2013

An Examination of Maximum Isometric Lingual Pressure and Total Oral Phase Duration in the Healthy Adult Swallow

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AN EXAMINATION OF MAXIMUM ISOMETRIC LINGUAL PRESSURE AND TOTAL ORAL PHASE DURATION IN THE HEALTHY ADULT SWALLOW

By

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A Dissertation submitted to the School of Communication Science and Disorders in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Degree Awarded:
Summer Semester, 2013
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I dedicate this dissertation to all of my family members, mentors, friends, and colleagues who supported me throughout this journey.
ACKNOWLEDGEMENTS

First, I would like to acknowledge my mother, Pamela Rhoads, and step-father, Rodney Rhoads, who planted the seeds for my success and always believed in me. Thank you to my loving sister, Danelle Betancourt, a seasoned speech-language pathologist who has supported my professional goals throughout my life. Also, I would like to thank my father, Walter Headley, for encouraging me to pursue my research dream. I wish you were still here to celebrate this accomplishment with me, Dad.

I would like to acknowledge Caitlin Reichle, Hillary Guest, and Kristen Alberico who served as my research assistants throughout this project. Your hard work and dedication during this project has been incredible, and I could not have completed this research without your help.

I would like to acknowledge all of my fellow doctoral student friends at Florida State University (FSU) who stood by me along this journey: Jane Messier, Rachel Johnson, Emily Diehm, Sheri Stronach, Nicole Sparapani, Emily Lakey, Katharine Bedsole, David McCoy, Lakeisha Johnson, and Maya Callender. Although distance may separate us as we pursue our career paths, we always will share an unbreakable bond. Thank you to my other dear academic friends, Dr. Toby Park, Dr. Marytza Gawlik, Dr. Toby Macrae, Dr. Kaitlin Lansford, Dr. Megan MacPherson, and Dr. Madison Peschock, who comforted and guided me with their wisdom.

I want to thank my “dream team” committee for their patience and valuable mentoring during this process: Dr. Julie Stierwalt, Dr. Leonard LaPointe, Dr. Richard Morris, and Dr. Gary Heald. I would especially like to extend my deepest gratitude to my major professor, Dr. Julie Stierwalt. You inspired me, provided me with countless experiences which have shaped my academic skills, and were instrumental in launching my career in academia. You have been the rock which grounded me throughout this journey. Words cannot express my appreciation for your superb mentorship during my time at FSU. I will miss you, but I know that we always will maintain a strong friendship and professional relationship for several years to come.

Finally, I want to acknowledge Stephen Totter, who provided me with unconditional love and support during my entire doctoral program. Words cannot express the joy that you have brought to my life.

With much love and appreciation,

Derek Headley
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ABSTRACT

Purpose: To examine maximum isometric lingual pressure (MIP) and total oral phase duration (oral preparation time + oral transport time) (TOP) in healthy adults, and to explore the relations among these variables.

Method: One hundred healthy adults (50 males and 50 females), with no significant medical history affecting oral musculature or swallowing, volunteered to participate in this study. Lingual-palatal pressures were recorded via the Iowa Oral Performance Instrument (IOPI) by placing a tongue bulb at both anterior and posterior locations to obtain maximum isometric lingual pressures generated by the anterior portion of the tongue (MIPa) and maximum isometric lingual pressures generated by the posterior portion of the tongue (MIPp). Surface electromyography (sEMG) using the Biopac MP150WSW System was utilized to record the onset and offset of swallowing muscle activity indicating TOP durations across six consistencies of food and liquid.

Results: Significant negative correlations ($p < 0.05$) were observed between MIPa and all consistencies tested except for puree, and significant negative correlations were evident between MIPp and chewable solids (i.e., banana and graham cracker). MIPa was found to significantly predict TOP duration for thin liquid, mechanical soft and regular solids, and MIPp was found to significantly predict TOP duration for mechanical soft and regular solids. MIPa and MIPp values were significantly greater in males than in females. Age was discovered to significantly predict MIPa but not MIPp. There were no statistically significant differences in TOP durations between sexes. Age was revealed to have the strongest predictive value with TOP durations for liquids as opposed to TOP durations for food consistencies.

Conclusion: This was the first study to demonstrate that significant relations exist between MIP and TOP duration in the healthy adult population. Sarcopenia is most likely responsible for the decrease in MIPa and longer TOP durations observed in older adults. Findings from this investigation lend support for implementing regular MIPa exercise in healthy adults to possibly combat lingual weakness and minimize or alleviate symptoms of oral phase dysphagia later in life.
CHAPTER ONE

INTRODUCTION

Overview of Dysphagia

It is estimated that 18 million adults suffer from dysphagia, the medical diagnosis for swallowing impairment, in the United States (Robbins et al., 2008). The prevalence has been estimated to be as high as 22% in those over 50 years of age (Howden, 2004). Consequently, the elderly constitute the highest group of individuals with dysphagia in the United States. A common cause of dysphagia in adults is stroke (Spieker, 2000). A study which investigated the prevalence of swallowing impairments in an acute care hospital revealed that 64% of hospitalized acute stroke patients were found to have a form of dysphagia (Mann, Hankey, & Cameron, 1999).

In addition to stroke, there are a variety of etiologies which are neurogenic in nature (e.g., Parkinson’s disease, Huntington’s disease, and Amyotrophic Lateral Sclerosis). Dysphagia can also present secondary to structural impairment (mechanical dysphagia). Mechanical dysphagia includes etiologies that physically alter the normal swallowing mechanism; mechanical dysphagia etiologies include: head and neck cancer, any physical injury (e.g., gunshot wound), or trauma which negatively impacts swallowing. Dysphagia may also occur without an obvious cause, as swallowing efficiency decreases with normal aging (Logemann et al., 2000; Shaker & Lang, 1994). This declining function is thought to be secondary to reduction of muscle fibers, a condition known as sarcopenia (Burkhead, Sapienza, & Rosenbek, 2007). Regardless of etiology, the health complications that are associated with dysphagia are concerning and may include malnutrition, aspiration pneumonia, and death (Plowman-Prine et al., 2009; Langmore, Skarupski, Park, & Fries, 2002; Perry & Love, 2001; Schmidt, Holas, Halvorson, & Reding, 1994).

When food and liquid intake is compromised due to swallowing impairment, malnutrition is commonly observed (Crawley, 2009). Malnutrition is a condition in which the body does not receive adequate nutrients and can lead to weight loss, dehydration, prolonged healing of skin breakdowns (e.g., decubitus ulcers), and reduced immune response (Davis & Spicer, 2007). Previous research reported that individuals who had suffered strokes with concomitant dysphagia had a significantly higher presence of malnutrition than did individuals who had suffered strokes.
without dysphagia (Foley, Martin, Salter, & Teasell, 2009). Aspiration, the instance in which food or liquid is misdirected into the trachea, is particularly concerning due to potential growth of bacteria from the aspirated material. Such bacterial growth in the lungs can cause pneumonia, which can be fatal in medically fragile individuals (Lambert et al., 2005). Studies have revealed that a diagnosis of aspiration pneumonia results in increased duration of hospitalization and costs of medical care (Rosevinge et al., 2005; Langmore et al., 2002; Finestone et al., 1996; Smithard, et al., 1996; Odderson, Keaton, & McKenna, 1995). Moreover, researchers have reported dysphagia as an independent predictor of mortality in individuals who have suffered from neurologic disease (Rosevinge & Starke, 2005; Schmidt, Holas, Halvorson, & Reding, 1994; Smithard et al., 1997).

To better understand dysphagia and the potential for remediation, it is important to address muscle morphology and the act of normal swallowing physiology. The capacity for muscle activation, strength and endurance depends on the specific composition of its fibers and its ability to produce adenosine triphosphate (ATP), which is the body’s energy currency (McArdle, Katch & Katch, 2007). Regardless of the type of work (e.g., chewing, swallowing), ATP must be produced to execute the activity. Phosphocreatine (PC) is also readily available in the body as an energy source. The body monitors the ratio of these phosphates and replenishes them as needed. ATP is used to perform work that requires two to four seconds and then must be replenished. PC can provide energy for a few more seconds than ATP (around five to seven seconds). These two sources, which fuel muscular contractions, are collectively known as the ATP PC system. Once the ATP PC system has been exhausted, the body must create energy through the utilization of glycogen reserves (Powers & Howley, 2009).

The swallowing mechanism is primarily comprised of skeletal muscle, with the exception of the thoracic and abdominal portions of the esophagus, which contain combinations of skeletal and smooth, or entirely smooth muscle respectively. Skeletal muscles are composed of Type I (slow twitch; fatigue resistant) fibers and larger Type II (fast twitch; fast fatigable) fibers. Type I fibers utilize aerobic (i.e., presence of oxygen) metabolism and are more efficient producers of ATP and PC but generate less force than Type II fibers. Type II fibers belong to one of two categories: Type IIb fibers which generate the most force and engage anaerobic (i.e. absence of oxygen) metabolism for ATP PC production, and Type IIa fibers which are fast-oxidative/glycolytic fibers and utilize both aerobic and anaerobic metabolism to produce ATP.
and PC. Muscles involved in the act of swallowing are comprised of Type I, IIa, and IIb fibers; a predominance of Type II fibers is found in the oropharyngeal region (Burkhead, Sapienza & Rosenbek, 2007; Kent, 2004).

The process of swallowing has common features across individuals. However, variability does exist in the normal system to accommodate variations in the type and volume of the bolus. Although the swallow is thought to occur from a central pattern generator, for the sake of simplicity and to assist clinicians with diagnosis and management, swallowing has been described to occur in stages. It should be noted that although these stages have been operationally defined, some degree of overlap in function occurs between the stages (Groher & Crary, 2010).

The accepted method to describe the normal sequence of swallowing has been to divide the process into four phases which include: (1) oral preparatory phase, (2) oral transport phase, (3) pharyngeal phase, and (4) esophageal phase. The first two phases are voluntary to meet the physical demands of the various consistencies of foods and liquids introduced. The oral preparatory phase begins when the individual presents food or liquid into the oral cavity. Once the material is introduced, a labial seal secures the food or liquid to prevent it from escaping from the mouth. Because the mouth is closed, the individual must maintain an open nasal passageway for breathing. The Type I and Type IIa muscle fibers which comprise the anterior portion of the tongue enable the tongue to produce fast and precise movements in order to manipulate the material and mix it with saliva to form a bolus. Additionally, the posterior segment of the tongue, which has a higher density of muscular tissue compared to the anterior tongue, is mostly comprised of Type I fibers assists in bolus formation (Miller, Watkin, & Chen, 2002).

Liquids enter the oral cavity already in a cohesive unit. However oral preparation of liquids, particularly thicker liquids, varies across individuals. It is not abnormal for individuals to hold the liquid bolus between the midline of the tongue and hard palate or in the floor of the oral cavity for a moment prior to swallowing it. Additionally, it is not abnormal to spread the liquid bolus around in the oral cavity and manipulate it by moving the mandible and tongue in a lateral rotary action before initiating the swallow. For all chewable foods, this rotary jaw movement is essential for adequate mastication to form a bolus. Mastication cycles are repeated several times prior to forming a bolus and initiating oral transit.
Once the bolus has been formed, the second phase of swallow is initiated. During the oral transport phase, the anterior portion of the tongue initiates bolus transit. Additionally, the Type IIb fibers which largely constitute the base of the tongue allow for the greater force needed to propel food and liquid into the pharynx to prepare for swallowing (Burkhead et al., 2007). Lingual movement during the oral phase is also described as a stripping action as the tongue squeezes the bolus in an anterior to posterior fashion against the hard palate to propel it toward the pharynx (Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993). Lingual pressure during the oral transport phase increases as the viscosity of the food or liquid increases (Youmans & Stierwalt, 2006; Dantas & Dodds, 1990). Furthermore, a negative pressure is created through contraction of the buccal musculature which also assists in anterior to posterior bolus propulsion in this second phase of normal swallowing (Logemann, 1998).

When the bolus reaches the region of the anterior faucial pillars in the oral cavity (the posterior tongue base near the valleculae in the elderly), sensory receptors in the tongue and oropharynx are stimulated and send a neural signal to the cortex and medulla of the brain stem to initiate the pharyngeal phase of swallow (Logemann, 1998). This third phase is partially involuntary due to the activation of the swallowing pattern generator and also voluntary as individuals can modify the aspects of the swallow (e.g., swallowing with more or less force) to accommodate the wide variety of bolus consistencies. During the pharyngeal phase, a series of physiologic events occur which include the following: elevation of the velum to close off the nasopharynx and eliminate nasal regurgitation, lowering of the epiglottis to aid in airway protection, activation of the pharyngeal constrictor muscles, and hyolaryngeal elevation and forward excursion to further assist with safe and efficient transport of the bolus. The natural force of gravity and the serial peristaltic contraction of the pharyngeal constrictor muscles also facilitate bolus transit to the opening of the esophagus.

The final phase of swallowing, the esophageal phase, is initiated by the involuntary relaxation of the upper esophageal sphincter (UES). Once the UES opens, the volume of combined cavities (pharynx + esophagus) is dramatically increased resulting in a drop in pressure (i.e., Boyle’s Law) ahead of the bolus to further assist with bolus propulsion as the bolus enters the esophagus and continues its descent via gravitational force and esophageal peristalsis. When the bolus reaches the inferior portion of the abdominal esophagus, the lower esophageal sphincter (LES) muscle relaxes and allows the bolus to enter the stomach for
digestion purposes (Groher & Crary, 2010). Depending on the consistency swallowed, normal esophageal transit time has been reported to range from eight to 20 seconds (Logemann, 1998).

Physical trauma to the swallowing mechanism and/or neurologic damage to anatomical structures responsible for swallowing can cause individuals to experience difficulty during any of the four phases of swallowing. If impairment is isolated to the oral preparatory and/or oral transport phase, this condition is diagnosed as oral phase dysphagia. Impairment that occurs only during the pharyngeal phase of swallowing is pharyngeal phase dysphagia. If the individual’s swallowing difficulty is specific to the esophageal phase, then a diagnosis of esophageal phase dysphagia is given. Although dysphagia can solely occur during a single phase of swallow, many individuals have difficulty with multiple phases of swallow (Bulat & Orlando, 2005). For instance dysfunction during the oral preparatory, oral transport and pharyngeal phases is diagnosed as oropharyngeal dysphagia. Swallowing impairment in the pharyngeal and esophageal phases is referred to as pharyngoesophageal dysphagia.

Speech-language pathologists (SLPs) evaluate swallowing through either instrumental methods (i.e., videofluoroscopic examination and fiberoptic endoscopic evaluation) or a non-instrumental method (i.e., clinical swallowing evaluation, historically known as the “beside swallow evaluation”) (Logemann, 1998). The gold standard for swallowing evaluation is the modified barium swallow study (MBSS), a dynamic videofluoroscopic examination conducted by SLPs and radiologists. During the MBSS, consistencies of food and liquid are mixed with barium contrast to enable visualization of the bolus on x-ray as it passes through all four stages of swallowing. Upon completion of the swallowing examination, the SLP determines the presence or absence of dysphagia and works closely with registered dietitians (RDs) to provide specific recommendations for remediation if warranted (Davis & Spicer, 2007).

Traditionally, a primary focus for managing dysphagia symptoms has been diet modification (e.g., altering the texture of food or thickening liquid). For example, if an individual has difficulty with bolus formation during the oral preparatory phase, a texture that requires less chewing (e.g., pudding) may be recommended. In the event that a client presents with sensory deficits that result in a delayed swallow, thin liquids may be problematic due to the fast rate of propulsion into the pharynx, increasing the risk of aspiration. In this case a thicker viscosity of liquid, which has a slower rate of propulsion, may dramatically reduce the risk of aspiration. Medical professionals involved in dysphagia management utilize a team approach to prescribe
modified diets, which not only reduce or eliminate the risk of aspiration but also promote adequate nutrition (Davis & Spicer, 2007). Also, several compensatory strategies (e.g., postural techniques, altering bite sizes) can be employed in dysphagia rehabilitation to facilitate a safer method of nutritional intake and reduce the risk of aspiration.

In addition to diet modification and compensatory maneuvers, exercise regimens have been proposed to improve swallowing function. By strengthening Type I, IIa, IIb, and hybrid fibers in oral, pharyngeal, and laryngeal muscles, clinicians aim to increase both strength, defined by the ability to produce or resist force, as well as endurance, which refers to muscle capability to sustain force over time (Clark, 2012) of the swallowing system. As the human swallowing mechanism is predominantly composed of Type II fibers, swallowing exercise protocols primarily target these fast contracting but easily fatigable muscles by employing the overload principle (McArdle, Katch & Katch, 2007). This principle simply states that force-generating capacity and functional reserve can only be increased by progressively overloading the normal physiologic demands of the muscle. In addition, exercise physiology studies have suggested that gains in muscle strength and endurance can be maximized over time by progressively adjusting the absolute value of load placed on the muscle over the course of the exercise program; this concept is known as progressive resistance (Kraemer & Newton, 2000). Research has demonstrated that skeletal muscle responds to resistance training exercise protocols that begin with an initial resistive load of approximately 60% of the 1-repetition maximum (1RM), i.e., the load one can bear with maximum effort to complete a single repetition (Deschenes & Kraemer, 2002). Traditionally, resistance training programs designed to strengthen oropharyngeal muscle for dysphagia rehabilitation require 60% to 75% of 1RM (Robbins, et al., 2005; Silverman, et al., 2006).

During the process of dysphagia rehabilitation, one indication of swallowing improvement relates to whether the diet level (i.e., the consistencies of food and liquid that he/she can safely swallow) can be advanced. The diet level is determined from the individuals’ ability to manage the following consistencies of liquids and solids during swallowing evaluations: (a) thin liquid, (b) nectar thick liquid, (c) honey thick liquid, (d) puree consistency (e.g., pudding), (e) mechanical soft consistency (e.g., diced pears), and (f) regular consistency (e.g., a graham cracker) to patients suspected of having dysphagia. These six consistencies represent a sample of the foods and liquids commonly consumed in everyday life (Logemann, 1998). In an attempt
to standardize “diet levels” across facilities, many SLPs utilize the National Dysphagia Diet (NDD), published in 2002 by the American Dietetic Association (now known as the Academy of Nutrition and Dietetics), as it provides standard terminology and practice applications of dietary texture modification in dysphagia management. The NDD consists of four diet levels. Level One, labeled dysphagia pureed, has a consistency that does not require any chewing. Level Two, labeled dysphagia mechanically altered, allows for small bite size foods of very soft texture and ground meats mixed with gravy or sauce. Level Three, labeled dysphagia advanced, comprises bite-sized foods excluding hard, dry consistencies (e.g., nuts) and requires that meats be chopped. Level Four, which constitutes a normal, unmodified diet, has no restrictions. The NDD levels do not include specific consistencies of liquid; therefore, upon evaluation the SLP prescribes the safest consistency of liquid (e.g., thin or “regular” liquid, nectar-thick liquid or honey-thick liquid) that is least restrictive for the individual.

Medical professionals who treat individuals with dysphagia have become increasingly interested in how quality of life (QOL) is affected by modified diets, which often are prescribed for individuals with dysphagia. The Swallowing Quality of Life (SWAL-QOL) questionnaire is a tool that researchers and clinicians have utilized to explore this issue from the patient’s perspective (McHorney et al., 2002). The SWAL-QOL is a 44-item questionnaire that assesses 10 QOL domains related to the individual’s swallowing impairment (e.g., food selection, eating duration, eating desire), and it takes approximately 15 minutes to complete. The individual with dysphagia is asked to rate his or her perception of the 44 items in the SWAL-QOL on a scale of one through five (worst to best); each domain has a standardized score range of zero to 100 (the higher the rating corresponds to more favorable QOL perceptions in each domain of the questionnaire). Adding the domain scores and dividing by 10 will derive a total SWAL-QOL score. Several studies which have utilized the SWAL-QOL have reported significantly lower scores in individuals with dysphagia compared to matched control subjects (McHorney et al., 2002; Plowman-Prine et al., 2009; Leow, Huckabee, Anderson, & Becker, 2010). Research also has reported a negative correlation between a standardized depression index, the Beck Depression Inventory II (BDI-II; Beck, Steer, & Brown, 1996) scores and total SWAL-QOL scores in individuals with dysphagia (i.e., as the SWAL-QOL decreases, the level of depression increased) (Plowman-Prine et al., 2009).
Given these adverse effects of dysphagia on individuals, researchers have conducted studies to establish optimal methods to evaluate and remediate swallowing impairment. Furthermore, accurate diagnosis of dysphagia, as well as the management of specific types of dysphagia, is informed by research on the biomechanical measurements of swallowing. In a study investigating dysphagia following stroke researchers reported that one element of dysphagia, delayed oral transit, was “the single independent predictor of failure to return to a normal diet” (p. 744) in a group of 128 individuals who were six months post-stroke (Mann et al., 1999). Despite this finding, studies that have examined temporal components of the oral phase have been limited. Further research is warranted to provide clinicians with acceptable standards for a normal range of function regarding the total oral phase (oral preparatory stage + oral transport stage or TOP) duration across consistencies.

A related physiologic aspect of swallowing that has a growing literature base relates to tongue strength and endurance. An emergence of research reporting lingual pressure measurements in both normal, healthy adults and individuals with swallowing impairment has surfaced. To better understand tongue function, researchers have measured lingual strength and endurance during swallowing and non-swallowing tasks through the use of the Iowa Oral Performance Instrument (IOPI) (Robin & Luschei, 1992). The IOPI is a hand-held device that contains a pressure transducer which enables investigators to place an air-filled bulb in various locations of the oral cavity to measure pressure in kilopascals (kPa) during swallowing and non-swallowing tasks. Studies which have utilized the IOPI to measure various aspects of lingual pressure have demonstrated that younger healthy adults tend to demonstrate greater lingual strength compared to older healthy adults (Youmans, Youmans, & Stierwalt, 2009). When sex is considered, previous research has reported males as having greater lingual strength compared to females, however, these sex differences in lingual strength have been inconsistent in the literature and are subsequently less robust (Stierwalt & Youmans, 2007; Youmans et al., 2009). Additional investigation of lingual pressures generated during the swallow has consistently demonstrated that lingual pressure increases as bolus viscosity increases (Youmans & Stierwalt, 2006; Gingrich, Stierwalt, Hageman, & LaPointe, 2012).

As reviewed, examination of swallowing impairment has included studies of temporal correlates of swallowing and lingual pressure in isolation. In spite of an intuitive relation among temporal events in the oral phase and tongue function, to our knowledge there are no published
studies which have specifically examined the nature of the relation between lingual pressure and oral phase timing in the normal system. As the tongue is highly involved during the oral phase and likely impacting TOP duration, research aimed to explore the contributions of lingual pressure to oral phase timing is warranted.

**Literature Review**

**Oral Phase Timing Studies**

An early study which analyzed temporal features of the normal adult swallow during a variety of consistencies (Palmer, Rudin, Lara, & Crompton, 1992) was instrumental in offering preliminary data for oral phase timing. The investigators recruited four healthy adult subjects (two males and two females) ranging in age from 21 to 62 years old with no prior history of swallowing problems, neurological disease, surgery of the head and neck, or symptoms of gastroesophageal reflux disease (GERD). Each subject participated in simultaneous videofluorography (VFG) and electromyography (EMG) to analyze swallowing features of the following materials mixed with barium to provide contrast: (1) a small piece of apple; (2) apple juice; (3) chewing gum; (4) a cube of sticky muffin; and (5) seven peanuts. Subjects were instructed to swallow each presentation normally. For the chewing gum trial, subjects were told to swallow the saliva and barium but hold the gum in the mouth until instructed to remove it. Between foods subjects rested for 2-3 minutes and drank water to cleanse the oral cavity. To report oral phase timing of each of the consistencies, the researchers opted to measure “oral containment time,” which was operationally defined as the period of time required to prepare a particular food for swallowing. Oral containment durations varied significantly among the items tested ($F = 7.29, p < 0.001$). Liquids resulted in the shortest mean oral containment time ($1.61 \text{s} \pm 0.55 \text{ seconds}$) and peanuts required the longest mean duration ($10.41 \pm 2.08 \text{ seconds}$).

Unfortunately, researchers did not control for an order effect in this study as all foods were consumed in the same order. Coupled with the small sample size, methodological flaws of this study made the results difficult to interpret.

Although it was not the primary purpose of the investigation, an additional study exploring various aspects of normal swallow function extended the examination of oral phase timing for chewable foods (Hieemae et al., 1996). These researchers utilized synchronous EMG to record swallowing events in 11 adults (five males and 6 females) with no history of swallowing impairment. Each participant was asked to take “large” bites from the following foods provided:
bananas, apples (peeled and unpeeled), apple peels, chicken spread, and “Ginger Nut” biscuits. Mean durations of chewing cycles and swallow cycles were obtained for all items administered to the subjects. The investigators did not directly measure total oral phase timing in this study, but they did report values for “total sequence duration,” which they defined as “the total time elapsed between first mouth opening and the end of terminal swallow” (p. 182). The shortest mean total sequence duration was found with the peeled apple (17.48 seconds; SD = 5.12) as opposed to the longest total sequence duration, which resulted from the biscuit item (21.51 seconds; SD = 5.5). This study was one of the first investigations which utilized EMG to isolate and measure temporal components of swallowing chewable foods. As a banana is commonly used to represent mechanical soft items in clinical swallowing evaluations (Headley, Stierwalt, Leinweber, Shioick, & Futchko, 2012), the normal timing intervals for swallowing a large bite of banana reported in this study could be clinically beneficial. However, given the small sample size of this investigation, the data reported cannot generalize to the normal adult population. Additionally, the authors did not report any reliability data for their measures, which reduces the integrity of their findings.

Shaw and colleagues investigated oral phase timing in a comparison of two instrumental measurement techniques. They compared scintigraphy measures versus videofluoroscopy measures in four groups of adults (Shaw et al., 2004). The researchers operationally defined oral transit time as “the interval between the onset and completion of oral emptying” (p. 38). Group I was a sex-balanced group which included nine healthy volunteers (mean age = 24; age range = 19-36 years) with no history of swallowing problems who underwent scintigraphic measures of bolus clearance and transit times. Group II, comprised of nine healthy male subjects (mean age = 23; age range = 18-25 years) with no history of swallowing, were examined under videofluoroscopy. Group III contained 26 dysphagic patients (13 males, 13 females; mean age of 72 years, age range = 50-88 years) who were evaluated via scintigraphy. Group IV included 21 healthy aged matched controls (mean age = 68 years; age range = 55-83 years). For both scintigraphy and videofluoroscopy conditions, average oral transit times were recorded for two trials of a 5-mL bolus and two trials of a 10-mL bolus of thin liquid. Subjects were instructed to swallow the entire bolus of water in a single swallow. Oral transit times in milliseconds using both scintigraphy and videofluoroscopy were reported for normal subjects but not for the dysphagic subjects. No significant differences in transit times were recorded by the two
techniques. The investigators reported good test-rest reliability at the 95% confidence interval for all measures. The small sample size of this study does not demonstrate strong enough statistical power for the results to represent the population of normal adults. In addition, as subjects may have required multiple swallows with a 10mL bolus, the instruction to “swallow the entire bolus” is problematic because the subjects’ swallowing performance may not have mimicked normal swallowing. Additionally, only providing two trials does not enable the researchers to examine internal consistency across measures. The authors did not perform oral phase timing comparisons between normal subjects and dysphagic subjects. In summary, the findings of this study contributed that scintigraphy and videofluoroscopy techniques do not significantly differ with regard to measuring timing components of the swallow. However, due to flaws in the methods investigation, the normal oral transit times reported for 5mL and 10 mL liquid boluses should not be used as a norm reference for swallowing diagnostic purposes.

Oral and pharyngeal transit times of puree consistency solids were measured in a study involving 20 patients with Chagas’ disease (CD), a disease causing esophageal dysmotility, and 21 control subjects (Gomes, Secar, & Kubo, 2008). The CD sample consisted of 14 women and 6 men (mean age = 55 years; age range = 27-81 years), and the healthy controls were 19 women and 2 men (mean age = 55; age range = 22-75 years). All subjects completed a scintigraphic evaluation of swallowing in which they swallowed a 10-mL paste bolus. The authors defined oral transit time as “the interval between the onset and completion of oral emptying” (p. 83). The results of the study indicated no significant differences in oral transit times between the patients with CD and the control subjects. Further analysis of normal oral transit time was conducted by dividing the patients with CD into two groups: (1) Younger (27-57 years, mean age = 45 years, \( n = 11 \)), and (2) an Older group (58-81 years, mean = 65 years, \( n = 10 \)). Additionally, the controls were separated into two groups: (1) Younger (27-56 years, mean = 43 years, \( n = 11 \)); and (2) Older (57-75 years, mean = 66 years, \( n = 10 \)). Although temporal durations of oral transit were shorter in the two younger groups compared to the two older groups, the researchers reported that the differences were not statistically significant. The mean oral transit time for all subjects (10 mL paste bolus) was 0.64 seconds (SD = 0.22). As mentioned with previous investigations, the small sample size of this study limits its statistical power and therefore, the oral transit times reported cannot represent the populations of normal adults and adults with CD. An additional weakness of this investigation was the absence of
Research which examined the effect of mastication on oral transit phase and swallow initiation divided the process of deglutition into five distinct and sequential stages, known as the “Process Model Paradigm”: (1) Processing, (2) Oropharynx aggregation time (OAT), (3) Postfaucial aggregation time (PFAT), (4) Vallecular aggregation time (VAT), and (5) Hypopharynx transit time (HTT) (Saitoh, Shibata, Baba, & Fujii, 2007). The authors cited previous studies which have validated the Process Model Paradigm and reported that the traditional method of dividing swallowing into four stages is “inappropriate for studies of feeding” (p. 101). Researchers recruited 15 healthy young adults (nine males and six females, mean age = 30 years), with no history of swallowing impairment or neurologic disease. Videofluorography (VFG) was performed to analyze the subject’s consumption of the following foods: liquid barium, corned beef hash with barium, shortbread cookie with barium, and a two-phase mixture of liquid barium and corned beef hash. For liquid barium, 10 mL of liquid barium was placed in the mouth with a syringe, and subjects were instructed to swallow normally; this was labeled the “liquid-no chewing” recording. For a control comparison, an additional recording was made with instruction to chew the 10mL of liquid barium and then swallow; this was labeled the “liquid-chew” recording. For corned beef hash and the cookie, 8g of food was placed in the mouth and subjects were instructed to eat the food normally. To evaluate mixed consistency, 4g of corned beef hash was placed in the mouth, and 5 mL of liquid barium was injected in the mouth with a syringe. As seen through visual imaging, leading edges of the bolus passing through the oropharynx and hypopharynx defined the initiation and termination of each of the five intervals. Reported timing measurements included the duration of each interval and the interval from the start of HTT until swallow onset (defined as the moment when the hyoid bone begins to elevate). Because the authors did not divide swallowing into the traditional four stages, standard oral phase timing intervals would be difficult to extrapolate from their data. Again, no reliability measures were reported by the researchers. Had the sample size been increased to strengthen statistical power, the temporal findings of this study could have been clinically beneficial for clinicians who perform videofluoroscopy to evaluate dysphagia but less beneficial for overt swallowing diagnostics protocols (i.e., the clinical swallow evaluation).
Oral, pharyngeal, and esophageal transit times of 26 people with dysphagia (age range = 26-83 years) resulting from stroke, either a single lesion or multiple lesions, and 15 control subjects (age range = 27 - 86 years) with no history of dysphagia or digestive complaints were measured in a scintigraphy study (Silva, Fabio, & Dantas, 2008). During the swallow evaluation, all subjects swallowed a 5-mL thin liquid bolus and a 5-mL paste bolus. The control subjects’ mean oral transit time for the liquid bolus was 0.97 seconds (SD = 0.19) and 0.76 seconds (SD = 0.37) for the paste bolus. No significant differences were found between single lesion stroke patients and controls with respect to oral and pharyngeal transit times. However, stroke patients who had suffered multiple lesions demonstrated significantly longer oral transit times with the paste bolus (1.81 seconds ± 1.17) compared to all other subjects ($p = 0.03$). Because the researchers only had the subjects swallow one trial of each bolus, reliability could not be calculated. This flaw along with the small sample size were problematic for this study, therefore, the oral transit times reported in the group samples should be replicated with additional study.

Mendell and Logemann (2007) conducted an investigation to analyze the temporal relationships of specific structural sequences during normal swallowing. This study utilized a retrospective analysis of videofluoroscopic swallows of 100 normal participants (50 males and 50 females; age range = 22 - 92 years). Each subject was asked to perform two swallows of 3-mL and 10-mL thin liquid as well as a 1-3-mL paste bolus, which corresponded to a pudding consistency. Temporal measurements were made by comparing bolus arrival points and structural movements to the onset of upper esophageal sphincter (UES) opening. The independent variables were age, bolus type, sex, and trial (e.g. presentation 1 and 2 of each bolus type). The dependent variables were the temporal measures relative to the onset of UES opening. The investigators of this study conducted a mixed repeated measures analysis of variance (ANOVA) across each of the temporal variables (Sex x Age x Bolus type x Trial). The effect of age was not significant for the temporal relation between the onset of oral transit and UES opening. However, when the researchers analyzed the effect of age with the removal of subjects who performed postures or maneuvers, a significant effect of age was reached: onset of oral transit, $F(4, 61) = 4.171, p = 0.005$; bolus over base of tongue, $F(4, 61) = 4.024, p = 0.006$; bolus head reaching the inferior border of the valleculae (IBV), $F(1, 61) = 4.372, p = 0.004$; and onset of tongue base retraction, $F(4, 61) = 7.319, p < 0.001$. The time difference between the onset of movement and the onset of UES opening was shortest for the largest liquid volume
swallowed, with longer times for the smaller bolus volume. The time difference between motor responses increased with age. As people age, the time difference between the onset of swallow events relative to the UES opening increases, indicating longer swallow duration. A statistically significant sex difference was only detected in one sequence measure as men demonstrated significantly longer time differences between the onset of BOT posterior movement relative to the onset of UES opening relative to women. The authors suggested that future research should be conducted to further investigate this sex difference in the onset of tongue base retraction. Moreover, the authors concluded that volume, consistency, and age all affect the timing of specific motor events involved in swallowing, thus, more specific study of this topic is indicated.

A study which examined the effects of bolus consistency on penetration-aspiration (P-A) and temporal measures of swallow added to the literature base of oral phase timing in persons with Parkinson’s Disease (PD) (Troche, Sapienza, & Rosenbek, 2008). Dependent variables included: oral transit time (OTT), pharyngeal transit time (PTT), number of tongue pumps, and P-A score. Ten participants with idiopathic PD (5 male; 5 female; mean age = 68.5 years) were examined videofluoroscopically; no control subjects were used in the investigation. The researchers defined the onset of OTT as “the onset of posterior movement by the bolus in the oral cavity; the point at which the tongue tip is raised and the bolus begins posterior movement toward the posterior aspect of the oral cavity” and offset of OTT as “the point at which the tail of the bolus passes the level of the ramus of the mandible” (p. 28). The subjects were instructed to perform the following swallowing tasks: dry swallow, six 5-cc trials of pudding-thick liquid from a spoon, and six 5-cc trials of thin liquid from a cup; all patients fed themselves during the study and the sequence of presentations was counterbalanced across participants to eliminate an order effect. A multivariate analysis of variance revealed no significant transit differences as a function of sex. As a function of consistency, mean oral transit time was significantly longer for pudding thick consistency (2.394 seconds; SD = 1.524) than for thin consistency (0.916 seconds; SD = 0.42) ($p < 0.01$). The authors stated that their findings were consistent with previous studies completed by healthy controls which found longer oral transit times with thicker consistencies than thin consistencies. The researchers speculated that increased OTT may be related to decreased lingual strength and abnormal lingual movements (i.e., “tongue pumping”) that commonly occur in the PD population. Although this study did not provide normative data
for OTT, it suggested that future research should explore the relationship between OTT and lingual strength.

Although several studies have incorporated measures of oral phase timing, there continues to be a lack of normative data in the total oral phase (TOP) durations across the standard consistencies administered in clinical swallowing evaluations. The absence of criterion reference norms for TOP is a problem because SLPs cannot confidently diagnose the presence of oral phase delays during swallowing diagnostic protocols. A national survey which explored 206 SLPs’ perceptions of acceptable TOP ranges across standard consistencies revealed significant variability across clinicians (Headley et al., 2013). Future studies which incorporate larger sample sizes to increase statistical power and include reliability measures for the dependent measures are warranted to increase our understanding and promote more uniformity in SLPs’ diagnostic judgments for normal temporal parameters of the oral phase of swallowing.

**Lingual Pressure Studies**

Previous research which explored the relationship between tongue strength and oral phase swallowing function demonstrated that tongue strength decreased with age in individuals with dysphagia (Clark, Henson, Barber, Stierwalt, & Sherill, 2003). In this study 63 patients (age range = 19 – 95; 28 males and 35 females) who presented with a variety of medical diagnoses completed both subjective and objective examination of tongue strength. The mean age for the male group was 72.5 years, and the mean age for the female group was 73 years. Clinicians measured tongue strength subjectively via an oral motor assessment, and objectively utilizing the IOPI. During the IOPI tasks, the tongue bulb was placed behind the incisors and made contact with the alveolar ridge. Participants were asked to use the tongue to “push as hard as possible” against the bulb and the pressures obtained were recorded for three attempts. The maximum pressures obtained as well as the average of the three trials were analyzed to determine which measure was more predictive of oral phase dysphagia. A high correlation was found ($r = 0.976$) between individuals’ maximum lingual pressure and the average of the recorded maximum pressures, which demonstrated strong stability of the measure. Results of this investigation did not reveal significant differences in tongue strength as a function of sex. Although one measure was not revealed as a better predictor compared to the other, the authors reported that both subjective and objective measures of tongue strength are good predictors of oral phase dysphagia, but they are not sensitive to other aspects of swallowing.
Although a sex effect related to tongue strength was not observed in dysphagic individuals as reported by Clark and colleagues (2003), this was not the case for a group of healthy, normal adults whose maximum isometric lingual pressure tasks were investigated by Youmans and Stierwalt (2006). In order to examine various measures of tongue function in normal swallowing, these researchers recruited 90 participants who were divided into three age groups (20–39 years, 40–59 years, and 60–79 years). The following dependent variables were recorded: maximum isometric pressure (MIP), average lingual pressure during swallowing, and percentage of peak lingual pressure exerted during swallowing tasks. For the MIP task, subjects were asked to use the tongue to press the bulb as hard as possible against the alveolar ridge for three seconds during three trials. For the swallowing tasks, lingual pressures were recorded during three trials of swallowing 30 mL of tap water and three trials of honey thick apple juice. To calculate the percentage of peak lingual pressure engaged during swallowing, investigators divided the mean peak tongue pressure during swallowing tasks by the MIP and multiplied this value by 100. Results of this investigation revealed that males presented with significantly higher maximum isometric lingual pressure than females \((p = 0.001)\); the mean for MIP for male subjects was 64 kPa (SD = 2.03) and the mean MIP for female subjects was 55.9 (SD = 1.86). The youngest group of subjects demonstrated significantly greater tongue pressures (MIP = 69.9 kPa; SD = 2.77) than the oldest group (MIP = 54.5 kPa; SD = 2.02) \((p = 0.01)\). Additionally, this study demonstrated that healthy adults’ MIPs ranged from 32 to 94 kPa with an average MIP of 60 kPa. As observed in previous research, tongue strength measurements demonstrated strong internal consistency within subjects \((r > 0.9)\). High internal consistency was also revealed across lingual pressure measures during the swallowing tasks \((r > 0.8)\). Significant differences in mean swallowing pressures were also found with regard to bolus type. Individuals generated significantly greater mean swallowing pressures with honey thick liquid (29.5 kPa; SD = 1.45) than they did with thin liquid (31.4 kPa; SD = 1.5) \((p = 0.01)\). However, there were no significant differences in mean swallowing pressures as a function of age or sex. Finally, in this investigation the percentage of maximum pressure generated during honey thick liquid was significantly greater (52.8 kPa; SD = 2.22) than thin liquids (49.9 kPa; SD = 2.15) \((p = 0.015)\); however, no age or sex differences were observed.

To expand on previously established lingual pressure literature in both the normal and dysphagic populations, Stierwalt and Youmans (2007) conducted an investigation involving 200
healthy adults (age range = 19 – 91 years; 80 mean and 120 women) with no history of swallowing impairment and 50 adults (age range = 44 – 91 years) who presented with dysphagia. Researchers used the IOPI to obtain both strength and endurance measures in these groups. Strength measures were determined via maximum lingual pressures across three trials. Endurance was measured as the interval at which the individual could sustain 50% of the peak pressure. As documented in their previous study (Youmans & Stierwalt, 2006), a considerable range of maximum lingual pressure (28 – 94 kPa) and a similar mean peak lingual pressure (59.78 kPa; SD = 13.73) was replicated in the control group. Support for their earlier findings was observed as significantly greater Maximum pressures were generated by the male control group (63.24 kPa; SD = 13.86) compared to the female control group (57.15 kPa; SD = 13.50) ($p = 0.001$). When divided into three age groups (19 – 39 years, 40 – 59 years, and 60 – 91 years), the youngest group demonstrated significantly greater maximum pressures compared to the oldest group, a similar finding in the authors’ 2006 study. There were no statistically significant differences in endurance across age or sex in this investigation. As a subset of their larger control group, strength measures were obtained from 42 age- and sex-matched pairs (controls versus individuals with dysphagia) and analyzed via an independent one-tailed $t$ test. A statistically significant difference was discovered between the two groups’ performances as the control group generated significantly greater maximum pressures than the group of individuals with dysphagia ($p < 0.0001$). An additional group analysis was completed to examine endurance in 26 age- and sex-matched pairs. In this case, no significant difference in endurance was revealed between groups ($p = 0.82$). These findings lend support for further examination of the relation between lingual pressure and oral phase measures, as those individuals with dysphagia demonstrated lingual weakness.

Researchers who conduct physiologic studies examining muscle strength and endurance are also interested in the amount of reserve present after a physical activity. To examine whether tongue strength reserve (i.e., amount of available lingual pressure following a swallowing task) decreased as a function of age or sex in healthy adults, 96 participants with normal swallowing were recruited to record lingual MIP, mean swallowing pressure (MSP) generated by the anterior tongue, and percentage of maximum tongue pressure utilized during swallowing (PMPS) (Youmans et al., 2009). As with previous studies, subjects were grouped into three age categories (20-39 years, 40-59 years, 60-79 years) and balanced for sex. This study differed
from previous studies with regard to bolus presentations as the participants were administered various volumes (i.e., 5 mL, 10 mL, and 15 mL) of thin liquids, nectar thick liquids, honey thick liquids, and puree. Unlike previous findings, there was no significant difference in MIP as a function of sex ($p = 0.25$). However, a significant difference in MIP between the young group and oldest group was supported ($p < 0.0001$). With regard to MSP, there were no significant differences as a function of age. The authors did reveal a main effect for sex for MSP; the female group demonstrated significantly higher mean MSP (41.53 kPa) compared to their male counterparts (34.52 kPa). In addition, measures of MSP differed significantly as a function of bolus type. As bolus volume and viscosity increased, increases in MSP were noted. Upon analysis of the PMPS data, the female group revealed a significantly greater PMPS mean (62.88 kPa) compared to the male group (49.65 kPa). The researchers concluded that females appear to have a reduced lingual strength reserve in comparison to males.

Kays and colleagues (2010) conducted a lingual pressure study which explored the effects of eating a meal on lingual endurance. Researchers recruited 22 healthy adults and grouped them into two sex-balanced age groups: young adults, 20-35 years; older adults, 65-82 years. Prior to initiating the meal, subjects were engaged in maximum lingual pressure tasks and endurance tasks (i.e., interval of maintaining 50% of maximum pressure) and data was recorded via the IOPI. To obtain both anterior and posterior lingual pressures, the tongue bulb was first placed 10 mm posterior to the lingual apex and then 10 mm anterior to the most posterior circumvallate papilla. After two baselines recordings were made, individuals were asked to eat a half bagel with peanut butter, carrot sticks, and milk. Following this meal, the researchers recorded maximum lingual pressures and endurance measures again to determine if lingual strength declined post-meals. The results of this study revealed that all subjects had significantly decreased anterior and posterior lingual strength after the meal. Interestingly, these differences were not attributed to age or sex. With regard to tongue endurance following the meal, all groups had significant reductions. This study has important clinical implications for individuals with lingual weakness, if normal lingual function is affected by daily tasks such as eating a meal; it seems intuitive that individuals with impaired function might have amplified effects.

Lingual propulsive pressures generated at the anteromedian and posteromedian segments of the tongue for dry swallows (saliva), thin liquids, and honey thick liquids were recorded in two groups (30 males and 32 females respectively) of healthy young adults (age range = 18–34 years)
(Gingrich et al., 2012). To collect this data, researchers used the IOPI and placed the tongue bulb at the center of the tongue for the anteromedian location and parallel to anterior edge of the back molars for the posteromedian location. Several anterior and posterior lingual pressure measures, including: lingual swallow pressures across the three consistencies (LSP), anterior and posterior maximum isometric lingual pressures (MIP), and percentage of maximum isometric pressure (PMTP) were collected. The investigators sought to examine whether anteromedian lingual pressures significantly differed from posteromedian lingual pressures. In addition, this study explored possible sex and bolus consistency effects on anteromedian and posteromedian lingual pressures. Finally, potential changes in PMTP according to tongue location, bolus consistency, and sex were also examined. A repeated-measures analysis of variance demonstrated significantly higher lingual swallowing pressures were generated by the anteromedian portion of the tongue. Although women generated greater lingual swallow pressures than men across conditions, no sex effect was present for the lingual swallowing pressures across consistencies. As observed in previous research (Younans et al., 2006; Youmans et al., 2009), lingual pressure increased as the viscosity of the consistency increased. There were no observed interactions with regard to sex or consistency on either tongue location in the LSP task. Males demonstrated significantly greater MIPs at the anteromedian tongue location compared to females, but there was no significant sex difference in the posteromedian tongue location. Finally, PMTP was significantly greater in the posteromedian portion of the tongue.

To conclude, the review of the lingual pressure literature revealed the following important findings:

- The IOPI is a valid and reliable tool to measure lingual strength and endurance and lingual swallowing pressures.
- A sex difference in lingual strength has not been firmly established.
- Lingual strength reduces with advanced age (i.e., 60+ years).
- Lingual swallowing pressures do not significantly differ as a function of age.
- There is a reduction in anterior and posterior lingual strength after meals.
- A positive correlation between lingual swallowing pressure and consistency viscosity exists (i.e., as viscosity increases, lingual swallowing pressure increases).
- Females have a significantly lower lingual strength reserve compared to males.
• Significantly higher lingual swallowing pressures are generated by the anteromedian portion of the tongue as compared to the posteromedian portion of the tongue.
• The posteromedian portion of the tongue has a greater PMSP.
• Males demonstrate significantly greater swallowing pressure in the anteromedian segment of the tongue compared to females.
• Posteromedian lingual swallowing pressures do not significantly differ as a function of sex.

Statement of Purpose

The tongue is highly involved during the oral preparatory and oral transport phases of swallowing. Previous research has reported that delayed oral transit time was the most accurate predictor of failure to return to a normal diet. In spite of the interrelation between tongue function and the timing of oral phase events, to our knowledge no studies have explored the relationship between lingual pressure and timing of the oral phase. Therefore, the primary purpose of this investigation is to investigate the relation that exists between lingual strength and total oral phase (TOP) duration. Our operational definition of TOP was the interval between labial closure at the start of the oral preparation phase and the peak of laryngeal elevation muscle activity as observed in the sEMG signal. If a strong negative correlation exists between these two variables (i.e., individuals who generate greater maximum lingual pressure have shorter TOP durations), this finding could be clinically relevant for dysphagia rehabilitation. A secondary purpose of this investigation was to examine the influence of age and sex on MIP and TOP duration.

Research Questions

The current investigation aimed to answer the following primary research questions:
1. What is the relation between maximum isometric pressure means of the anterior portion of the tongue (MIPA) and TOP duration means across standard consistencies in healthy adults?
2. What is the relation between maximum isometric pressure means of the posterior portion of the tongue (MIPP) and TOP duration means across standard consistencies in healthy adults?

We wanted to further explore the nature of the relation among these variables by examining the effects of age and sex. Therefore, the following supporting research questions were posed:
1. How do MIPa and MIPp differ across sex in healthy adults?

2. What is the relation between maximum isometric pressure (MIPa and MIPp) and normal aging throughout the adult lifespan?

3. Do TOP durations for standard consistencies differ across sex in healthy adults?

4. What is the relation between age of healthy adults and TOP duration across consistencies?
CHAPTER TWO

METHODS

Participants and Procedures

This investigation was conducted upon receiving approval from the Institutional Review Board (IRB) at Florida State University. The approved informed consent form and the IRB approval letter are provided in the appendices of this document.

Investigators

The investigators in this study included the author and three trained research assistants, two undergraduates in the FSU Communication Science & Disorders program and one master’s student in the FSU Speech-Language Pathology program. Prior to performing data collection, all trained research assistants completed 3 hours of on-site training with the primary investigator which included written and verbal instructions regarding the research protocol. During the training, the primary investigator reviewed the operational definitions for all measures with each of the research assistants. Also, the primary investigator demonstrated how to collect each measurement. After modeling the measurement procedure, the research assistant was instructed to return demonstration of the procedure in front of the primary investigator. A criterion of 90% performance was established prior to the research assistants conducting any data collection independently, and each research assistant exceeded the criterion. The primary examiner observed each participant perform all measurements for their first three participants to ensure that they adhered to proper protocol.

Participants

Subjects were recruited via two methods: (a) flyers posted throughout the Tallahassee community and (b) classroom announcements at Florida State University. One hundred healthy adult subjects (50 males, 50 females; age 20 to 86) with no history of dysphagia, neurological injury or disease, or other structural or physical impairment that might influence swallowing volunteered to participate in this study. Descriptive statistics for participants’ age and sex are listed in Table 1.
Table 1

Descriptive statistics for age among the total sample and by sex

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<th>Mean age (SD)</th>
<th>Range</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
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<td>Total sample</td>
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<td>42.95 (17.80)</td>
<td>66</td>
<td>20</td>
<td>86</td>
</tr>
<tr>
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</tr>
<tr>
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<td>40.22 (17.68)</td>
<td>60</td>
<td>20</td>
<td>80</td>
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Intake Procedures

Following the informed consent process, investigators gathered general health information and conducted a brief examination of the oral mechanism to assess normal structure and function. Exclusion criteria included: any history of swallowing impairment, neurological diseases, or structural disorders which could negatively impact swallowing function. Also, participants must have been dentate or wore partials, which do not cover any segment of the hard or soft palate, to participate in the study.

Instrumentation

The Biopac MP150WSW System (Biopac Systems, Inc., Santa Barbara, CA), a valid and reliable piece of research instrumentation commonly used in physiologic data acquisition and analysis, was used to measure TOP duration across bolus consistencies via the system’s surface electromyography (sEMG) application. To measure lingual pressure, the Iowa Oral Performance Instrument (IOPI; Version 2.0; IOPI medical, Carnation, WA) was used. Previous research has utilized the IOPI to examine lingual function and the tool has reported excellent inter and intra-rater reliability (Youmans et al., 2006; Youmans et al., 2009; Steele, Bailey, Molfenter, & Yeates, 2009) for measuring lingual pressure during swallowing and non-swallowing strength and endurance tasks. All participants were tested using the same IOPI device, the IOPI 2.2 model, which was calibrated on a monthly basis according to the protocol provided in the IOPI manual. The IOPI can be viewed in Figure 1.

Surface Electromyography (sEMG) Placement

All subjects were seated upright in a straight-backed chair for the duration of the study. Prior to electrode placement, the investigator removed excess dirt, oil, and makeup from each participant’s face and neck area via alcohol prep pads to promote optimal sEMG electrode placement and function at each electrode site. First, a ground electrode was affixed to the
subject’s forehead. Next, an electrode was applied at midline to the muscle portion just behind the mental protuberance of the mandible to record submental muscle activity. This electrode placement detected movement of the tongue and supporting musculature during bolus manipulation and transit. Finally, a third electrode was placed to the left of midline adjacent to the thyroid notch to record infrahyoid muscle activity. Placement of the laryngeal electrode indicated laryngeal elevation, which represented the termination of TOP. Figure 2 illustrates placement of the sEMG electrodes.

*Figure 1. Iowa Oral Performance Instrument (IOPI).*
Swallowing Protocol

Once electrode placement was completed, the investigator provided three presentations each of the following standard consistencies to the subject to self-administer: (a) 20 mL of thin liquid, (b) 20 mL of nectar thick liquid, (c) 20 mL of honey thick liquid, (d) 1 teaspoon (5 mL) of pudding, (e) 1 teaspoon of diced pears, and (f) one-fourth of a standard size graham cracker. The rationale for administering the 20 mL presentation for liquids was that this amount represents the average drink size for adults (Adnerhill, Eckberg, & Groher, 1989). To our knowledge, average bite sizes of pudding, diced pears, and graham crackers have not been established so those were approximated based on general consensus of the examiners. The liquid and food stimuli were selected to represent the consistencies commonly utilized in the assessment of swallowing (Headley et al., 2012). To reduce viscosity measurement error, Resource® pre-thickened nectar and honey thick apple juice were used for the thickened liquid bolus administration. To control
for an order effect, the order of presentation was counter-balanced across subjects. Prior to the subject taking a drink or bite, the investigator instructed the subject: “Please place the entire presentation into your mouth and eat or drink as you would normally. After you have completely swallowed the entire amount, raise your hand.” After each of the semi-solid and solid trials (i.e., puree, mechanical soft, and regular) had been administered, the subject swallowed a sip of water to clear the palate and eliminate any oral residue.

**TOP Duration**

Using the Biopac System software, the investigator indicated the onset of the TOP duration, using a preprogrammed keystroke on the keyboard. The onset of TOP was operationally defined as the moment labial closure was achieved after the cup or spoon exited the lips. As mentioned previously, for each stimulus the subject raised his or her hand to signal to the investigator that the item had been completely swallowed. Upon receiving the signal, the investigator clicked on the “End” key on the Biopac screen to terminate recording for the trial. The offset for TOP duration was operationally defined as the peak amplitude for the muscle activity observed in the sEMG signal. The sEMG recordings for all trials of food and liquid presentations were saved for further analysis.

**IOPI Placement**

To record anterior lingual pressure, the investigator placed the IOPI bulb on the center the tongue behind the teeth as illustrated in Figure 3. To ensure proper placement for each trial, the investigator placed a strip of standard medical tape on the tubing of the IOPI and used a marker to indicate the location immediately anterior to the subject’s closed lips. To obtain posterior lingual pressure measurements, the investigator placed the straight edge of the IOPI bulb parallel to the subjects’ first set of back molars as illustrated in Figure 4. Again, the investigator marked the location on the tape anterior to the closed lips to ensure posterior lingual pressure placement reliability.

**IOPI Measurements**

Once anterior and posterior placements of the bulb had been established, the investigator collected the following lingual pressure measurements: anterior maximum isometric pressure (MIPa) and posterior maximum isometric pressure (MIPp). The instructions for the MIP tasks were as follows “Use your tongue to press the bulb against the roof of your mouth as hard as possible until I tell you to stop.” As described in the IOPI User’s Manual (Luschei, 2011), the
investigator verbally encouraged the subject to “press as hard as you can; keep going” to facilitate maximum effort. Three trials of MIPa and three trials of MIPp were performed. The kilopascal measurements for each trial were recorded manually for further analysis.

Figure 3. Anterior tongue bulb placement.

Figure 4. Posterior tongue bulb placement.
Data Analysis

As performed in similar sEMG swallowing research studies (Ding, Logemann, Larson, & Rademaker, 2003; Criswell, 2011), the original sEMG recordings were processed to reduce the variability of muscle activity and make the signal easier to interpret. The first step in this process entailed rectifying the raw signal. Rectification artificially takes the portion of the signal that resides below the 0 point (the negative electrical potential) and places it above the 0 crossing line. Next, the signal was smoothed (also referred to as digital filtering) through the root mean square process (RMS). This method takes the square root of the average of the squared values of data points across time. After RMS had been completed, the signal underwent integral averaging. This method took the average of every 3 data points of the processed sEMG signal to reduce variability of muscle activity by a factor of 3 and assisted in reduction of artifact (i.e., noise) in the signal. Once the signal had been completely processed, the researcher calculated TOP by measuring the interval between onset (i.e., the “1” marker indicating the onset of the oral preparatory phase) and offset (i.e., the peak amplitude of the signal which was operationally defined as the termination of the oral phase of swallow). Figure 4 illustrates each step of processing the raw signal as well as determining TOP duration for each trial swallow.

All TOP durations for each participant’s swallow trials were entered into a spreadsheet to conduct further statistical analysis. The spreadsheet containing all data for each participant was uploaded into SPSS Version 19.0 for Windows in order to complete all statistical analyses. In addition to conducting internal consistency and computing descriptive statistics, the following statistical procedures were completed to answer the research questions for this investigation: correlation and bivariate linear regression to examine the relation between MIP and TOP duration, the relation between age and MIP, and the relation between age and TOP duration; independent sample t-tests to determine if MIPa and MIPp significantly differed between sexes; and a multivariate analysis of variance (MANOVA) to examine TOP duration differences as a function of sex. An alpha level of 0.05 was used for all statistical tests, including post hoc testing.
Figure 5. Screenshot of Biopac MP150WSW System display of the sEMG signals. A = raw EMG signal; B = average rectified EMG; C = root mean square; D = integrated EMG; E = Maximum EMG. Shaded blue area indicates the onset of TOP duration (marked by the “1”) and the offset of TOP duration which is defined as the max peak of the EMG signal in this study. The black diamond immediately following the offset of TOP indicates the swallow has been completed. In this example, a TOP duration of 1.568 seconds is visible in the box labeled “Delta T.”

Reliability

Intra-rater Reliability

Intra-rater reliability measures were performed to examine the consistency for each investigator’s measurements of TOP duration. A random selection of 10% of the raw sample data that each examiner had obtained was provided to re-analyze. The extent of intra-rater reliability was analyzed via the kappa statistic. In this analysis, a value of above 0.70 is conventionally considered to be adequate (Reinard, 2006). For the 10% sample conducted for
this investigation results ranged from 0.96 to 0.98, which indicated that intra-rater reliability was very high.

**Inter-rater Reliability**

Similar to the method in which intra-rater reliability was assessed, each investigator was instructed to examine 10% of the raw TOP duration data obtained by one of the other investigators. Upon completion of the two data sets, a kappa statistic was calculated. Results ranged from 0.95 to 0.99, which suggests high inter-rater reliability for the measurement of dependent variables used in this study.
CHAPTER THREE

RESULTS

Internal Consistency

Internal consistency of the dependent variables was assessed across the three trials of MIP measures (both anterior and posterior) and the three swallow trials of TOP durations for each consistency to evaluate the stability of the measures. To justify the use of means for all statistical analyses, a Cronbach’s alpha criterion of $\alpha \geq 0.7$ was established for each measure. As seen in Table 2, Cronbach’s alpha coefficients ranged from $\alpha = 0.78$ to 0.97.

Normal Distribution Testing

To determine if the measures were normally distributed, a series of exploratory analyses were conducted including normality plots, histograms, and the Shapiro-Wilks test. Results from these tests revealed a normal distribution for each of the dependent measures for the total sample and within sex groups as confirmed by the Kolmogorov-Smirnov test. Descriptive statistics including Z-scores for skewness, kurtosis, and Kolmogorov-Smirnov test $p$-values for the dependent measures are reported in Table 3 and Table 4.

Table 2

<table>
<thead>
<tr>
<th>Task</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lingual Task Measures</td>
<td></td>
</tr>
<tr>
<td>MIPa</td>
<td>0.97</td>
</tr>
<tr>
<td>MIPp</td>
<td>0.97</td>
</tr>
<tr>
<td>Swallowing Task Measures</td>
<td></td>
</tr>
<tr>
<td>Thin TOP duration</td>
<td>0.78</td>
</tr>
<tr>
<td>Nectar TOP duration</td>
<td>0.90</td>
</tr>
<tr>
<td>Honey TOP duration</td>
<td>0.88</td>
</tr>
<tr>
<td>Puree TOP duration</td>
<td>0.88</td>
</tr>
<tr>
<td>Mechanical soft TOP duration</td>
<td>0.92</td>
</tr>
<tr>
<td>Regular TOP duration</td>
<td>0.91</td>
</tr>
</tbody>
</table>
Table 3

*Descriptive statistics and Kolmogorov-Smirnov (KS) one-sample test probabilities for anterior and posterior maximum isometric pressure (MIP) measures in kilopascals for the total sample and by sex*

<table>
<thead>
<tr>
<th></th>
<th>MIPa Mean (SD)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>KS p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (n = 100)</td>
<td>56.11 (14.46)</td>
<td>56.84</td>
<td>20.00</td>
<td>85.33</td>
<td>65.33</td>
<td>-0.04</td>
<td>-0.42</td>
<td>0.20</td>
</tr>
<tr>
<td>Females (n = 50)</td>
<td>53.14 (12.36)</td>
<td>53.34</td>
<td>20.00</td>
<td>83.33</td>
<td>63.33</td>
<td>-0.33</td>
<td>0.47</td>
<td>0.20</td>
</tr>
<tr>
<td>Males (n = 50)</td>
<td>59.07 (15.88)</td>
<td>60.17</td>
<td>26.30</td>
<td>85.33</td>
<td>59.00</td>
<td>-0.14</td>
<td>-0.98</td>
<td>0.20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MIPp Mean (SD)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>KS p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (n = 100)</td>
<td>51.75 (11.28)</td>
<td>52.84</td>
<td>30.00</td>
<td>76.00</td>
<td>46.00</td>
<td>0.12</td>
<td>-0.76</td>
<td>0.06</td>
</tr>
<tr>
<td>Females (n = 50)</td>
<td>49.02 (10.00)</td>
<td>50.17</td>
<td>30.00</td>
<td>74.67</td>
<td>44.67</td>
<td>0.41</td>
<td>0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>Males (n = 50)</td>
<td>54.49 (11.90)</td>
<td>56.00</td>
<td>32.30</td>
<td>76.00</td>
<td>43.67</td>
<td>-0.25</td>
<td>-0.92</td>
<td>0.20</td>
</tr>
</tbody>
</table>

*Note. * A significant Kolmogorov-Smirnov (KS) test (p < 0.05) indicates that the data does not reflect a normal distribution. All KS p-values for TOP duration were ≥ 0.05 and therefore suggest the data were normally distributed.

Table 4

*Descriptive statistics and Kolmogorov-Smirnov (KS) one-sample test probabilities for total oral phase (TOP) duration measures in seconds across six consistency conditions for the total sample and by sex*

<table>
<thead>
<tr>
<th></th>
<th>Mean (SD)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>KS p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total sample (n = 100)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Consistency</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin</td>
<td>1.18 (.45)</td>
<td>1.12</td>
<td>0.36</td>
<td>2.36</td>
<td>2.00</td>
<td>0.49</td>
<td>-0.38</td>
<td>0.09</td>
</tr>
<tr>
<td>Nectar</td>
<td>1.97 (.84)</td>
<td>1.79</td>
<td>0.45</td>
<td>3.91</td>
<td>3.46</td>
<td>0.47</td>
<td>-0.51</td>
<td>0.05</td>
</tr>
<tr>
<td>Honey</td>
<td>2.25 (.67)</td>
<td>2.21</td>
<td>1.02</td>
<td>3.93</td>
<td>2.91</td>
<td>0.35</td>
<td>-0.62</td>
<td>0.07</td>
</tr>
<tr>
<td>Puree</td>
<td>2.36 (.89)</td>
<td>2.23</td>
<td>0.74</td>
<td>5.14</td>
<td>4.40</td>
<td>0.65</td>
<td>0.42</td>
<td>0.07</td>
</tr>
<tr>
<td>Mechanical Soft</td>
<td>5.46 (1.72)</td>
<td>5.33</td>
<td>2.23</td>
<td>9.59</td>
<td>7.36</td>
<td>0.21</td>
<td>-0.66</td>
<td>0.05</td>
</tr>
<tr>
<td>Regular</td>
<td>10.62 (3.27)</td>
<td>10.26</td>
<td>5.03</td>
<td>21.03</td>
<td>16.01</td>
<td>0.85</td>
<td>0.73</td>
<td>0.08</td>
</tr>
</tbody>
</table>

|               |           |        |      |      |       |          |          |            |
| **Group by sex** |           |        |      |      |       |          |          |            |
| Females (n = 50) |           |        |      |      |       |          |          |            |
| Consistency   |           |        |      |      |       |          |          |            |
| Thin          | 1.12 (.43)| 1.08   | 0.36 | 2.21 | 1.85  | 0.59     | -0.05    | 0.10       |
| Nectar        | 1.90 (.80)| 1.77   | 0.63 | 3.91 | 3.28  | 0.45     | -0.40    | 0.20       |
| Honey         | 2.28 (.62)| 2.27   | 1.09 | 3.77 | 2.68  | 0.27     | -0.42    | 0.20       |
| Puree         | 2.35 (.96)| 2.15   | 0.74 | 5.14 | 4.4   | 0.79     | 0.81     | 0.20       |
| Mechanical Soft | 5.53 (1.84)| 5.43  | 2.23 | 9.59 | 7.36  | 0.25     | -0.71    | 0.20       |
| Regular       | 11.13 (3.68)| 10.73 | 5.03 | 21.03| 16.07 | 0.82     | 0.42     | 0.20       |
Table 4 continued

Descriptive statistics and Kolmogorov-Smirnov (KS) one-sample test probabilities for total oral phase (TOP) duration measures in seconds across six consistency conditions for the total sample and by sex

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Mean (SD)</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
<th>Range</th>
<th>Skewness</th>
<th>Kurtosis</th>
<th>KS p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>1.25 (.47)</td>
<td>1.19</td>
<td>0.49</td>
<td>2.36</td>
<td>1.87</td>
<td>0.38</td>
<td>-0.57</td>
<td>0.20</td>
</tr>
<tr>
<td>Nectar</td>
<td>2.03 (.87)</td>
<td>1.81</td>
<td>0.45</td>
<td>3.82</td>
<td>3.37</td>
<td>0.47</td>
<td>-0.60</td>
<td>0.08</td>
</tr>
<tr>
<td>Honey</td>
<td>2.23 (.72)</td>
<td>2.06</td>
<td>1.02</td>
<td>3.93</td>
<td>2.91</td>
<td>0.43</td>
<td>-0.74</td>
<td>0.06</td>
</tr>
<tr>
<td>Puree</td>
<td>2.38 (.84)</td>
<td>2.30</td>
<td>1.00</td>
<td>4.54</td>
<td>3.54</td>
<td>0.46</td>
<td>-0.13</td>
<td>0.20</td>
</tr>
<tr>
<td>Mechanical Soft</td>
<td>5.39 (1.62)</td>
<td>5.17</td>
<td>2.24</td>
<td>8.71</td>
<td>6.47</td>
<td>0.13</td>
<td>-0.64</td>
<td>0.20</td>
</tr>
<tr>
<td>Regular</td>
<td>10.10 (2.73)</td>
<td>9.95</td>
<td>5.56</td>
<td>17.12</td>
<td>11.56</td>
<td>0.50</td>
<td>-0.23</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Note. *A significant Kolmogorov-Smirnov (KS) test (p < 0.05) indicates that the data does not reflect a normal distribution. All KS p-values for TOP duration were ≥ 0.05 and therefore suggest the data were normally distributed.

Inferential Statistics

Relation between Maximum Isometric Pressure (MIPa) and TOP Duration

To answer the first primary research question regarding the relation between MIPa and TOP duration across standard consistencies, correlation and linear regression analyses were computed with MIPa as the independent (predictor) variable and TOP duration for the specified consistency as the dependent (predicted) variable. A separate regression analysis was completed for each of the six consistencies. In order to extrapolate accurate information from these analyses, the researcher verified through exploratory analysis that the necessary assumptions for linear regression were met.

Correlation analysis revealed a medium negative correlation existed between MIPa and the TOP duration for regular consistency solids, $r(98) = -0.30, p < 0.01$. Although not as strong, additional medium negative correlation relationships were present with MIPa and the TOP duration for mechanical soft solids, $r(98) = -0.25, p < 0.01$, as well as with MIPa and the TOP duration for thin liquids, $r(98) = -0.25, p < 0.01$. Small correlations were demonstrated for MIPa and nectar-thick liquid, $r(98) = -0.19, p < 0.05$, as well as honey-thick liquid, $r(98) = -0.18, p < 0.05$. The correlation between MIPa and puree food was not significant, $r(98) = -0.12, p = 0.11$. 
Bivariate linear regression analyses were conducted to further examine the influence of MIPa on the six standard consistencies during swallowing tasks. Results of the MIPa/thin liquid analysis were statistically significant \((r^2 = 0.06, F[1, 98] = 6.67, p < 0.01)\) indicating that MIPa accounted for 6% of the variance in TOP duration for thin liquids. The unstandardized regression coefficient, \(B\), for MIPa was \(-0.01 (t = -2.58, p = 0.01)\) suggesting that as MIPa increases by 1 kilopascal (kPa), mean TOP duration decreases by \(1/100^{th}\) of a second (1 centisecond). The constant (or intercept) also was statistically significant at 1.63 \((t = 9.16, p < 0.01)\) which indicated that TOP duration would be 1.63 seconds if MIPa theoretically was 0 kPa.

Additional significant regressions were evident when assessing the influence of MIPa on chewable solids (i.e., mechanical soft and regular consistencies). The MIPa/mechanical soft analysis revealed that MIPa accounted for 6% of the variance in TOP duration for mechanical soft solids \((r^2 = 0.06, F[1, 98] = 6.28, p < 0.05)\). Analysis of the unstandardized regression coefficient suggested that as MIPa increases by 1 kPa, mean TOP duration decreases by 3 centiseconds. In this analysis, the constant coefficient indicated that TOP duration for mechanical soft would last approximately 7.1 seconds if MIPa were 0 kPa \((t = 10.51, p < 0.01)\). The MIPa/regular regression also yielded significant results \((r^2 = 0.09, F[1, 98] = 9.91, p < 0.01)\), which explained that MIPa accounted for 9% of the variance with regard to TOP duration of regular solids. No statistically significant results \((p < 0.05)\) were obtained with regard to MIPa predicting TOP duration for the following consistencies: nectar thick liquids, honey thick liquids, and puree.

**Relation between Maximum Isometric Pressure (MIPp) and TOP Duration**

Correlation and bivariate linear regression analyses also were computed to answer the second primary research question. Again, all necessary assumptions for these statistical tests were met. Only two significant correlations were revealed in this analysis, which included MIPp with chewable solids (i.e., mechanical soft and regular consistencies). A strong negative correlation existed between MIPp and the TOP duration for regular consistency solids \(r(98) = -0.37, p < .001\). A small negative correlation was evident upon examining MIPp and the TOP duration for mechanical soft solids \(r(98) = -0.20, p < .05\). There was an absence of significant correlations \((p < 0.05)\) when the relation of MIPp to each of the remaining consistencies (i.e., thin liquid, nectar-thick liquid, honey-thick liquid, and puree) was examined.
Similar to the analyses for MIPa, the bivariate regression analyses, which specified MIPp as the predictor variable and TOP duration as the dependent variable, revealed significant findings for TOP durations with mechanical soft and regular solids. MIPp comprised 4% of the variance for mechanical soft ($r^2 = 0.04, F[1, 98] = 4.00, p < 0.05$) and 14% of the variance for regular consistency ($r^2 = 0.14, F[1, 98] = 15.88, p < 0.001$). Assessment of the unstandardized coefficients suggested that timing for TOP decreases by 3 centiseconds for each kPa increase in MIPp ($t = 2.00, p < 0.05$) and TOP duration decreases by approximately $1/10$th of a second as MIPp increases by 1 kPa ($t = -3.99, p < 0.001$). No statistically significant analyses results ($p > 0.05$) were revealed with regard to MIPp predicting TOP durations for any of the liquid or the puree consistencies.

Correlation coefficients for both MIP measures and TOP duration measures for the standard consistencies are presented in Table 5. The bivariate regression analyses assessing whether the MIP measures predicted TOP durations are presented in Tables 6 and 7. Although not included in Tables 6 and 7, it should be noted that all residuals for each regression analysis approximated 0 ($0^7$), which provided support for the assumption of heteroscedasticity for this data.

Table 5

Pearson Correlation (one-tailed) analysis of anterior tongue and posterior tongue maximum isometric pressure measures (MIPa and MIPp) by total oral phase (TOP) durations in seconds, across six standard consistency conditions for total sample ($n = 100$)

<table>
<thead>
<tr>
<th>Consistency conditions</th>
<th>MIPa</th>
<th>MIPp</th>
</tr>
</thead>
</table>
| TOP duration (thin)    | Pearson r  
                         | $-0.25^{**}$ | $-0.16^*$ |
|                        | $p$-value  
                         | 0.006 | 0.06 |
| TOP duration (nectar)  | Pearson r  
                         | $-0.19^*$ | $-0.13^*$ |
|                        | $p$-value  
                         | 0.03 | 0.10 |
| TOP duration (honey)   | Pearson r  
                         | $-0.18^*$ | $-0.16^*$ |
|                        | $p$-value  
                         | 0.04 | 0.06 |
| TOP duration (puree)   | Pearson r  
                         | $-0.12^*$ | $-0.13^*$ |
|                        | $p$-value  
                         | 0.11 | 0.09 |
| TOP duration (mech soft) | Pearson r  
                         | $-0.25^{**}$ | $-0.20^*$ |
|                        | $p$-value  
                         | 0.007 | 0.02 |
| TOP duration (regular) | Pearson r  
                         | $-0.30^{**}$ | $-0.37^{**}$ |
|                        | $p$-value  
                         | 0.001 | 0.000 |

Note. * denotes statistical significance at $p < 0.05$  
** denotes statistical significance at $p < 0.01$
Table 6

Linear Regression: MIPa as predictor variable and TOP duration as predicted variable

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Beta</th>
<th>$r^2$</th>
<th>df</th>
<th>F</th>
<th>B</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>-0.25</td>
<td>0.06</td>
<td>1.98</td>
<td>6.67*</td>
<td>-0.01</td>
<td>-2.58</td>
<td>0.01*</td>
</tr>
<tr>
<td>Nectar</td>
<td>-0.19</td>
<td>0.04</td>
<td>1.98</td>
<td>3.76</td>
<td>-0.01</td>
<td>-1.94</td>
<td>0.06</td>
</tr>
<tr>
<td>Honey</td>
<td>-0.18</td>
<td>0.03</td>
<td>1.98</td>
<td>3.31</td>
<td>-0.01</td>
<td>-1.82</td>
<td>0.07</td>
</tr>
<tr>
<td>Puree</td>
<td>-0.12</td>
<td>0.02</td>
<td>1.98</td>
<td>1.53</td>
<td>-0.01</td>
<td>-1.24</td>
<td>0.22</td>
</tr>
<tr>
<td>Mech Soft</td>
<td>-0.25</td>
<td>0.06</td>
<td>1.98</td>
<td>6.28*</td>
<td>-0.03</td>
<td>-2.51</td>
<td>0.01*</td>
</tr>
<tr>
<td>Regular</td>
<td>-0.30</td>
<td>0.09</td>
<td>1.98</td>
<td>9.91**</td>
<td>-0.07</td>
<td>-3.15</td>
<td>0.002**</td>
</tr>
</tbody>
</table>

Note. * denotes statistical significance at $p < 0.05$
** denotes statistical significance at $p < 0.01$

Table 7

Linear Regression: MIPp as predictor variable and TOP duration as predicted variable

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Beta</th>
<th>$r^2$</th>
<th>df</th>
<th>F</th>
<th>B</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>-0.16</td>
<td>0.03</td>
<td>1.98</td>
<td>2.56</td>
<td>-0.01</td>
<td>-1.60</td>
<td>0.11</td>
</tr>
<tr>
<td>Nectar</td>
<td>-0.13</td>
<td>0.02</td>
<td>1.98</td>
<td>1.75</td>
<td>-0.01</td>
<td>-1.32</td>
<td>0.19</td>
</tr>
<tr>
<td>Honey</td>
<td>-0.16</td>
<td>0.02</td>
<td>1.98</td>
<td>2.40</td>
<td>-0.01</td>
<td>-1.55</td>
<td>0.13</td>
</tr>
<tr>
<td>Puree</td>
<td>-0.13</td>
<td>0.18</td>
<td>1.98</td>
<td>1.77</td>
<td>-0.01</td>
<td>-1.33</td>
<td>0.19</td>
</tr>
<tr>
<td>Mech Soft</td>
<td>-0.20</td>
<td>0.04</td>
<td>1.98</td>
<td>4.00*</td>
<td>-0.03</td>
<td>-2.00</td>
<td>0.048*</td>
</tr>
<tr>
<td>Regular</td>
<td>-0.37</td>
<td>0.14</td>
<td>1.98</td>
<td>15.90**</td>
<td>-0.11</td>
<td>-3.99</td>
<td>0.000**</td>
</tr>
</tbody>
</table>

Note. * denotes statistical significance at $p < 0.05$
** denotes statistical significance at $p < 0.01$

Comparison of MIPa and MIPp across Sex

This question was addressed using an independent samples t-test (Table 8) to determine if statistically significant ($p < 0.05$) differences existed between anterior and posterior lingual pressures across sex. Levene’s test for equality of variances was significant at 0.027 for MIPa, therefore, the equal variances not assumed tests were utilized for analysis. Results revealed that the mean for the male MIPa sample was significantly greater (M = 59.07; SD = 15.88) than the mean female sample for MIPa (M = 53.14, SD = 12.36), $t(92.43) = -2.08$, $p = 0.04$.

On the contrary, Levene’s test was not significant for the MIPp independent samples t-test ($p = 0.17$), therefore, the equal variances assumed tests were conducted (Table 8). This analysis demonstrated that the male MIPp mean (M = 54.49, SD = 11.90) also was significantly greater than the female MIPp mean (M = 49.02, SD = 10.00), $t(98) = -2.49$, $p = 0.015$. 

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Table 8

Independent Samples t-test comparing mean MIPa and mean MIPp measures by sex

<table>
<thead>
<tr>
<th></th>
<th>Sex</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>Levene's Test</th>
<th>t-test for equality of means</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>F</td>
<td>p</td>
</tr>
<tr>
<td>MIPa</td>
<td>Female</td>
<td>50</td>
<td>53.14</td>
<td>12.36</td>
<td>5.06*</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50</td>
<td>59.07</td>
<td>15.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIPp</td>
<td>Female</td>
<td>50</td>
<td>49.02</td>
<td>10.00</td>
<td>1.93</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>50</td>
<td>54.49</td>
<td>11.90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Relation between MIP and Normal Aging in Adults

To explore the relation among anterior and posterior maximum isometric lingual pressure and normal adult aging, correlation and regression analyses were completed. As with the majority of previous analyses, all necessary assumptions for these statistical tests were met.

Correlation analysis revealed a medium negative correlation existed between age, the predictor variable, and MIPa, the outcome variable, $r(98) = -0.31$, $p < 0.01$. These results demonstrated that MIPa significantly decreased as adult age increased. Only a small effect was observed when correlating MIPp with age, $r(98) = -0.12$, however, this correlation was not found to be significantly significant, $p > 0.05$. As in the MIPa analysis, the direction of this relationship indicated a decrease in MIPp as adult age increased.

To examine the degree to which age predicts MIPa and MIPp, bivariate linear regression analyses were completed. The first regression, which investigated the relation between age and MIPa, demonstrated statistically significant results ($r^2 = 0.10, F [1, 98] = 10.65, p < 0.01$) indicating that age accounted for 10% of the variance in adult MIPa (Figure 6). The unstandardized regression coefficient (B) for age was -0.25 ($t = -3.26, p < 0.01$) suggesting MIPa decreases by 0.25 kPa with each year throughout the adult lifespan; lower bound = -0.41 kPa and upper bound = 0.08 kPa at the 95% confidence interval.

A significant regression analysis did not result with age as the predictor variable and MIPp as the outcome variable ($r^2 = 0.01, F [1, 98] = 1.42, p = 0.237$) (Figure 7). Correlation and
regression analyses data examining the relation among age and MIP measures are presented in Table 9.

Figure 6. Fitted regression line using age to predict mean MIPa measures.
Figure 7. Fitted regression line using age to predict mean MIPp measures.

Table 9

Linear Regression using age to predict mean MIPa and mean MIPp measures in kilopascals (n = 100)

<table>
<thead>
<tr>
<th>MIP</th>
<th>Beta</th>
<th>p</th>
<th>r²</th>
<th>F</th>
<th>p</th>
<th>B</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIPa</td>
<td>-0.31</td>
<td>0.001</td>
<td>0.10</td>
<td>10.65</td>
<td>0.002</td>
<td>-0.25</td>
<td>-3.26</td>
<td>0.002</td>
</tr>
<tr>
<td>MIPp</td>
<td>-0.12</td>
<td>0.12</td>
<td>0.01</td>
<td>1.42</td>
<td>0.24</td>
<td>-0.08</td>
<td>-1.19</td>
<td>0.24</td>
</tr>
</tbody>
</table>

Note. * denotes statistical significance at p < 0.001
Comparison of TOP Duration across Sex

To examine if differences in TOP durations were statistically significant as a function of sex, a multivariate general linear model was performed. Levene’s test for equality of variances was not significant (p > 0.05) for each of the consistencies; therefore, the equal variances assumed tests were employed. As seen in Table 10, male TOP durations did not significantly differ from female TOP durations across the six standard consistencies measured in this study.

Table 10

<table>
<thead>
<tr>
<th>Consistency</th>
<th>df</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>1, 98</td>
<td>2.04</td>
<td>0.16</td>
</tr>
<tr>
<td>Nectar</td>
<td>1, 98</td>
<td>0.64</td>
<td>0.42</td>
</tr>
<tr>
<td>Honey</td>
<td>1, 98</td>
<td>0.09</td>
<td>0.76</td>
</tr>
<tr>
<td>Puree</td>
<td>1, 98</td>
<td>0.04</td>
<td>0.85</td>
</tr>
<tr>
<td>Mech soft</td>
<td>1, 98</td>
<td>0.17</td>
<td>0.68</td>
</tr>
<tr>
<td>Regular</td>
<td>1, 98</td>
<td>2.52</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Note. * denotes statistical significance at p < 0.05 at the 95% confidence interval

Relation between TOP Duration and Normal Aging in Adults

To explore the relation between TOP duration and normal adult aging, Pearson correlation and regression analyses were computed. The data met the necessary assumptions required by these statistical tests; therefore, the results from these computations are considered valid. Correlation and linear regression data for this question are presented in Table 10.

Correlation analysis revealed strong correlations between age and TOP durations for all three liquid consistencies (i.e., thin, nectar, honey). The strongest correlation was evident with age and nectar-thick liquids, $r_{(98)} = 0.47, p < 0.001$. The next strongest correlation was observed with age and thin liquids, $r_{(98)} = 0.40, p < 0.001$, followed by age and honey-thick liquids, $r_{(98)} = 0.39, p < 0.001$. This correlation analysis demonstrated that TOP durations of standard liquid consistencies significantly increase as age increases. With regard to food consistencies, a medium correlation was found between age and mechanical soft TOP duration, $r_{(98)} = 0.32, p <$
0.01. However, only small correlations resulted when considering age and regular solids, \( r (98) = 0.21, p < 0.05 \), and pureed food, \( r (98) = 0.19, p < 0.05 \).

In order to examine the extent to which age predicts TOP durations with liquid consistencies, bivariate linear regression analyses were conducted. The first regression which investigated the relation between the predictor variable, age, and the predicted variable, TOP duration for thin liquids, demonstrated statistically significant results (\( r^2 = 0.16, F [1, 98] = 19.04, p < 0.001 \)) (Figure 8). These data indicated that age accounted for 16% of the variance in the adult TOP duration for thin liquids. The unstandardized regression coefficient, \( B \), for age was 0.10 (\( t = 4.36, p < 0.001 \)) stating that TOP duration for thin liquids increases by 1/100th of a second with each additional year during the adult lifespan; lower bound = 0.01 and upper bound = 0.02 seconds at the 95% confidence interval. The next regression demonstrated that age accounted for 22% of the variance for TOP duration of nectar-thick liquids (\( r^2 = 0.22, F [1, 98] = 27.13, p < 0.001 \)) (Figure 9). Furthermore, the beta coefficient, 0.02 (\( t = 5.21, p < 0.001 \)), implied that TOP duration for nectar-thick fluid increases by approximately 2 centiseconds each year during the normal adult lifespan. The age and honey-thick liquid regression again yielded significance (\( r^2 = 0.15, F [1, 98] = 17.77, p < 0.001 \)) suggesting that TOP for honey-thick liquids increases by 1 centisecond with each additional year of the healthy adult lifespan (\( t = 4.22, p < 0.001 \)) (Figure 10).

Bivariate linear regressions also were computed to examine the relationship between age and TOP duration for food consistencies (i.e., puree, mechanical soft, and regular). The regression model, which investigated the extent to which age predicts TOP duration for puree, approached statistically significant results (\( r^2 = 0.04, F [1, 98] = 3.83, p = 0.053 \)) and implied that age accounted for 4% of the variance in normal adult TOP duration of puree food (Figure 11). Further analysis of this model indicated that TOP duration for puree increases by one centisecond during each year throughout the normal adult lifespan, \( b = 0.01, t = 1.96, p = 0.05 \). A significant linear regression model was present with age predicting TOP duration of mechanical soft solids, (\( r^2 = 0.10, F [1, 98] = 11.20, p < 0.01 \)) demonstrating that age comprised 10% of the variability in TOP duration for this consistency (Figure 12). The unstandardized coefficients revealed that TOP duration for mechanical soft foods increases by 3 centiseconds with each year of adulthood (\( t = 3.35, p < 0.01 \)). Finally, it was demonstrated that age accounted for 5% of the variance in TOP duration of regular solids (\( r^2 = 0.05, F [1, 98] = 4.63, p < 0.05 \)).
With each year of life, healthy adults’ TOP duration for regular solids increases by 4 centiseconds (b = 0.04, t = 2.15, p < 0.05).

Table 11

Linear Regression using age to predict TOP duration in seconds across six consistency conditions (n = 100)

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Beta</th>
<th>r²</th>
<th>F</th>
<th>B</th>
<th>t</th>
<th>constant</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin</td>
<td>0.40**</td>
<td>0.16</td>
<td>19.04**</td>
<td>0.01**</td>
<td>4.36**</td>
<td>0.74**</td>
<td>6.76**</td>
</tr>
<tr>
<td>Nectar</td>
<td>0.47**</td>
<td>0.22</td>
<td>27.13**</td>
<td>0.02**</td>
<td>5.21**</td>
<td>1.03**</td>
<td>5.25**</td>
</tr>
<tr>
<td>Honey</td>
<td>0.39**</td>
<td>0.15</td>
<td>17.77**</td>
<td>0.02**</td>
<td>4.22**</td>
<td>1.62**</td>
<td>9.92**</td>
</tr>
<tr>
<td>Puree</td>
<td>0.19*</td>
<td>0.04</td>
<td>3.83</td>
<td>0.01</td>
<td>1.96</td>
<td>1.95**</td>
<td>8.41**</td>
</tr>
<tr>
<td>Mech Soft</td>
<td>0.32**</td>
<td>0.10</td>
<td>11.2**</td>
<td>0.03**</td>
<td>3.35**</td>
<td>4.13**</td>
<td>9.59**</td>
</tr>
<tr>
<td>Regular</td>
<td>0.21*</td>
<td>0.21</td>
<td>4.63*</td>
<td>0.04*</td>
<td>2.15*</td>
<td>8.94**</td>
<td>10.63**</td>
</tr>
</tbody>
</table>

Note. * indicates significance at p < 0.05
** indicates significance at p < 0.01

Figure 8. Fitted regression line using age to predict mean TOP duration in seconds for regular (thin) liquid.
Figure 9. Fitted regression line using age to predict mean TOP duration in seconds for nectar-thick liquid.

Figure 10. Fitted regression line using age to predict mean TOP duration in seconds for honey-thick liquid.
Figure 11. Fitted regression line using age to predict mean TOP duration in seconds for puree consistency.

Figure 12. Fitted regression line using age to predict mean TOP duration in seconds for mechanical soft consistency.
Figure 13. Fitted regression line using age to predict mean TOP duration in seconds for regular consistency.
CHAPTER FOUR
DISCUSSION

The primary purpose of this investigation was to examine the relation between tongue strength, as measured by anterior and posterior maximum isometric lingual pressure (i.e., MIPa and MIPp respectively), and timing of the total oral phase duration (TOP) (i.e., oral preparation phase time + oral transport phase time) across six standard consistencies tested in swallowing evaluations (i.e., thin liquid, nectar-thick liquid, honey-thick liquid, puree, mechanical soft, and regular solids). Secondary questions were to explore the effects of age and sex across these variables. This study specifically examined these measures in a sample of healthy adults ($n = 100$). Preliminary analyses of dependent measures revealed strong internal consistency for MIPa, MIPp, and TOP duration. The internal consistency findings for MIP were consistent with previous findings (Gingrich et al., 2012; Youmans et al., 2009). The range of Cronbach’s alpha scores obtained (0.78 to 0.97) for each variable confirmed that the measures utilized for this research were stable.

Relationships between Measures of MIP and TOP Duration

As delayed oral phase timing has been highly correlated with dysphagia (Mann et al., 1999) and researchers have implied that increased oral transit time may be associated with lingual weakness (Troche et al., 2008), the present study investigated the impact of tongue strength on TOP duration in the normal adult swallowing system.

MIPa and TOP Duration

Correlation analysis and a bivariate regression explored the relation between MIPa and TOP duration. With the exception of puree foods (e.g., pudding), the findings from this investigation suggest that TOP duration significantly increases as MIPa decreases in healthy adults. Although MIPa is significantly correlated to all liquid consistencies and mechanical soft TOP intervals, the strongest relation indicated that greater anterior lingual strength is most important for regular consistency solids (e.g., graham crackers), which break into pieces and require more oral preparation to obtain a cohesive bolus. Additionally, more lingual force may be necessary to transport regular consistency boluses to the posterior portion of the oral cavity prior to the onset of the pharyngeal phase of swallow; this notion is supported by previous findings of greater
pressures generated as viscosity of a bolus is increased (Gingrich et al., 2012; Youmans & Stierwalt, 2006; Youmans et al., 2009). Although not as strong, MIPa also was found to significantly predict TOP duration for mechanical soft solids. Again, the finding is intuitive given the greater need for management (i.e. mastication and collection) of semi-solid consistencies. Predictive relationships were not apparent in the cases of thickened liquids or puree food.

Interestingly, a significant predictive relation was discovered with MIPa and thin liquids but not for thickened liquids. This may be due to the nature of a thin viscosity of fluid requiring more lingual management to maintain this consistency in the oral cavity and avoid premature spillage into the pharynx, which could potentially lead to aspiration. Thickened liquids may not involve extensive lingual force as their flow rate is significantly slower during the swallowing process. Therefore, tongue strength does not play as strong of a role with regard to oral containment of thickened liquids.

**MIPp and TOP Duration**

Consistent with the correlations between MIPa and TOP duration, MIPp most strongly correlated with TOP duration of regular consistency solids. MIPp also significantly correlated with TOP duration of mechanical soft solids. These findings suggest that adult TOP duration for chewable foods decreases as a function of MIPp gain. Because the entire length of the tongue body is involved in oral preparation and propulsion, it seems natural that posterior strength of the tongue, along with the same requirement from the anterior tongue, would be an instrumental factor for TOP duration in the consistencies that require the most lingual involvement, namely mechanical soft and regular solid foods. Additionally, it is intuitive that greater muscular effort must be recruited to contribute to the transformation of solid consistencies into cohesive boluses prior to swallow. Correlations that did not reach statistical significance between MIPp and TOP duration for liquid consistencies and puree food imply that MIPp does not play an instrumental role in TOP intervals for those consistencies in normal functioning adults. This finding was expected considering that less posterior lingual strength is needed for boluses that do not require extensive oral preparation (i.e., liquids and puree foods).

With regard to regression analysis of MIPp and TOP duration, MIPp was the strongest predictor for TOP duration of the regular consistency (i.e. graham cracker) used in this investigation. An additional significant predictive relationship was discovered with MIPp and
TOP duration for mechanical soft consistency. These findings suggest that posterior lingual strength appears to be more critical with regard to the efficiency of oral preparation and oral transport of chewable solids.

**Comparison of MIPa and MIPp across Sex**

**MIPa**

With regard to differences in MIP as a function of sex in healthy adults, this study replicated findings from previous investigations (Gingrich et al., 2012; Stierwalt & Youmans, 2007; Youmans et al., 2006; Clark et al., 2003) in that males generated significantly greater MIPa than females. Tongue bulb location for this investigation was consistent with all previous studies that measured MIPa in adults. As these results lend additional support that males exhibit stronger anterior lingual strength, that has not been a universal finding (Youmans et al., 2009), perhaps due to sampling issues. Regardless, the findings from the present investigation are consistent with the majority of outcomes that favor the notion of a gender advantage of MIPa for males. More specifically, because men have greater lingual mass (Liegeois, Albert, & Limme, 2010) they are able to recruit more fibers in the intrinsic tongue muscles necessary to forcefully elevate the tongue. Moreover, the extrinsic tongue muscle, genioglossus, as well as the muscles comprising the floor of the mouth, are instrumental in generating MIPa by acting as a stable platform. It is possible, for the same anatomical reason that these muscles may be stronger in males as well.

**MIPp**

MIPp also was found to be significantly greater in healthy adult males compared to healthy adult females. This discovery is inconsistent with a prior study (Gingrich et al., 2012) in which no significant differences in MIPp between sexes were discovered. As males generally present with greater lingual mass, they may be able to generate greater force with the posterior portion of the tongue during maximum isometric tasks. An additional explanation may be that the male extrinsic lingual muscles involved in elevating the posterior tongue (i.e., styloglossus and palatoglossus) are able to recruit more Type I motor units than the female extrinsic lingual muscles and subsequently generate greater posterior lingual pressure during isometric tasks.
Relation between MIP and Normal Aging in Adults

MIPa and Age

Correlation analysis between MIPa and age demonstrated a significant relationship consistent with previous research (Gingrich, 2011; Youmans et al., 2009; Stierwalt & Youmans, 2007; Clark et al., 2003) that indeed MIPa decreases as a function of aging in healthy adults. The age range in this investigation (20 to 86 years) approximated the adult age ranges in previous studies that examined this relation. As healthy adults age, sarcopenia is the factor most likely contributing to the reduction in lingual muscle fibers which are essential for generating MIPa. Regression analysis predicted that healthy adults lose approximately ¼ kPa of MIPa strength with each year during the adult lifespan. The medium correlation found between age and MIPa supports earlier group studies (Youmans et al., 2009; Clark et al., 2003), which suggested a large range of MIPa values (20 kPa to 85 kPa) is present in normal human performance and older adults (> 60 years of age) tend to exhibit lower anterior tongue strength compared to younger adults (< 40 years of age). Consistent with the effects of sarcopenia, which affects other muscle groups in the body, a selective reduction in type II fibers also may develop in the anterior portion of the tongue as adults advance in age.

MIPp and Age

Inconsistent with previous work (Gingrich, 2011), MIPp did not have a significant relationship with age as observed in the correlation analysis between these variables. With regard to age predicting MIPp in normal adults, there were no significant findings to support this notion. Posterior lingual strength appears to remain stable throughout the healthy adult lifespan. Contrary to the anterior tongue muscles, sarcopenia does not seem to affect MIPp performance. Perhaps the predominance of type I muscle fibers that support MIPp, (primarily palatoglossus and styloglossus muscles, which facilitate posterior tongue elevation, and genioglossus which comprises the bulk of the posterior tongue base), do not markedly deteriorate with aging. The posterior segment of the tongue contributes to bolus management; it may not be as involved in the breakdown of chewable consistencies compared to the anterior segment. The role of the posterior tongue in assisting with respiration may also attribute to the stability of MIPp performance with advanced age. As previously described, significant atrophy of muscle fibers in the posterior tongue could potentially be life threatening if a patent airway were not maintained.
Humans indeed may be designed to sustain posterior lingual strength throughout the adult lifespan as a protective mechanism.

**TOP Duration for Standard Consistencies across Sex**

Previous studies have not investigated the effects of sex on TOP duration. One may assume that bolus preparation and transport would take longer in larger oral cavities (i.e., males). With regard to TOP intervals in healthy adults, no observed sex effects were evident in this study. It appears that regardless of structural differences in the oral cavities of males versus females (e.g., size of the tongue, dimensions of the oral cavity), TOP durations across standard consistencies are essentially equivalent. This finding was surprising considering previous research which reported that healthy adult males present with larger oral/palatal dimensions compared to healthy adult females (Gingrich, 2011). The larger tongue mass and greater MIPa present in males may be factors which compensate for their ability to approximate female TOP durations across consistencies. Another possible explanation in insignificant differences in TOP duration across sexes could be a feature of scale and proportion (i.e., the smaller dimensions of the oral cavity and oral structures in females are proportional to those of males). Subsequently, the proportional relationship between size of the oral structures and dimensions of the oral cavity across sexes yields similar TOP intervals.

**Relation between Age and TOP Duration in Healthy Adults**

Significant correlation relationships were found to exist between age and TOP durations of the six standard consistencies measured from the sample participants; specifically, as age increased TOP duration for each consistency also increased. Interestingly, when classifying the consistencies according to foods or liquids, large correlations were evident when relating age to TOP durations for the three liquid consistencies; however, a medium correlation was found between age and mechanical soft solids, and only small correlations were present when comparing age to puree and regular solids. A larger range of variability of TOP durations for foods between subjects may have accounted for the smaller correlations in comparison to liquids, in which TOP durations varied less. As liquids do not require extensive oral manipulation, there is less room for variability during the oral preparation phase. Liquids are already in a bolus form upon entry of the oral cavity and merely have to be transported directly into the pharynx to be swallowed. However, semi-solids and solid foods require considerably more manipulation to form a cohesive bolus. For various reasons (e.g., childhood habits which extended into
adulthood, cultural differences, and personal preferences), some individuals may chew foods significantly longer than other individuals prior to transporting the bolus posteriorly. Such variability in chewing patterns attributes to the large range of TOP duration for mechanical soft and regular solids in healthy adults. Considering the larger degree of oral involvement with foods compared to liquids, it is not surprising that more variability in TOP duration is evident in foods. Nonetheless, the findings of this study concur with previous studies, which reported that oral phase timing for liquid and solid boluses increased as a function of age in healthy adults (Gomes et al., 2008; Mendell et al., 2007).

Aging was found to significantly predict TOP durations across all consistencies, except for with puree in which the regression model approached significance ($p = 0.053$). These findings support previous research regarding delays in the initiation of the pharyngeal phase of swallowing in healthy, older adults compared to younger cohorts (Logemann et al., 2000; Shaker et al., 1994). Sarcopenia likely plays a role in the gradual increase of TOP duration throughout the adult lifespan. However, given that age only accounted for 22% of the variance in TOP duration in this investigation, other factors must be contributing to the prolonged TOP intervals observed with normal aging. These factors might include: one’s preferential eating habits, dental status, activation of other muscles involved in the oral phase (e.g., orbicularis oris, buccinators, masseter, medial and lateral pterygoid), salivary function, time of day, sensory decline with advanced age, and level of alertness.

**Limitations and Future Directions**

Certainly a larger sample size in this investigation would have strengthened the statistical power. Although a power analysis revealed that a sample size of 84 would correspond to 80% power at the 95% confidence interval and this study exceeded that ($n = 100$), the present sample size was adequate to represent the healthy adult population as a whole (i.e., without specifying sex differences). However, as participants were grouped by sex (50 males and 50 females) to answer two of the research questions, a larger sample for each sex would be necessary to increase confidence that this study’s findings generalize to the healthy adult male and healthy adult female population.

The food and liquid items selected to represent standard consistencies tested in swallowing evaluations stem from previous survey research of medical SLPs involved in the diagnosis of dysphagia. The utilization of multiple foods and liquids, which also have been reported to
represent standard consistencies, would have strengthened the external validity of this investigation. By only having one item to represent each consistency, SLPs are limited in implementing the results from this study into clinical practice as they will need to offer the same items in their swallowing evaluations as were presented in this research. Moreover, participants only received one bolus size per consistency, which also weakens external validity. Again, SLPs can only rely on the bolus volumes administered in this study if they intend to compare their findings to the preliminary normative TOP intervals from this investigation.

Further limitations from this study pertain to specific aspects of the methods and setting of data collection. Although the sEMG recording provided an objective method to record TOP duration, some degree of subjectivity was involved with regard to capturing the onset of TOP for each swallow trial. As the researcher had to visually observe when labial closure was achieved with each trial presentation and then simultaneously press a computer key to insert a marker on the recorded signal to indicate the initiation of TOP, some human error in reaction time may have occurred. This reaction time issue may be the most problematic of limitations in this study as there were four researchers who recorded the data. Similarly, although the primary investigator trained all examiners, it would have strengthened the reliability of the IOPI measurements if each researcher were observed by another to ensure placement of the bulbs and recording of the data. Finally, the laboratory setting of this investigation may have interfered with the internal validity of the TOP trials. As all participants were wearing electrodes and asked to remain still during each swallow trial to reduce sEMG artifact, the “naturalness” factor of drinking and eating may have been disrupted. Perhaps recording these data in a more natural eating environment would have been optimal in capturing true swallowing performance.

**Clinical Implications**

The findings from this investigation have beneficial clinical implications with regard to the evaluation and treatment of swallowing in adults. This investigation was the first attempt at establishing a normative database of TOP durations for each of the standard consistencies across the adult lifespan. Prior to this research, clinicians performing overt swallow evaluations (i.e., the clinical swallow evaluation) did not have a reference tool for TOP durations. The lack of normative TOP data has posed challenges in diagnosing prolonged versus normal oral preparation and oral transit time (Headley et al., 2012). The data provided in this study will assist clinicians who do not have access to instrumental swallowing diagnostic methods (e.g.,
MBSS and FEES) and provide a useful guide in determining when the pharyngeal phase of swallow should be initiated across the adult lifespan when performing overt swallowing evaluations (e.g., the clinical swallow evaluation). In a non-instrumental dysphagia diagnostic (i.e., the clinical swallow evaluation), clinicians typically palpate the thyroid notch to feel the onset of laryngeal elevation, which signifies that the pharyngeal phase of swallow has begun. With the contribution of the TOP duration data obtained in this study, clinicians can begin to time TOP duration by using a stopwatch for precision (or simply counting out loud to approximate the true interval). Timing for TOP should begin once food or liquid enters the oral cavity and labial closure has been achieved. Timing should cease once the clinician feels the height of laryngeal elevation. The clinician can then record the patient’s TOP interval for the particular consistency and compare it to the normative data obtained in the current and future investigations. If the client exceeds the maximum value for TOP duration for the given consistency, then the clinician can assume that the individual presents with an abnormally prolonged or delayed oral phase. This timing factor is critical in the evaluation of dysphagia as individuals who present with prolonged oral containment are at higher risk for weight loss, malnutrition, and aspiration (Troche et al., 2008; Mann et al., 1999).

As these findings demonstrated that age and MIP were significant predictors of TOP durations, the information gained from this study will allow clinicians to potentially formulate stronger prognoses for lingual strength recovery in the adult population. Additionally, age was found to significantly predict MIPa. Because a significant decline in MIPa appears to occur as a function of aging, it may benefit adults to begin to implement regular anterior tongue resistance exercise to possibly slow down the effects of sarcopenia and subsequently preserve a more efficient swallow for a longer period of time. Most healthy adults would not initiate a tongue strengthening exercise regimen unless warranted due to the presence of an oral phase dysphagia. However, an emergence of literature is suggesting that exercise, particularly strength and endurance training, can combat the deleterious effects of muscular atrophy associated with the onset of neurological disease. Perhaps, building up the lingual musculature and securing a larger volume of muscular reserve in the tongue could prove to benefit adults prior to the unlikely event of a stroke or onset of a progressive degenerative neurological disease (e.g., Parkinson’s disease, Multiple Sclerosis, and Progressive Supranuclear Palsy) which inevitably would affect the oral phase of swallow.
Although several significant correlation relationships and regression models were evident from this investigation, the magnitude of these relationships was not very strong (i.e., the predictor variables did not account for greater than 25% of the variance of the predicted variables in any of the analyses). Clearly, other factors are contributing to the declines in MIP and prolonged TOP durations that occur with normal aging. Future study is warranted to investigate the nature of the relation between MIP and TOP duration in participants who present with oral phase dysphagia that is marked by lingual weakness. It seems intuitive that the strength of the relation between these two variables would be stronger in a disordered population (i.e., individuals with dysphagia) as compared to healthy adults, and future research is warranted to support or refute this notion. Finally, the logical step would be to initiate an intervention study to examine if MIP can significantly increase and TOP can significantly decrease as a result of a rigorous lingual strengthening protocol (e.g., a resistance training program involving the IOPI).
APPENDIX A

INFORMED CONSENT

INFORMED CONSENT FORM FOR PARTICIPANTS

TITLE: Physiologic and Temporal Correlates of the Adult Normal Swallow

Principal Investigator: Derek Headley, M.S., CCC-SLP, Florida State University

I, ___________________________ freely and voluntarily consent to be a participant in the research project entitled, "Physiologic and Temporal Correlates of the Adult Normal Swallow." The total number of participants enrolling in this study is 180.

Dr. Julie Stierwalt, an Associate Professor of Communication Science and Disorders at Florida State University, and Derek Headley, a Speech-Language Pathologist and doctoral student at Florida State University are conducting this research. I understand that the purpose of this research project is to gain clinically relevant physiologic and temporal information of normal swallowing in adults (age 18+).

I understand that if I agree to participate in the project I will be asked to partake in data collection sessions that will last approximately one-half hour. Data collection will occur in the 5th floor Neuroscience lab in the Warren Building at Florida State University. During the sessions the following standard clinical procedures may be completed:

- An oral mechanism examination. This examination will include a brief look at the structures of swallowing (face, lips, teeth, tongue, hard palate, and soft palate) at rest and during routine movements.
- Measures of tongue function (strength and swallowing pressures measured by pressing my tongue against an air filled bulb connected to the Iowa Oral Performance Instrument).
- Tongue strengthening protocol (pushing against the tongue bulb repeatedly in the form of an exercise).
- Swallowing 5 presentations of each of the following: 20 mL of thin water; 20 mL of nectar thick juice; 20 mL of honey thick juice; tsp of pudding; tsp of diced pears; half of a graham cracker. Surface electrodes (sEMG) will be placed on the neck and face to measure muscle activity during the eating and drinking process.

I understand that I have been asked to be in the study because I do not have any history of swallowing impairment. I will be excluded from the study if I am unable to complete the tasks after they have been explained to me. I know that my participation is totally voluntary and that I may stop at any time without penalty, or loss of benefits. I understand that I will receive no financial compensation for participating in this research. However, the knowledge gained from this study will offer important information to researchers and clinicians for understanding clinical measures that indicate normal swallowing.

FSU Human Subjects Committee Approved on 1/10/2013. Void after 1/08/2014. HSC # 2012.9627
Information obtained during this study will be kept confidential to the extent allowed by law. The information may be published in professional journals or presented at professional meetings, but my name or any other identifiable information will not be used. The release of my medical records is granted to all study personnel, the sponsor, the FDA and the Institutional Review Board (IRB) as necessary. However, only the investigators and research assistants will have access to this data. All material gathered in this investigation will be destroyed by January 15, 2020 (after publication of the study results or within 7 years of the end of the study).

I understand that there is no real risk involved if I agree to participate in this study. It is possible that I may experience fatigue from pressing on the tongue bulb, but I understand that every effort will be made to ensure that I am comfortable during my participation.

I have been given the opportunity to ask any questions regarding the study and all questions have been answered to my satisfaction. I understand that I may contact Dr. Stierwalt at the School of Communication Science and Disorders, Florida State University (850 644-2238), Derek Headley or a representative from the Florida State University Human Subjects Committee (850 644-8836) for answers to questions about this research or my rights.

Florida State University will not provide compensation for injury, illness, or other loss resulting from participation in this study. In the event of physical injury resulting to you as a result of this investigation, medical care, including hospitalization, is available; however, Florida State University cannot assure that this medical care will be provided without charge.

The results of this investigation will be sent to me at my request. My signature below means that I have freely agreed to participate in this experimental study.

Participant Name ___________________________ Date ________

Investigator Name __________________________ Date ________

FSU Human Subjects Committee Approved on 1/10/2013. Void after 1/08/2014. HSC # 2012.9627
APPENDIX B

IRB APPROVAL LETTER

The Florida State University
Office of the Vice President For Research
Human Subjects Committee
Tallahassee, Florida 32306-2742
(850) 644-8673, FAX (850) 644-4392

RE-APPROVAL MEMORANDUM

Date: 1/18/2013

To: Derek Headley
From: Thomas L. Jacobson, Chair

Re: Re-approval of Use of Human subjects in Research
Physiologic and Temporal Correlates of the Adult Normal Swallow

Your request to continue the research project listed above involving human subjects has been approved by the Human Subjects Committee. If your project has not been completed by 1/8/2014, you are must request renewed approval by the Committee.

If you submitted a proposed consent form with your renewal request, the approved stamped consent form is attached to this re-approval notice. Only the stamped version of the consent form may be used in recruiting of research subjects. You are reminded that any change in protocol for this project must be reviewed and approved by the Committee prior to implementation of the proposed change in the protocol. A protocol change/amendment form is required to be submitted for approval by the Committee. In addition, federal regulations require that the Principal Investigator promptly report in writing, any unanticipated problems or adverse events involving risks to research subjects or others.

By copy of this memorandum, the Chair of your department and/or your major professor are reminded of their responsibility for being informed concerning research projects involving human subjects in their department. They are advised to review the protocols as often as necessary to insure that the project is being conducted in compliance with our institution and with DHHS regulations.

Cc: []
HSC No. 2012.9627
REFERENCES


Han, T., Paik, N.J., Park, J.W., & Kwon, B.S. The prediction of persistent dysphagia beyond six months after stroke. *Dysphagia, 23*, 59-64.


BIOGRAPHICAL SKETCH

Derek Headley received his Bachelor of Arts degree in Communication Science and Disorders from the University of Pittsburgh in 1998. He then attended West Virginia University (WVU), where he received his Master of Science degree in Speech-Language Pathology in 2001. Upon completing his MS, Derek worked as a Speech-Language Pathologist in various acute and sub-acute hospitals, skilled nursing facilities, and home health agencies in numerous cities which include Washington D.C., San Francisco, CA, and Fort Lauderdale, FL. He specialized in the evaluation and treatment of dysphagia and adult neurogenic communication disorders. After nearly a decade of clinical practice, Derek decided to pursue a research career by entering the PhD program in Communication Science and Disorders at Florida State University (FSU) in 2010. His major professor in the doctoral program was Dr. Julie Stierwalt, Ph.D., and their combined research focused on exploring methods to improve the clinical swallowing evaluation. In addition to his full time coursework, Derek worked part-time as a clinical education instructor at the FSU Speech and Hearing Clinic for the first two years of his doctoral program. During his second year at FSU, Derek received the Instructor of the Year award for the College of Communication from the FSU Lambda Pi Eta Chapter. He also served as the Assistant Editor for Contemporary Issues in Communication Science and Disorders (CICSD) for the entire three years of his doctoral studies. Derek’s areas of interest in the field of speech-language pathology include: normal and abnormal swallowing, aphasia, and apraxia of speech. After earning his PhD from FSU, he will be joining the Communication Science and Disorders faculty at University of Northern Colorado where he will be teaching coursework and conducting research in dysphagia and adult language disorders.