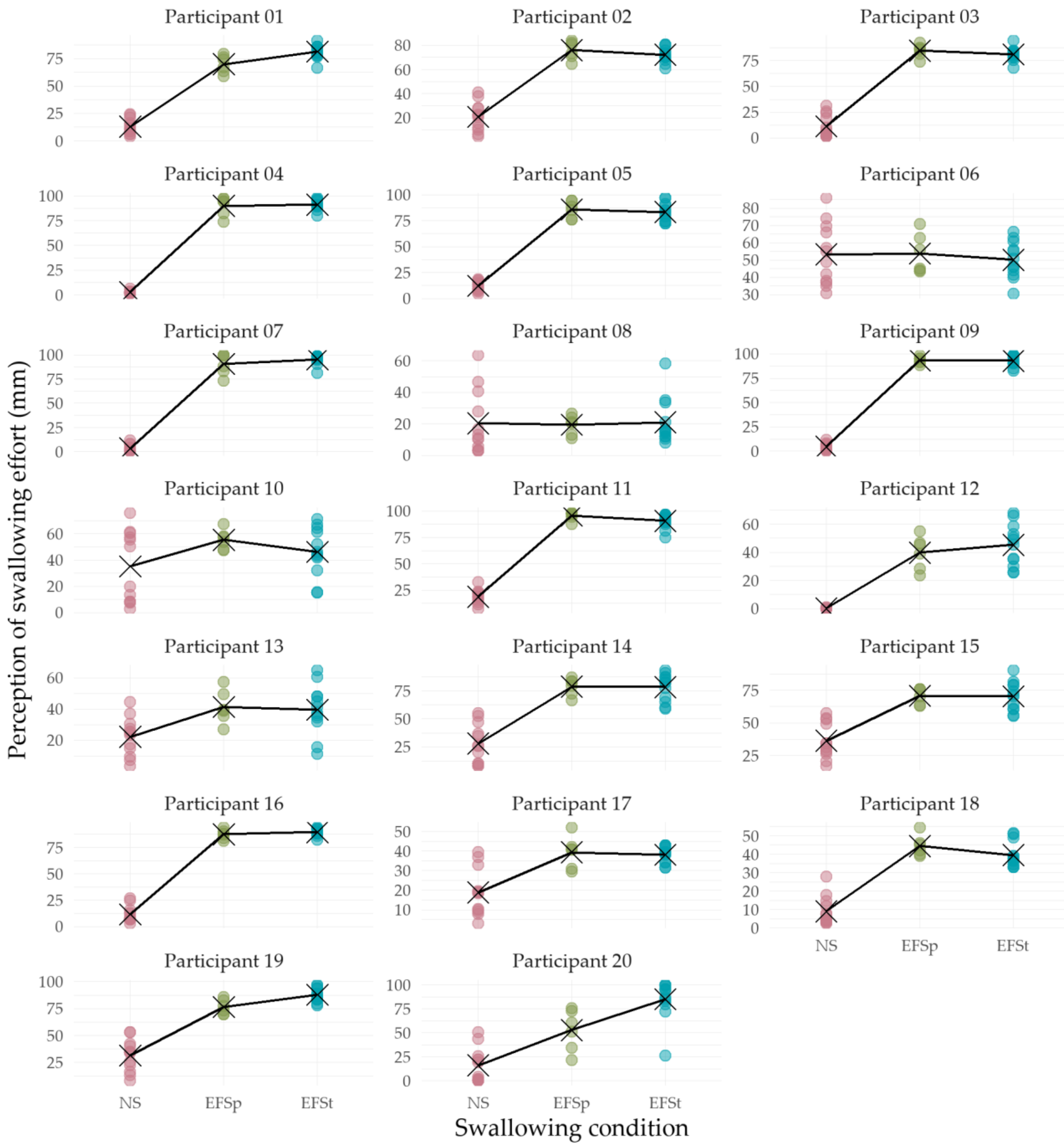
Coef.: coefficients. β: estimate. SE: standard error. t: t value. p: p-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. O: older participants. Y: younger participants.

Table E.4: Regression results of absolute perceived effort used to swallow (VAS) by swallowing condition including individual participant effects.

Coef.	β	SE	t	p	Coef.	β	SE	t	p
Intercept	32.779	3.477	9.42	<0.001	P20_O	-31.283	4.828	-6.48	<0.001
EFSp	41.417	1.478	28.01	<0.001	P01_Y	-7.450	4.828	-1.54	0.123
EFSt	45.095	1.207	37.36	<0.001	P02_Y	-6.733	4.828	-1.39	0.163
P02_O	-5.183	4.828	-1.07	0.283	P03_Y	-5.217	4.828	-1.08	0.280
P03_O	-8.600	4.828	-1.78	0.075	P04_Y	-3.600	4.828	-0.74	0.456
P04_O	-21.233	4.828	-4.40	<0.001	P05_Y	-3.733	4.828	-0.77	0.439
P05_O	-6.650	4.828	-1.38	0.168	P06_Y	-6.983	4.828	-1.44	0.148
P06_O	-18.250	4.828	-3.78	<0.001	P07_Y	-1.483	4.828	-0.31	0.758
P07_O	-27.583	4.828	-5.71	<0.001	P08_Y	-38.750	4.828	-8.02	<0.001
P08_O	-10.867	4.828	-2.25	0.024	P09_Y	-1.400	4.828	-0.29	0.771
P09_O	-43.600	4.828	-9.03	<0.001	P10_Y	-15.500	4.828	-3.21	0.001
P10_O	-15.150	4.828	-3.14	0.001	P11_Y	3.833	4.828	0.79	0.427
P11_O	-33.100	4.828	-6.85	<0.001	P12_Y	-33.033	4.828	-6.84	<0.001
P12_O	-26.383	4.828	-5.46	<0.001	P13_Y	-26.117	4.828	-5.41	<0.001
P13_O	-31.833	4.828	-6.59	<0.001	P14_Y	-0.817	4.828	-0.17	0.865
P14_O	-8.917	4.828	-1.85	0.065	P15_Y	-2.267	4.828	-0.47	0.638
P15_O	-17.500	4.828	-3.62	<0.001	P16_Y	-1.083	4.828	-0.22	0.822
P16_O	-37.900	4.828	-7.85	<0.001	P17_Y	-28.450	4.828	.5.89	<0.001
P17_O	-9.633	4.828	-1.99	0.046	P18_Y	-30.767	4.828	-6.37	<0.001
P18_O	-7.900	4.828	-1.63	0.010	P19_Y	3.850	4.828	0.80	0.425
P19_O	-13.600	4.828	-2.82	0.004	P20_Y	-8.117	4.828	-1.68	0.093
R^2					0.782				
Adjusted R^2					0.774				
Observations					1200				

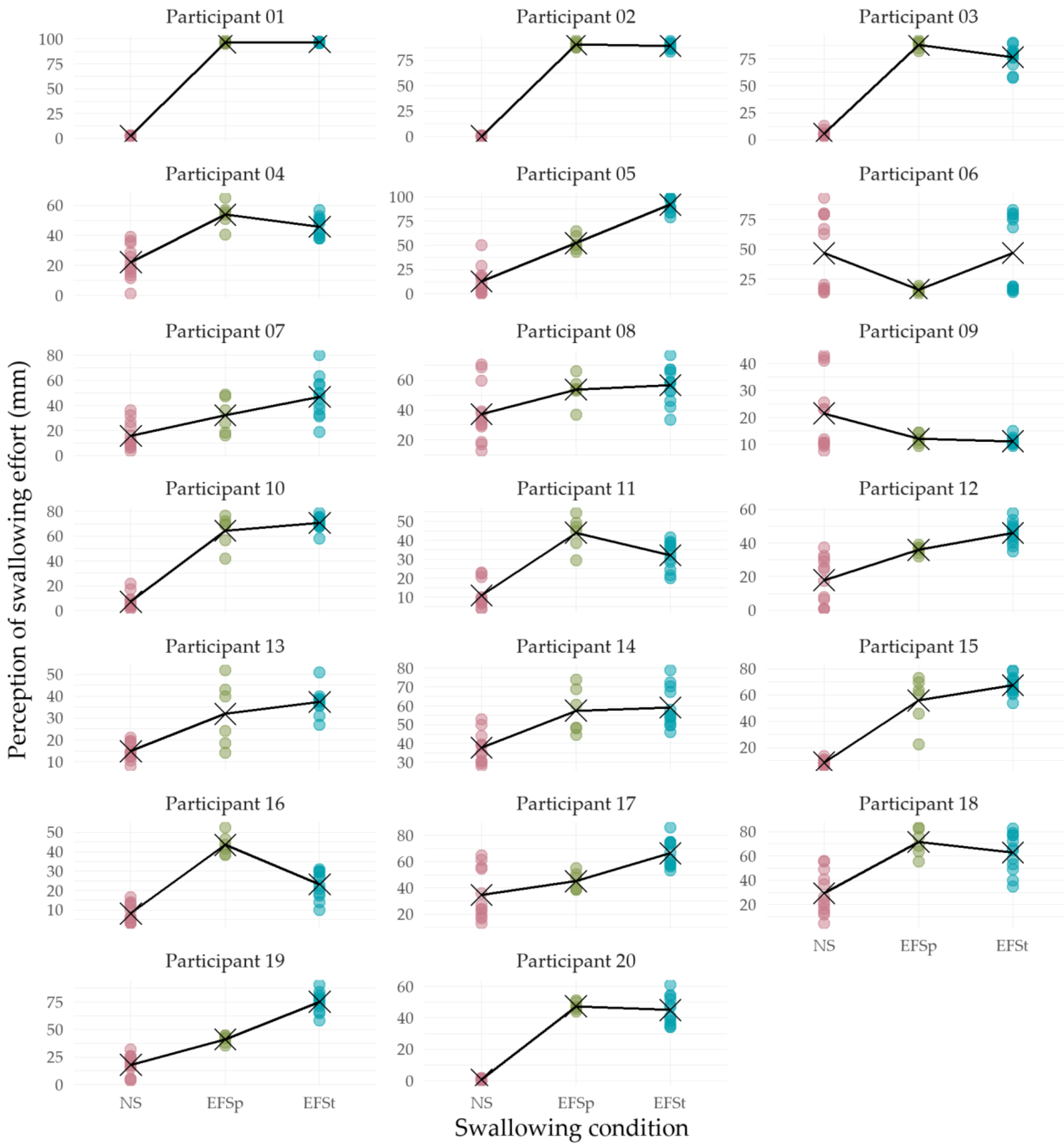
Coef.: coefficients. β: estimate. SE: standard error. *t: t* value. *p: p*-value. EFSp: effortful swallow produced with pharyngeal squeezing. EFSt: effortful swallow produced with tongue emphasis. P: participant. O: older participants. Y: younger participants.

Figure E.2: Individual absolute perceived effort to swallow (*VAS*) by swallowing condition in younger participants.



Notes: Dots represent swallow events at which perceived effort were recorded (30 swallows per participant). Black crosses in each swallowing condition indicate mean *VAS* score. Black lines connect mean *VAS* score. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

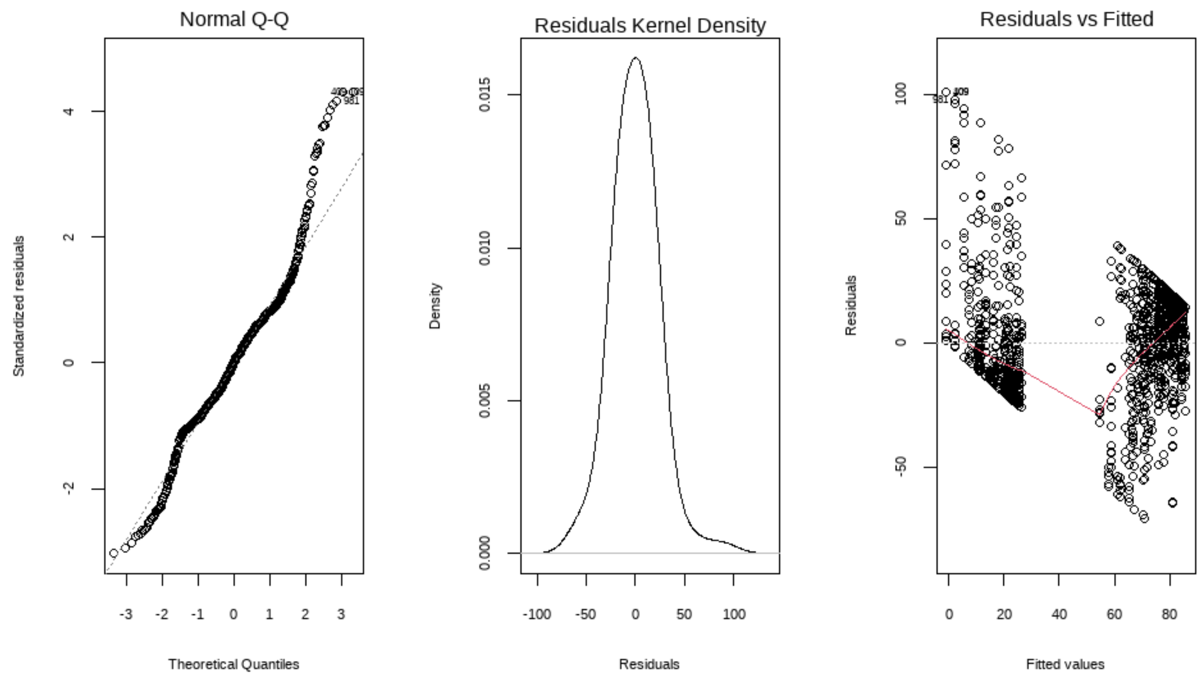
Figure E.3: Individual absolute perceived effort used to swallow (VAS) across swallowing condition in older participants.



Notes: Dots represent swallow events at which perceived effort were recorded (30 swallows per participant). Black crosses in each swallowing condition indicate mean VAS score. Black lines connect mean VAS score. Swallowing conditions: normal swallow (NS), effortful swallow produced with pharyngeal squeezing (EFSp), effortful swallow produced with tongue emphasis (EFSt).

Figure E.4 shows the regression diagnostics for the regression model [10].

Figure E.4: Regression diagnostics for the regression model [10].



Appendix F: Associations

Table F.1 presents the full results of the regression model of $T\%peak$ by $H\%change$ as shown in Table 15. In this table (E.1) all regression coefficient estimates are provided including individual participant effects. Similarly, Tables E.2 displays the full results of the regression model of $T\%peak$ by $HL\%change$ presented in Table 16 and Table E.3 shows the full results of the regression model of $T\%peak$ by $VASnorm$ displayed in Table 17.

Table F.1: Regression results of percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid displacement ($H\%change$) including individual participant effects.

Coef.	B	SE	t	p	Coef.	B	SE	t	p
Intercept	-3.382	7.466	-0.45	<0.001	P01_Y	6.622	8.726	0.76	0.448
$H\%change$	2.691	0.140	19.21	<0.001	P02_Y	6.991	9.341	0.75	0.454
P02_O	-17.940	9.089	-1.97	0.049	P03_Y	13.631	9.654	1.41	0.158
P03_O	-42.361	8.919	-4.80	<0.001	P04_Y	-25.983	10.500	-2.47	0.013
P04_O	-22.673	8.877	-.255	0.011	P05_Y	0.906	10.512	0.08	0.931
P05_O	-5.309	8.883	-0.60	0.550	P06_Y	-19.669	9.088	-2.16	0.031
P06_O	-16.957	9.345	-1.81	0.070	P07_Y	-19.434	9.107	-2.13	0.033
P07_O	2.472	9.348	0.64	0.791	P08_Y	-26.009	10.501	-2.47	0.013
P08_O	-20.414	8.700	-2.34	0.019	P09_Y	-38.728	10.013	-3.87	<0.001
P09_O	-18.971	8.898	-2.12	0.033	P10_Y	-8.838	8.878	-0.99	0.320
P10_O	-21.251	10.035	-2.12	0.034	P11_Y	-3.033	10.032	-0.30	0.762
P11_O	-22.183	8.715	-2.54	0.011	P12_Y	11.581	8.699	1.33	0.183
P12_O	-1.233	8.734	-0.14	0.887	P13_Y	-37.806	8.724	-4.33	<0.001
P13_O	-17.624	9.338	-1.89	0.060	P14_Y	-38.435	9.111	-4.22	<0.001
P14_O	-10.590	8.700	-1.22	0.224	P15_Y	-25.014	8.879	-2.82	0.005
P15_O	-4.635	8.882	-0.52	0.602	P16_Y	-19.386	8.907	-2.17	0.030
P16_O	-18.639	8.716	-2.14	0.033	P17_Y	-10.997	8.878	-1.24	0.216
P17_O	-27.073	8.904	-3.04	0.002	P18_Y	-4.457	8.878	-0.50	0.616
P18_O	-28.103	9.093	-3.09	0.002	P19_Y	-23.319	8.699	-2.68	0.007
P19_O	-27.413	8.703	-3.15	0.001	P20_Y	-18.719	9.095	-2.06	0.040
P20_O	17.694	8.922	1.98	0.048					
R^2					0.586				
Adjusted R^2					0.540				
Observations					405				

Coef.: coefficients. B: estimate. SE: standard error. *T:* t value. *P:* p-value. $H\%change$: percent change of hyoid displacement. P: participant. O: older participants. Y: younger participants.

Table F.2: Regression results of percentage of peak tongue pressure ($T\%peak$) by percent change of hyoid-larynx approximation ($HL\%change$) including individual participant effects.

Coef.	Β	SE	*t*	*p*	Coef.	Β	SE	*t*	*p*
Intercept	-28.141	7.744	-3.63	<0.001	P01_Y	-6.164	8.595	-0.72	0.473
$HL\%change$	1.264	0.064	19.80	<0.001	P02_Y	-8.532	10.375	-0.82	0.411
P02_O	19.419	9.256	2.09	0.036	P03_Y	-10.851	9.906	-1.09	0.274
P03_O	1.322	8.996	0.15	0.883	P04_Y	-1.896	9.227	-0.20	0.837
P04_O	11.723	8.610	1.36	0.174	P05_Y	20.185	9.223	2.20	0.029
P05_O	7.807	11.000	0.71	0.478	P06_Y	-18.980	9.564	-1.98	0.048
P06_O	-3.229	10.364	-0.31	0.755	P07_Y	-13.103	8.990	-1.46	0.145
P07_O	29.251	8.631	3.39	<0.001	P08_Y	-21.454	9.536	-2.25	0.025
P08_O	-13.087	8.977	-1.46	0.145	P09_Y	-42.697	10.024	-4.26	<0.001
P09_O	15.853	9.892	1.60	0.109	P10_Y	-13.057	9.014	-1.45	0.148
P10_O	-0.596	8.771	-0.07	0.945	P11_Y	-0.496	9.524	-0.05	0.958
P11_O	15.286	8.793	1.74	0.083	P12_Y	5.157	9.918	0.52	0.603
P12_O	29.235	9.270	3.15	0.001	P13_Y	-25.229	9.268	-2.72	0.006
P13_O	-10.525	8.975	-1.73	0.241	P14_Y	-30.115	9.241	-3.26	0.001
P14_O	14.684	8.629	1.70	0.089	P15_Y	-24.496	10.390	-2.36	0.018
P15_O	16.630	9.959	1.67	0.095	P16_Y	1.568	9.223	0.17	0.865
P16_O	-7.473	8.976	-0.83	0.405	P17_Y	-29.207	8.790	-3.32	<0.001
P17_O	1.405	8.772	0.16	0.872	P18_Y	-6.091	8.782	-0.70	0.488
P18_O	-3.954	9.891	-0.40	0.689	P19_Y	-4.483	8.772	-0.51	0.609
P19_O	-12.972	8.994	-1.44	0.150	P20_Y	-2.354	9.006	-0.26	0.793
P20_O	-17.701	9.246	-1.91	0.056					
R^2					0.593				
Adjusted R^2					0.543				
Observations					365				

Coef.: coefficients. Β: estimate. SE: standard error. *T: t* value. *P: p*-value. $HL\%change$: percent change of hyoid-larynx approximation. P: participant. O: older participants. Y: younger participants.

Table F.3: Regression results of percentage of peak tongue pressure ($T\%peak$) by normalized perceived effort used to swallow ($VASnorm$) including individual participant effects.

Coef.	B	SE	t	p	Coef.	B	SE	t	p
Intercept	34.516	3.994	8.64	<0.001	P01_Y	-2.292	5.529	-0.41	0.678
$VASnorm$	0.558	0.016	34.09	<0.001	P02_Y	-2.221	5.530	-.040	0.688
P02_O	-2.033	5.529	-0.37	0.712	P03_Y	7.386	5.529	1.33	0.182
P03_O	-12.297	5.530	-2.23	0.026	P04_Y	-7.854	5.529	-1.42	0.155
P04_O	-9.850	5.529	-1.78	0.075	P05_Y	19.119	5.529	3.46	<0.001
P05_O	2.291	5.530	0.41	0.678	P06_Y	-6.100	5.530	-1.10	0.270
P06_O	-1.623	5.530	-0.29	0.769	P07_Y	-4.759	5.529	-0.86	0.389
P07_O	16.429	5.531	2.97	0.003	P08_Y	1.414	5.535	0.25	0.798
P08_O	-16.679	5.529	-3.01	0.002	P09_Y	-19.901	5.529	-3.60	<0.001
P09_O	11.563	5.532	2.09	0.036	P10_Y	-1.680	5.529	-0.30	0.761
P10_O	-6.821	5.529	-1.23	0.217	P11_Y	-5.185	5.529	-0.94	0.348
P11_O	3.659	5.533	0.66	0.508	P12_Y	24.723	5.532	4.47	<0.001
P12_O	19.158	5.529	3.46	<0.001	P13_Y	-11.142	5.531	-2.01	0.044
P13_O	-10.275	5.530	-1.85	0.063	P14_Y	-22.207	5.530	-4.00	<0.001
P14_O	-1.670	5.530	-0.30	0.762	P15_Y	-15.598	5.529	-2.82	0.004
P15_O	-8.264	5.530	-1.49	0.135	P16_Y	0.564	5.529	0.10	0.918
P16_O	6.451	5.539	1.16	0.244	P17_Y	-14.565	5.530	-2.63	0.008
P17_O	-9.801	5.530	-1.77	0.076	P18_Y	5.138	5.530	0.93	0.353
P18_O	-11.865	5.529	-2.14	0.032	P19_Y	-16.408	5.529	-2.97	0.003
P19_O	-10.334	5.529	-1.87	0.062	P20_Y	-17.076	5.529	-3.08	0.002
P20_O	6.430	5.531	1.16	0.245					
R^2					0.607				
Adjusted R^2					0.590				
Observations					960				

Coef.: coefficients. B: estimate. SE: standard error. *T:* t value. *P:* p-value. $VASnorm$: normalized visual analog scale. P: participant. O: older participants. Y: younger participants.

Figures F.1, F.2, and F.3 show the regression diagnostics for the regression models [11], [12], and [13], respectively.

Figure F.1: Regression diagnostics for the regression model [11].

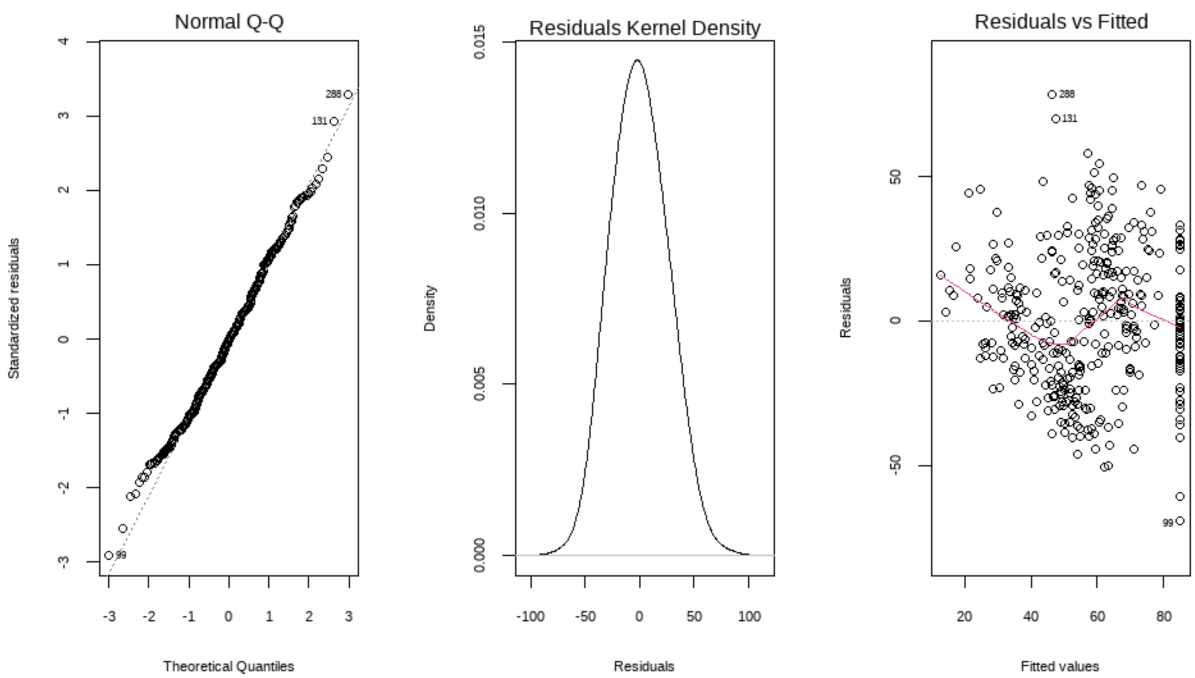


Figure F.2: Regression diagnostics for the regression model [12].

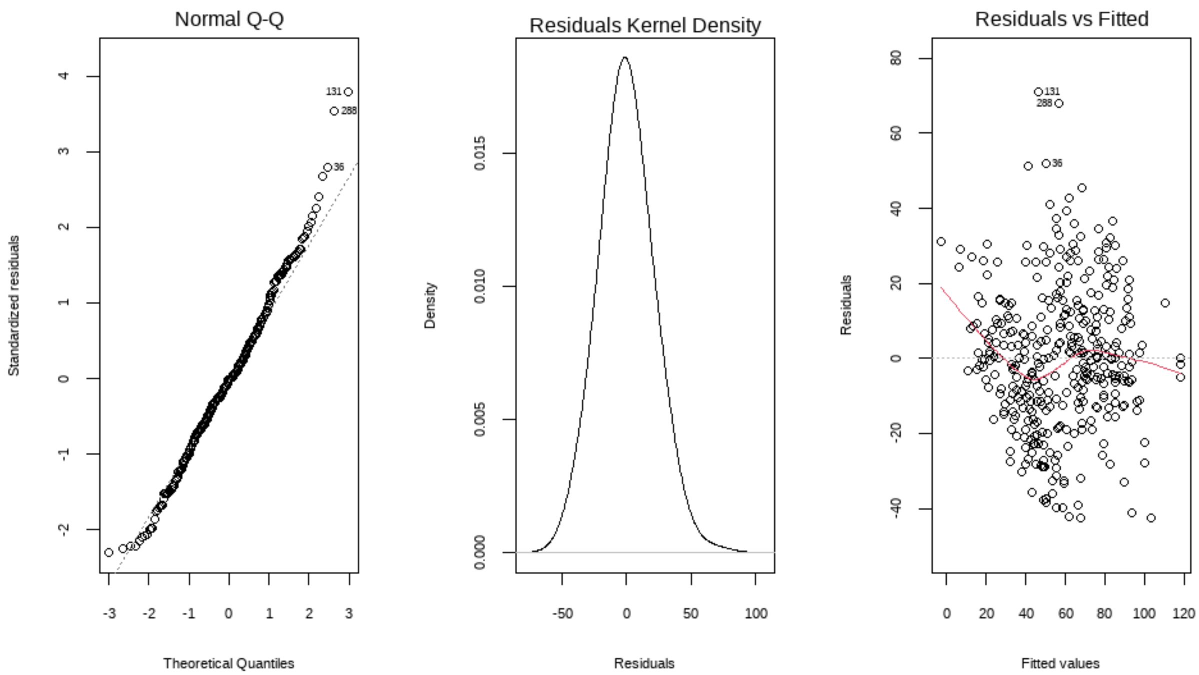
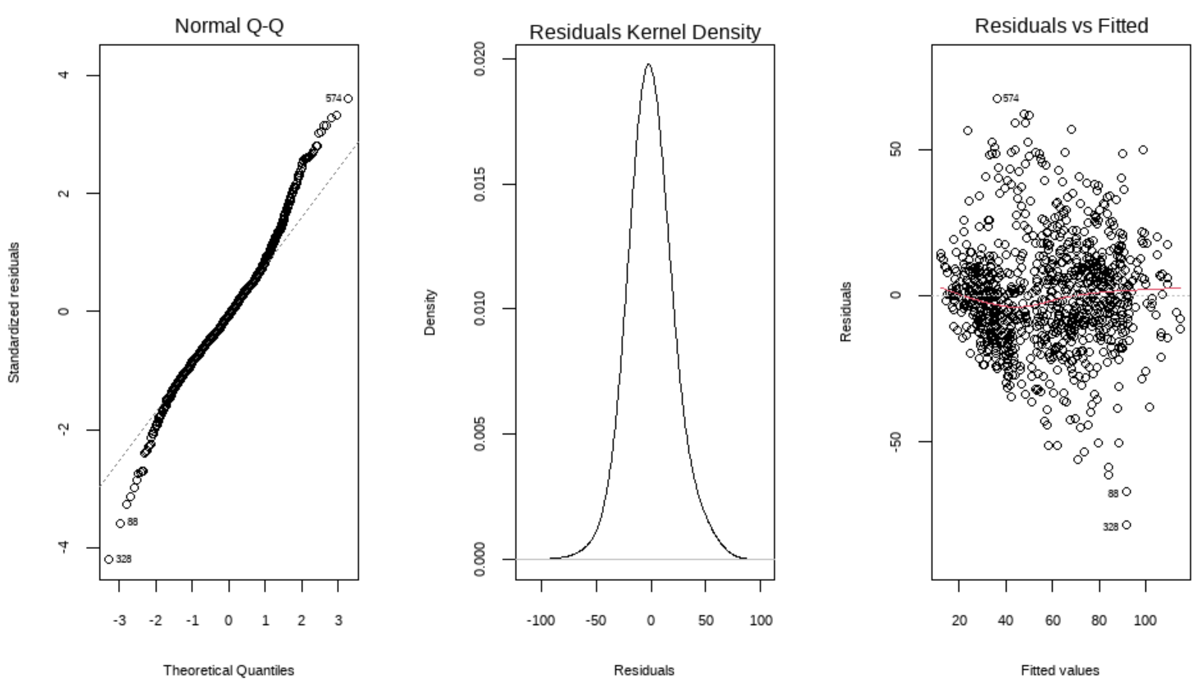


Figure F.3: Regression diagnostics for the regression model [13].



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Rehabilitation, *89*(5), 822–828. http://doi.org/10.1016/j.apmr.2007.08.167

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Youmans, S. R., Youmans, G. L., & Stierwalt, J. A. G. (2009). Differences in tongue strength across age and gender: Is there a diminished strength reserve? *Dysphagia, 24*(1), 57-65. http://doi.org/10.1007/s00455-008-9171-2

VITA

Mariana Mendes Bahia

EDUCATION

Ph.D. Candidate	Speech-Language Pathology, Concentration: Neuroscience Syracuse University, Dept. Communication Sciences & Disorders *Mentor*: Dr. *Soren Lowell*	Summer 2022 (expected)
M.S.	Medical Pathophysiology, Concentration: Neuroscience University of Campinas, Dept. of Neurology, Brazil	2014
Clinical Specialization	Speech-Language Pathology in Neurology University of Campinas, Dept. Human Development & Rehabilitation, Brazil	2011
B.S.	Speech-Language Pathology & Audiology University of Campinas, Dept. Human Development & Rehabilitation, Brazil	2009

PUBLICATIONS

Peer-Reviewed Publications

1. **Bahia MM** & Lowell SY. A systematic review of the physiological effects of the effortful swallow maneuver in adults with normal and disordered swallowing. (2020). *American Journal of Speech-Language Pathology,* 29(3): 1655-1673.

2. Pitts L, Rogers L, Wang X, **Bahia MM**, & Cherney, LR. (2020). Functionally navigated transcranial magnetic stimulation to evoke lingual pressure in stroke survivors with dysphagia and healthy adults: a proof-of-concept trial. *Topics in Stroke Rehabilitation*, 27(4): 241-250.

3. Dallaqua GB, **Bahia MM**, Li ML, & Chun RYS. (2019) Stroke Communication Scale based on the International Classification of Functioning, Disability and Health (ICF-SCS). *Disability and Rehabilitation,* 43(12): 1722-1729.

4. **Bahia MM**, Mourão LF, & Chun RYS. (2016). Dysarthria as a predictor of dysphagia following stroke. *NeuroRehabilitation*, 38(2): 155-162.

5. Almeida SRM, **Bahia MM**, Lima FO, Paschoal IA, Cardoso TAMO, & Li ML. (2015) Predictors of pneumonia in acute stroke in patients in an emergency unit. *Arquivos de Neuro-Psiquiatria,* 73(5): 415-419.

6. **Bahia MM** & Chun RYS. (2014). Quality of life in aphasia: differences between fluent and non-fluent aphasic augmentative and alternative communication users. *Audiology Communication Research,* 19(4): 352-359.

7. **Bahia MM** & Chun RYS. (2014). Augmentative and Alternative Communication repercussion on non-fluent aphasia. *Revista CEFAC*, 16(1): 147-160.

8. Chun RYS & **Bahia MM**. (2009). Changes in health education: the portfolio as an innovative practice in Speech-Language Pathology undergraduate program. (In Portuguese). *Distúrbios da Comunicação*, 21(3): 339-349.

9. Chun RYS & **Bahia MM**. (2009). The use of a portfolio in Speech-Language Pathology undergraduate education from the perspective of a comprehensive training (In Portuguese). *Revista CEFAC*, 11(4): 688-694.

Book Chapters

1. **Bahia MM**, Quintana J, Mendes L, & Correa TTM. (2013). Speech-Language Pathology intervention in the intensive care unit (In Portuguese). In: Dragosavac D & Araujo S (Eds.), Protocols and intervention in the intensive care unit. São Paulo, SP: Atheneu.

2. Mourão LF, **Bahia MM**, & Chun RYS. (2013). Swallowing and language following a stroke. (In Portuguese). In: Li ML, Fernandes PT, Avelar WM, & Carvalho S (Eds.), Stroke: from research to clinical practice. São Paulo, SP: Plêoade.

RESEARCH EXPERIENCE

Syracuse University, Dept. of Communication Sciences & Disorders 2018-2022

Doctoral Researcher, Voice and Swallowing Physiology Laboratory, supervised by Dr. Soren Lowell on topics

- Effects of the effortful swallow maneuver on swallowing biomechanics
- Changes in muscle activity during swallowing treatment
- Instrumentation expertise: FEES, PowerLab multichannel digital signal acquisition and analysis through LabChart, sEMG with signal analysis, the Iowa Oral Performance Instrument, Computerized Speech Lab with software add-ons (MDVP, ADSV).

University of Northern Iowa, Dept. of Communication Sciences & Disorders Spring, 2018

Research Assistant to Dr. Laura Pitts on projects

- Transcranial magnetic stimulation to evoke lingual pressure in post-stroke dysphagia
- Expiratory muscle strength training in Parkinson's disease

Research Assistant to Dr. Angela Burda on project

- Using visual phonics to address accent modification in non-native English speakers

University of Campinas, Dept. of Neurology, Brazil 2012-2014

Master's Researcher, supervised by Dr. Li Li Min and Dr. Lucia Mourão on topics

- Clinical predictors of dysphagia in acute stroke
- Swallowing screening in acute stroke
- Medical complications in acute stroke
- Medical cost of pneumonia in post-stroke patients

University of Campinas, Dept. of Human Development & Rehabilitation, Brazil 2006-2010

Clinical Researcher, supervised by Dr. Regina Yu Shon Chun and Dr. Lucia Mourão on topic

- Language and swallowing disorders in post-stroke individuals

Undergraduate Researcher, supervised by Dr. Regina Yu Shon Chun on topics

- Quality of life in post-stroke and aphasia
- Augmentative and alternative communication in non-fluent aphasia
- Portfolio in speech-language pathology education

TEACHING EXPERIENCE

Syracuse University, Dept. Communication Sciences & Disorders

Teaching Assistant Spring 2021

- Clinical Classroom Practicum

Instructor of record — Fall, 2020
- Anatomy & Physiology of the Speech & Hearing Mechanisms

Guest Lecturer — 2019-2021
- Clinical Classroom Practicum

Lecture: Exercise-Induced Laryngeal Obstruction (Apr 2019, Feb 2020, May 2021, April 2022)
- Introduction to Communication Sciences & Disorders

Lecture: Speech-Language Pathology clinical practice (Oct 2019)

University of Northern Iowa, Dept. Communication Sciences & Disorders

Teaching Assistant — Spring, 2018
- Introduction to Neurogenic Disorders

University of Campinas, Dept. Human Development & Rehabilitation, Brazil

Instructor & Clinical Supervisor — Fall, 2013
- Dysphagia in adults

Guest Lecturer — 2010-2014
- Speech-language Pathology Intervention II

Lecture: Alzheimer's Disease & Amyotrophic Lateral Sclerosis (Oct 2013, Nov 2014)
- Dysphagia in Adults

Lecture: Dysphagia following a stroke (Mar 2013, Sep 2013, Nov 2014)
- Stuttering

Lectures: Different approaches to evaluate and treat stuttering (Sep 2010)
Stuttering in adults: A case study (Oct 2010)
- History of Speech-Language Pathology

Lecture: Language disorders in children and adults (Apr 2010)

Teaching Assistant — Fall, 2009
- Stuttering
- Speech Therapy, Language, & Pathological Processes

FELLOWSHIPS & AWARDS

Barbara Lerner Kurman Travel Funding, Syracuse University	2022
2021 Graduate Student Scholarship, American Speech-Language-Hearing Foundation	2021
Research Excellence Doctoral Funding Fellowship, Graduate School, Syracuse University	2021-2022
Summer Dissertation Fellowship, Graduate School, Syracuse University	2021
Summer Fellowship, Dept. of Communication Sciences & Disorders, Syracuse University	2019, 2020 & 2021
Research Tuesday, Article highlighted by the American Speech-Language-Hearing Association	2020
University Fellowship, Syracuse University	2018-2020
Nu Rho Psi member, National Honor Society in Neuroscience	2019
Scientific Abstract Poster Winner, Dysphagia Research Society	2019
Master's Scholarship, São Paulo Research Foundation, Brazil	2012-2014
Best Thesis, Specialization Graduate Program, University of Campinas, Brazil	2011
Specialization Scholarship, Administrative Development Foundation, Brazil	2010-2011
Best Poster Presentation, VII Speech-Language Pathology & Audiology Week, Brazil	2009
Scientific Initiation Scholarship, São Paulo Research Foundation, Brazil	2006-2007 & 2008-2009

SELECTED PRESENTATIONS & INVITED TALKS

Conference Presentations

Bahia MM & Lowell S. (April 2022). *Masseter muscle activity during regular swallows and effortful saliva swallows*. Oral presentation, 1st New York Communication Disorders Colloquium Series (NYCDCS) Doctoral Student Data Blitz, New York City, New York (online).

Bahia MM & Lowell S. (April 2022). *Electromyographic activity of the masseter muscle during regular and effortful swallows*. Poster presentation, 8th Annual Neuroscience Research Day, Syracuse, New York.

Bahia MM & Lowell S. (March 2022). *Changes in masseter muscle activity during the effortful swallow*. Poster presentation, 30th Annual Dysphagia Research Society Meeting, San Juan, Puerto Rico (online).

Pitts LL, Rogers L, Wang X, **Bahia MM,** & Cherney LR. (March 2019). *Navigated transcranial magnetic stimulation to evoke lingual pressure in stroke survivors and controls.* Poster presentation, 27th Annual Dysphagia Research Society Meeting, San Diego, CA.

Jenks J, Crimmins S, Powers M, **Bahia M,** Lawson C, Schlepe R, Miner M, Bergin K, Pitts LL, & Bohnenkamp T. (November 2018). *Outcomes of an intensive swallowing program for persons with Parkinson's disease.* Poster presentation, 2018 America Speech-Language-Hearing Association Convention, Boston, MA.

Bahia MM, Mourão LF, Lima FO, & Li ML. (March 2014). *Clinical predictors of oropharyngeal dysphagia following acute stroke*. Poster presentation, 22nd Annual Dysphagia Research Society Meeting, Nashville, TN.

Bahia MM, Almeida SRM, Lima FO, & Li ML. (March 2014). *Cost of pneumonia in acute stroke in Brazil*. Poster presentation, 22nd Annual Dysphagia Research Society Meeting, Nashville, TN.

Bahia MM, Almeida SRM, Lima FO, & Li ML. (October 2013). *Comparison of medical costs: post-stroke patients with and without pneumonia in the Brazilian Public Health System*. Poster presentation, IX Brazilian Stroke Conference, Fortaleza, CE, Brazil.

Bahia MM, Almeida SRM, Lima FO, & Li ML. (October 2013). *Medical complications in acute stroke*. Poster presentation, IX Brazilian Stroke Conference, Fortaleza, CE, Brazil.

Bahia MM, Mourão LF, Lima FO, & Li ML. (October 2013). *Clinical predictors of dysphagia in acute stroke*. Poster presentation, IX Brazilian Stroke Conference, Fortaleza, CE, Brazil.

Bahia MM, Chun RYS, & Mourão LF. (February 2011). *Association between post-stroke sequels: language and swallowing*. Oral presentation, IX Seminar of the Specialization Graduate Program of the School of Medical Sciences, University of Campinas, Campinas, SP, Brazil.

Bahia MM & Chun RYS. (September 2010). *Evaluation of quality of life in aphasia: AAC users and non-users*. Oral presentation, 18th Brazilian Speech-Language Pathology & Audiology Conference, Curitiba, PR, Brazil.

DiGiulio RM, Chun RYS, & **Bahia MM**. (September 2010). *The impact of aphasia on the perspective of caregiver*. Poster presentation, 18th Brazilian Speech-Language Pathology & Audiology Conference, Curitiba, PR, Brazil.

Bahia MM, Ramos RL, & Chun RYS. (October 2009). *Speech therapy in groups: AAC in aphasia*. Oral presentation, III Brazilian AAC Conference ISSAC Brazil, São Paulo, SP, Brazil.

Bahia MM & Chun RYS. (October 2009). *Stroke Specific Quality of Life Scale and language in aphasia AAC users*. Oral presentation, 17th Brazilian Speech-Language Pathology & Audiology Conference and 1st Ibero-America Congress of Speech-Language Pathology & Audiology, Salvador, BA, Brazil.

Invited Speaker

5th Annual Campinas Stroke Conference, Brazil 2014

World Parkinson's Disease Day, Brazil	2014
ABCérebro (Brain) TV, Brazil	2014
World Stroke Day, Brazil	2012
10th Annual Speech-Language Pathology & Audiology Week, Brazil	2012

ADDITIONAL TRAINING

Deciphering Dysphagia with Ampcare's Effective Swallowing Protocol (ESP™), Ampcare, LLC	2022
Write Winning NIH Grant Proposals, Grant Writers' Seminars and Workshops	2021
Certificate in University Teaching, Syracuse University	2021
MBSImP Training (University Student Access)	2018
Continued Improvement in the Treatment of Stoke, Brazilian Society of Cerebrovascular Diseases	2010
Augmentative and Alternative Communication, Center of Research Studies in Rehabilitation, Brazil	2009

SERVICE

Committees

Committee member, 7th & 8th Annual Syracuse University Neuroscience Research Day	2021-2022
Executive committee member, Campinas Stroke Campaign, Brazil	2012-2014
Committee Director, 7th Annual Speech-Language Pathology & Audiology Week, Brazil	2009
Committee member, 5th & 6th Annual Speech-Language Pathology & Audiology Week, Brazil	2007-2008
Committee member, 2nd Brazilian AAC Conference ISAAC Brazil	2007

Referee

Disability and Rehabilitation	2020-present
Archives of Physical Medicine and Rehabilitation	2018-present
Topics in Stroke Rehabilitation	2016-present
Reviewer, 8th Brazilian AAC Conference ISAAC Brazil	2019
Reviewer and Discussant, 10th Annual Speech-Language Pathology & Audiology Week, Brazil	2012

Organizations

Member, Latin America Research development & best practices on swallowing disorders	2021-present
Vice-President, SLP & Audiology undergraduate student association, University of Campinas	2007-2009

OTHER PROFESSIONAL EXPERIENCE

Clinical Fellow

Gebbie Speech-Language & Hearing Clinic, Syracuse University	2018-2021

Speech-Language Pathologist

Campinas Medical Center Hospital – Brazil	2011- 2015
Home care/Skilled Nursing Facility – Brazil	2011-2015
Louveira Interdisciplinary and Educational Clinic – Brazil	2011

Speech-Language Pathologist - M.S. Program 2012-2014

University Clinical Hospital, University of Campinas – Brazil

Speech-Language Pathologist - Specialization Program 2010-2011

University Clinical Hospital, University of Campinas – Brazil
Aphasia Center, University of Campinas – Brazil
Center of Research Studies in Rehabilitation, University of Campinas – Brazil

ADDITIONAL INFORMATION

Membership in Professional Associations

Dysphagia Research Society (DRS)
American Speech-Language-Hearing Association (ASHA)

Professional Licensures and Certifications

Ampcare's Effective Swallowing Protocol (ESP™), Apmcare LLC, Certification #22050714
Certificate of Clinical Competence in Speech-Language Pathology, American Speech-Language-Hearing Association (ASHA), ASHA #14198827
New York State Licensure, The University of the State of New York, Education Department, License #031643

Languages

Portuguese (native), English (fluent)