HYOID MOVEMENT AND SEMG ACTIVITY DURING NORMAL DISCRETE SWALLOWS, MENDELSOHN MANEUVER, EFFORTFUL SWALLOW AND EXPIRATORY PRESSURE THRESHOLD TASKS IN HEALTHY ADULTS

By

KAREN M. WHEELER

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2006
Copyright 2006

by

Karen M. Wheeler
This document is dedicated to my father, who I miss greatly and I trust is watching over me always.
ACKNOWLEDGMENTS

There are many people deserving of my deepest gratitude for their guidance, support, and friendship during the course of my life and during my doctoral work. These individuals have facilitated a balance in my life between family, friends, love, and intellect that is invaluable. First, I would like to thank my parents, for including in my upbringing emphasis on the value of education, for their encouragement through my prolonged educational process, for their love, and for their belief in me. I would like to thank Dustin Hegland for his support, understanding, enduring love and commitment to our relationship, and for ultimately making me a better person. Many thanks to my close friends, Michelle Goldszlager-Bernstein and Kristi Nesser, for their friendship and for keeping me sane during a tumultuous three years. I would like to thank my committee members for their mentorship throughout my doctoral program. Finally, I would like to thank Christine Sapienza, Ph.D., for recognizing potential in me as an undergraduate student. Dr. Sapienza’a guidance, support, encouragement, and friendship over the past six years have been priceless and I cannot adequately express my appreciation.
TABLE OF CONTENTS

ACKNOWLEDGMENTS ........................................................................................................ iv

LIST OF TABLES .............................................................................................................. vii

LIST OF FIGURES .......................................................................................................... viii

ABSTRACT ......................................................................................................................... ix

CHAPTER

1  INTRODUCTION AND REVIEW OF THE LITERATURE ..........................................1
   Anatomy and Physiology of Normal Swallowing ..........................................................1
   Evaluation of Swallowing .......................................................................................... 5
   Exercise and Rehabilitation ...................................................................................... 9
   Established Swallow Rehabilitation ....................................................................13
   Respiratory Based Swallow Therapy ..................................................................16
   Statement of the Problem ......................................................................................18
   Purpose ..................................................................................................................19
   Aims and Hypotheses ...........................................................................................19

2  METHODS ...................................................................................................................20
   Participants ..............................................................................................................20
   Description of the Expiratory Training Device .........................................................20
   Procedures ..............................................................................................................21
   Task Learning ...........................................................................................................22
   Surface EMG Procedure .......................................................................................23
   Videofluoroscopic Procedure ...............................................................................24
   Data Analysis ...........................................................................................................26
   sEMG Measures .....................................................................................................26
   Hyoid Trajectory Measures ...................................................................................27
   Participant Task Performance and Follow-up ......................................................29
   Statistical Analysis ...............................................................................................29

3  RESULTS ...................................................................................................................32
   Participant Task Performance and Follow-up ......................................................33
Trajectory Differences between Experimental Tasks ................................................. 33
sEMG and Hyoid Movement ...................................................................................... 34
Regression Analysis .................................................................................................... 39

4 DISCUSSION ............................................................................................................. 41

Components of Motion ............................................................................................... 42
Movement Pattern ....................................................................................................... 43
Motor Skill .................................................................................................................... 45
Motor Skill Acquisition ............................................................................................... 48
Task Specificity ............................................................................................................. 52
The Principle of Overload ............................................................................................ 63
Application to Swallowing Disorders ......................................................................... 65
Mendelsohn Maneuver ............................................................................................... 66
Effortful Swallow ........................................................................................................ 69
EMST ........................................................................................................................... 71
Summary and Conclusions ......................................................................................... 73

APPENDIX

A Health History Questionaire ..................................................................................... 75
B Memory and effort rating form .................................................................................. 76
LIST OF REFERENCES .................................................................................................. 78
BIOGRAPHICAL SKETCH ............................................................................................. 93
LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Participant information and task performance scores</td>
<td>31</td>
</tr>
<tr>
<td>2. Means (M) and standard deviations for each task</td>
<td>32</td>
</tr>
<tr>
<td>3. Results of post hoc analysis for trajectory and sEMG measures found to be significantly different between tasks</td>
<td>35</td>
</tr>
<tr>
<td>4. Bivariate and partial correlations for maximum sEMG measures (Max EMG), maximum displacement (D1), and maximum angle (A2)</td>
<td>38</td>
</tr>
<tr>
<td>5. Pearson correlations and paired samples t-tests for timing measures</td>
<td>39</td>
</tr>
<tr>
<td>6. Stepwise regression analysis with dependent variable task</td>
<td>40</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Pilot data: videofluoroscopic images of hyoid and palatal elevation during use of the EMST device</td>
<td>17</td>
</tr>
<tr>
<td>2.</td>
<td>EMST device used in the study.</td>
<td>21</td>
</tr>
<tr>
<td>3.</td>
<td>Waveforms obtained for sEMG biofeedback</td>
<td>23</td>
</tr>
<tr>
<td>4.</td>
<td>Electrode triad used for submental sEMG recording</td>
<td>25</td>
</tr>
<tr>
<td>5.</td>
<td>Concurrent videofluorographic and sEMG data recorded to the Kay Swallow Station</td>
<td>25</td>
</tr>
<tr>
<td>6.</td>
<td>Example of measurements the MATLAB routine makes during task analysis</td>
<td>28</td>
</tr>
<tr>
<td>7.</td>
<td>Post-hoc analysis for trajectory measures</td>
<td>36</td>
</tr>
<tr>
<td>8.</td>
<td>Post-hoc analysis of surface electromyographic measures</td>
<td>37</td>
</tr>
<tr>
<td>9.</td>
<td>Illustration of the relationships between task and individual predictor variables D1, A2, and Hmax EMG</td>
<td>40</td>
</tr>
<tr>
<td>10.</td>
<td>Schematic representing the paradigm for motor skill development for the Mendelsohn maneuver</td>
<td>52</td>
</tr>
<tr>
<td>11.</td>
<td>Schematic representing the temporal relationships between sEMG and hyoid movement for each of the experimental tasks</td>
<td>57</td>
</tr>
<tr>
<td>12.</td>
<td>Airway expansion and hyoid vertical excursion that occurs during the EMST task.</td>
<td>61</td>
</tr>
<tr>
<td>13.</td>
<td>Schematic representation of proposed pathways by which EMST would effect swallow</td>
<td>63</td>
</tr>
<tr>
<td>14.</td>
<td>Example of the correct execution of the Mendelsohn maneuver</td>
<td>69</td>
</tr>
<tr>
<td>15.</td>
<td>Schematic representing the paradigm for task-specific components of the effortful swallow</td>
<td>71</td>
</tr>
</tbody>
</table>
Dysphagia, or difficulty swallowing, can result from many different etiologies and significantly negatively affect an individual’s quality of life. Understanding of dysphagia has stemmed from study of healthy anatomy and physiologic processes required for normal swallowing. To date, swallow rehabilitation has included five swallow-specific (i.e., include a swallow) options which have been described both as compensatory techniques and as swallow exercises. Two of these, the Mendelsohn maneuver and effortful swallow, have been supported by evidence revolving around increased and/or prolonged activation in the submental musculature, which are primary mover muscles for the hyoid bone’s excursion during a swallow. As well, an expiratory muscle strength training (EMST) device has been shown to increase and prolong the activation of submental muscles when compared with activation during a normal swallow.

Subsequently, it was the goal of this investigation to examine the hyoid motion and
sEMG activity during each of these tasks in order to assess their potential and/or appropriateness as rehabilitative exercises for dysphagia.

Results revealed significant differences in the trajectory of hyoid motion as measured by overall displacement and angle of elevation of the hyoid bone. As well, timing and amplitude differences existed between tasks with regard to the activation of the submental musculature. These results suggest that the experimental tasks have differential effects regarding muscle activation, peripheral nerve firing, central nervous system drive, and cognitive requirements for task completion. Each experimental task is discussed specifically with regard to task skill, specificity to swallow, and overload on muscle activation. Further, conclusions are drawn regarding which dysphagic symptoms each are best suited to treat based on study results.
Dysphagia, or difficulty swallowing, can affect individuals of any age. Inability to swallow normally can disrupt a person’s capability to maintain sufficient nutritional status and may lead to infection associated with aspiration of foods and liquids ("Dysphagia", 2002, "Ninds swallowing disorders information page", 2006). As well, persons’ overall quality of life may decline if they are not able to participate in daily mealtimes, which are often socially oriented. In fact, quality of life measures are known to be negatively impacted by pathologies that result in dysphagia, including head and neck cancer, stroke, and neurodegenerative disease processes (Campbell et al., 2004; Chen et al., 2001; Gillespie, Brodsky, Day, Lee, & Martin-Harris, 2004; Jacquot, Poudroux, Piat, & Strubel, 2001; Logemann & Kahrilas, 1990; McHorney et al., 2000; McHorney et al., 2000; McHorney et al., 2002; Perry, Shaw, & Cotton, 2003; Sellars, Campbell, Stott, Stewart, & Wilson, 1999). Subsequently, successful rehabilitation of dysphagic symptoms is important with regard to both health status and overall quality of life.

**Anatomy and Physiology of Normal Swallowing**

Traditionally swallowing has been described as four separate phases: 1. The oral preparatory stage, consisting of mastication and bolus formation, 2. The oral stage, consisting of bolus transport from the posterior oral cavity into the pharynx, 3. The pharyngeal stage, consisting of epiglottic inversion, hyolaryngeal elevation and forward movement, vocal fold adduction, relaxation of the cricopharyngus (upper esophageal
(sphincter), and bolus flow in a caudal direction through the pharynx and into the proximal esophagus, and 4. The esophageal phase, consisting of bolus flow through the esophagus, propelled by peristaltic contractions, and lower esophageal sphincter relaxation allowing the material to flow into the stomach. The oral and pharyngeal stages are of particular interest because they are able to be volitionally controlled, and have a particularly important role with regard to protection of the airway (Dodds, Stewart, & Logemann, 1990; Langmore & Miller, 1994; Logemann et al., 1992).

Anatomical structures of the oral cavity and oropharynx, including the tongue, base of tongue, and hard and soft palate, are important with regard to their involvement with bolus transport and propulsion from the posterior oral cavity into the pharynx (Dodds et al., 1990; Dodds et al., 1989; Ekberg & Hillarp, 1986; Kahrilas, Lin, Logemann, Ergun, & Facchini, 1993; Logemann, 1988). Intrinsic lingual muscles (superior longitudinal muscle, transverse, and vertical muscles) along with extrinsic lingual muscles (mylohyoid, genioglossus, styloglossus, palatoglossus) manipulate the bolus and elevate the tongue, beginning anteriorly with the tongue tip and continuing in an anterior-posterior direction with the bolus being squeezed posteriorly via the action of lingual-palatal contact. Once in a more posterior position, bolus propulsion into the pharynx results from positive pressure created by lingual contact with the faucial pillars via palatoglossus and palatopharyngeus contraction, and soft palate contact with the posterior pharyngeal wall (Dodds et al., 1989; Ekberg & Hillarp, 1986; Gay, Rendell, & Spiro, 1994; Gay, Rendell, Spiro, Mosier, & Lurie, 1994; Kahrilas et al., 1993; Logemann, 1988; Miller, 1982).
The pharyngeal stage of swallow includes important events associated with airway protection and bolus flow into the esophagus, both of which are essential for normal swallowing (Bacon & Smith, 1994; Cook et al., 1989; Dodds et al., 1990; Ekberg, 1986 A, 1986 B; Logemann, 1988; Logemann et al., 1992; Sonies, Wang, & Sapper, 1996). Within the pharynx, anatomical structures active during swallowing include the base of the tongue, epiglottis, and the hyo-laryngeal complex, consisting of the hyoid bone and larynx. Once food or liquid has entered the oropharynx, it flows in either a unilateral or bilateral manner into each of the vallecular recesses, which direct the bolus around the laryngeal aditus. The bolus flows caudally through the hypopharynx and into the pyriform sinuses before passing through the upper esophageal sphincter (UES) and into the distal esophagus. During the pharyngeal phase of swallow, the epiglottis inverts, providing a line of defense against bolus entry into the laryngeal vestibule. Additional mechanisms of airway protection include the elevation of the hyolaryngeal complex, anterior tilting of the arytenoids, and vocal fold adduction (Cook et al., 1989; Dodds et al., 1990; Ekberg, 1986 A, 1986 B; Jacob, Kahrilas, Logemann, Shah, & Ha, 1989; Leonard, Kendall, McKenzie, Goncalves, & Walker, 2000; Shaker, Dodds, Dantas, Hogan, & Arndorfer, 1990). Contraction of the submental muscle group, consisting of the geniohyoid, mylohyoid, and anterior belly of the digastric, allows for hyoid elevation and anterior movement. The thyrohyoid muscles and thyrohyoid membrane connect the hyoid bone to the larynx, and as a result the entire hyolaryngeal complex elevates and is pulled forward during swallowing. Simultaneously, intrinsic laryngeal adductors, including the interarytenoids, lateral cricoarytenoids, and thyrovocalis of the thryoarytenoid muscles, contract resulting in vocal fold adduction (Dodds et al., 1990;
Ekberg, 1986 A, 1986 B; Ishida, Palmer, & Hiitemae, 2002; Jacob et al., 1989; Shaker et al., 1990). Infrahyoid muscles which connect the hyoid to the anterior portion of the UES permit the hyoid bone to act as a fulcrum, aiding in UES opening following cricopharyngeal relaxation, and allowing the bolus to flow into the esophagus (Cook et al., 1989; Dodds et al., 1990; Ekberg, 1986 A, 1986 B; Ishida et al., 2002; Jacob et al., 1989).

An additional mechanism of airway protection during the pharyngeal stage of swallowing includes a systematic coordination of the swallow and respiratory systems. Human anatomy is such that at the level of the upper airways, swallowing and respiration share anatomic space that must be allocated appropriately in order to protect the lower airway during a swallow (Dodds et al., 1990; Miller, 1982, 1993; Shaker et al., 1990). The coordination between respiration and swallowing requires precise timing for movements leading to laryngeal closure and protection of the lower airways, and in fact the act of swallowing has been shown to occur at consistent points in the respiratory cycle. For the majority of healthy individuals, a swallow is preceded by an inspiration and brief expiration. The expiration is interrupted by swallow-related apnea, during which time the airway is closed and the swallow is completed. In the late stages of pharyngeal swallow, occurring almost simultaneously with UES closure, there is typically expiration associated with lowering of the hyoid bone to the rest position, and then the resumption of normal breathing pattern (Jafari, Prince, Kim, & Paydarfar, 2003; Kendall, McKenzie, Leonard, Goncalves, & Walker, 2000; Kijima, Isono, & Nishino, 2000; Kuna & Vanoye, 1999; Martin-Harris, Brodsky, Price, Michel, & Walters, 2003; Martin, Logemann, Shaker, & Dodds, 1994; Medda et al., 2003; Morton, Minford, Ellis,
& Pinnington, 2002; Preiksaitis & Mills, 1996). It has been reported that this expiratory-apnea-expiratory pattern of breathing is present in approximately 80% of healthy individuals (Martin-Harris et al., 2003; Martin et al., 1994). Others have found that the pre-swallow respiratory phase is more variable (inspiratory or expiratory); however most (95%-100%) of these swallows end in expiration (Feroah et al., 2002; Klahn & Perlman, 1999; Martin-Harris et al., 2005; Martin-Harris et al., 2003; Martin et al., 1994; Perlman, He, Barkmeier, & Van Leer, 2005; Preiksaitis & Mills, 1996; Smith, Wolkove, Colacone, & Kreisman, 1989).

**Evaluation of Swallowing**

The neural and biomechanical properties of swallowing resulting from centrally-driven motor commands emerging primarily from the nucleus ambiguus within the brainstem medulla and modified by cortical and subcortical networks have been studied with regards to the magnitude of displacement of and durations of oral and pharyngeal structures during a swallow (Jean, 1972, 1984; Jean, Car, & Roman, 1975; Martino, Terrault, Ezerzer, Mikulis, & Diamant, 2001; Zald & Pardo, 1999). Specifically, the oropharyngeal stage of swallowing has been studied extensively because of its importance to airway protection, bolus transport to the esophagus, and ultimately the ability to maintain adequate overall nutritional and health status. Videofluoroscopic evaluation of swallowing has been the preferred method for measuring displacements and timings of oral and pharyngeal structures associated with swallowing, as it allows for structural visualization along with bolus visualization when barium contrast is used. Because black and white radiographic images are sensitive to tissue density, bone is much more readily identifiable than other, less dense tissue such as cartilage or muscle (Bacon & Smith, 1994; Donner, 1985; Ekberg & Hillarp, 1986). For this reason, many of
the measures made regarding the displacements and timings associated with a swallow have focused on the hyoid bone.

Multiple groups of investigators have described hyoid bone movement occurring within a swallow (Cook et al., 1989; Dodds et al., 1990; Ekberg, 1986 A, 1986 B; Ishida et al., 2002; Kendall & Leonard, 2001; Kendall, McKenzie, Leonard, & Jones, 1998; Leonard et al., 2000; Logemann et al., 2000; Logemann, Pauloski, Rademaker, & Kahrilas, 2002; Robbins, Hamilton, Lof, & Kempster, 1992; Schultz, Perlman, & VanDaele, 1994; Sonies, Parent, Morrish, & Baum, 1988; Vaiman, Eviatar, & Segal, 2004, 2004). The hyoid bone moves both superiorly and anteriorly; these two components of the hyoid trajectory have been examined with regards to tongue movement, airway protection and UES opening (Jacob et al., 1989; Kendall & Leonard, 2001; Leonard et al., 2000; Logemann, 1988; Sonies et al., 1996). It has been suggested that the superior component of hyoid motion is associated primarily with tongue (and jaw) movement, while the anterior component is primarily related to airway protection and UES opening following relaxation of the cricopharyngus. More specifically, the superior movement is significantly different between solid and liquid foods, with greater amplitude of movement for solid swallows due to the masticatory movements required (Ishida et al., 2002). Additionally, Ishida et al. report an increase in the amplitude of upward, but not forward, movement of the hyoid bone with increasing bolus size, which is also indicative of differing functions associated with superior and anterior hyoid movement. However, other investigators have reported an increased amplitude in both the superior and anterior components of hyoid movement with increased bolus size, and also with different bolus viscosities (Cook et al., 1989; Dantas & Dodds, 1990; Jacob et
Further, in some investigations the movement of the hyoid bone has not been parsed into superior and anterior components, but rather examined as a measure of the starting and ending points of hyoid movement (i.e., the trajectory of the hyoid movement) (Kendall & Leonard, 2001; Leonard et al., 2000). In these studies overall amplitude of movement was found to increase with increasing bolus volume. Further, in persons with oropharyngeal dysphagia the superior and anterior directions of hyoid movement are decreased compared to healthy individuals (Perlman, VanDaele, & Otterbacher, 1995).

There is a wealth of information regarding hyoid movements and displacements that has yielded differing and, at times, contradictory results. Possible reasons for this include the use of different measurement techniques, the use of different anatomical landmarks and identification of different initiation points within a swallow to begin measurement of hyoid movement. Additionally, basic anatomical and physiological differences between individuals, healthy or otherwise, likely play a role in different findings with regard to the pattern and displacements of hyoid movement (Ishida et al., 2002).

In 1986, Ekberg reported on the variability in movement patterns of the hyoid in young, healthy adults. He found that 80% of participants demonstrated a two-step hyoid movement pattern (clear superior-anterior distinction) during the swallow, while the remaining 20% exhibited a one-step pattern. A difference in force generation capability between anterior and posterior suprahyoid muscles was put forth as a possible explanation for these different patterns (Ekberg, 1986). Whatever the explanation for different patterns of movement, all participants exhibited normal swallowing and none had past complaints of dysphagia. Thus, it seems to be a logical hypothesis that the
“superior” component of swallowing may be multifunctional, depending on the individual. With regards to the oral preparatory and oral phases of swallowing, the superior component would be related to tongue and jaw movement. With regards to the pharyngeal stage of swallowing for individuals with a two-step swallow, both the superior and anterior components would be related to airway protection and UES opening.

Movement of the hyoid bone associated with the pharyngeal stage of swallowing (airway protection and UES opening) is accomplished primarily via contraction of the submental muscle group, which consists of the anterior belly of the digastric, mylohyoid, and geniohyoid muscles (Cook et al., 1989; Dantas & Dodds, 1990; Logemann, 1988; Perlman, Palmer, McCulloch, & Vandaele, 1999; Vaiman et al., 2004). Dysphagic symptoms including slow or decreased range of motion of hyoid movement may result in decreased extent and duration of UES opening and/or penetration/aspiration of the bolus into the airway. These symptoms likely result from weakness or discoordination in the submental muscles (Easterling et al., 2000; Kendall & Leonard, 2001; Schultz et al., 1994). Pathologies that could potentially impact the strength or timing of submental muscle contraction include structural changes, such as head or neck cancer, or neurodegenerative diseases or stroke (Bartolome & Neumann, 1993; Bosma & Brodie, 1969; Lazarus et al., 1996; Lazarus et al., 2000; Logemann, 1988; Logemann & Bytell, 1979; Martino et al., 2001; Nakagawa et al., 1997; Nilsson, Ekberg, Olsson, & Hindfelt, 1998; Sellars et al., 1999; Smithard, 2002). Consequently, the movement of the hyoid bone has been the focus of study regarding the rehabilitation of swallowing (Ding,

**Exercise and Rehabilitation**

The human body is sensitive to changes in physical activity in both health and disease (Celnik & Cohen, 2004; Salmons & Henriksson, 1981). Changes occur myogenically and neurally with increased or decreased use of striated skeletal muscle, which is evident from the strength gains associated with weight lifting, or muscle atrophy seen after a limb has been casted for a given amount of time (Carroll, Riek, & Carson, 2001; Frimel et al., 2005; Kraemer, Fleck, & Evans, 1996; McComas, 1994; Powers & Howley, 2004; Salmons & Henriksson, 1981; Shepherd, 2001). Rehabilitative exercises have been a major focus of research as they may enable patients to capitalize on the plasticity of muscle and of the peripheral and central nervous systems (Celnik & Cohen, 2004; Edstrom & Grimby, 1986; Salmons & Henriksson, 1981; Shepherd, 2001). As such, it has been of interest to rehabilitation scientists to study the adaptations which may occur in animals as well as in healthy humans in order to translate that knowledge into rehabilitative models appropriate to populations with different pathological states.

The application of specific exercises may lead to varying levels of functional gain over time (Celnik & Cohen, 2004; Duchateau & Enoka, 2002; McComas, 1994). Functional gain may translate to improvements in the ability to perform activities depending on a minimum amount of strength in that limb, such as household chores or playing a sport. The exercises chosen in a rehabilitation plan are not selected haphazardly; rather they are chosen based on known pathophysiology of the impairment, observed symptoms, and functional needs (Clark, 2003; Hamdy et al., 1998; Powers & Howley, 2004). Specifically, the principles of overload and specificity, which govern the
development of effective exercise programs in healthy individuals, along with current knowledge regarding the effects of skilled and unskilled movements on neuroplasticity, should also influence the rehabilitation program development for an individual patient.

The principle of overload holds that in order to increase the force-generating ability of a muscle, that muscle must be taxed beyond its current capacity to respond. That is, it must be exposed to a load greater than what it is typically exposed to on a daily basis (e.g., lifting a weight). The principle of specificity holds that the best way to train a certain function is to do exercises that are similar, or identical to, that function (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Behm & Sale, 1993; Edstrom & Grimby, 1986; Kraemer et al., 1996; Powers & Howley, 2004). These principles are not mutually exclusive, and it may be ideal for an exercise program to encompass both principles such that one may serve as a primer for another (e.g., improving force generation capacity in order to successfully engage in the functionally oriented exercise).

As stated previously, the adaptations that occur during a training program include both neural and myogenic changes. Neural changes have been shown to occur first, within the first 4-6 weeks of an exercise program. Peripherally, neural adaptations may include increased descending central neural drive to peripheral nerves, increased rate of motor unit firing frequency, increased number of motor units firing, and increased rate of force development. Additionally, changes may be present in the sensory feedback from the many sensory receptors within a muscle (Carroll et al., 2001; Duchateau & Enoka, 2002; Edstrom & Grimby, 1986; Salmons & Henriksson, 1981). This training-induced neuroplasticity therefore may affect both excitatory and inhibitory pathways at the central level, resulting in decreased co-activation of antagonistic muscles, and better
coordination of motor unit firing with a muscle and in synergistic muscles (Carroll et al., 2001; Duchateau & Enoka, 2002; Edstrom & Grimby, 1986; Salmons & Henriksson, 1981).

At the level of the central nervous system it is hypothesized that neuroplastic changes occurring within the cortex result from increased synapses per neuron, increased dendritic arborization of pyramidal cells, and enhanced synaptic responses (Jones, Kleim, & Greenough, 1996; Kleim et al., 2002; Kleim et al., 2004). Additionally, increased glucose uptake by muscles during any type of exercise may lead to prolonged and increased neurotransmitter release in neocortex, which may contribute to neuroplastic mechanisms (Kleim, Cooper, & VandenBerg, 2002; Powers & Howley, 2004). Observed neuroplastic changes may include changes in functional organization of the cortex, as may be measured using various neuroimaging techniques or transcranial magnetic stimulation (TMS) whereby a change in the shape of sites on the motor cortex responding to a stimulus is seen (Hamdy et al., 1998; Hamdy et al., 1996; Hamdy, Rothwell, Aziz, Singh, & Thompson, 1998; Kleim et al., 2002; Kleim et al., 2004). Additionally, the threshold of stimulation needed to elicit a motor or sensory cortical response may decrease. It is here that the distinction between skilled and unskilled exercise training and subsequent translation to task specificity must be made. Functional re-organization of the cortex and cortical threshold response changes have been shown to occur in response to skill training, but not unskilled training. For example, Kleim and colleagues (2002) demonstrated that teaching a fine movement pattern skill in a rat leads to changes in cortical representation of the rat forearm musculature, whereas a simple, non-skilled reaching task did not (Kleim et al., 2002). The immediate, short term changes following
the training of skilled exercises are thought to be due to increased neuronal excitability with subsequent addition or loss of synaptic material leading to enduring changes, termed consolidation or “learning,” within 7-10 days of initial skill exercise training (Kleim et al., 2004).

Changes within the muscle itself generally take longer to occur at 6+ weeks of training for both fast and slow twitch skeletal muscle fiber types, although the recruitment pattern may differ depending on the task and targeted functional outcome (e.g., strength versus skill training). Myogenic changes include changes to the muscles morphology, including addition of sarcomeres (hypertrophy) and in their pennation angles (Aagaard et al., 2002; Edstrom & Grimby, 1986; Sale, 1988; Salmons & Henriksson, 1981). Additionally, the metabolic properties of muscle fibers change with exercise, whereby a muscle may come to depend more or less on aerobic versus anaerobic energy production (type I versus type II fibers) as its primary means of producing adenosine triphosphate (ATP) (Powers & Howley, 2004; Salmons & Henriksson, 1981).

As stated above, myogenic and neural changes are sensitive to both increased and decreased use; the latter may occur following structural or neurologic injury or pathology and may affect the skeletal muscles’ force generating capacities, coordination and timings. With regard to swallowing, the submental muscle group, for example, which is important for oral bolus manipulation, hyolaryngeal excursion, and subsequent airway protection during swallowing (see above review), is comprised of striated skeletal muscles which are governed by the same rules as other striated skeletal muscle with regards to neural and myogenic adaptations to use or disuse (Hiiemae & Palmer, 2003;
Maier, 1979; Rokx, van Willigen, & Jansen, 1984). Following neurologic injury, a person may experience inability to swallow characterized by little to no movement of the hyolaryngeal complex, ineffective airway protection, and subsequent aspiration of foods and liquids. Based on knowledge regarding the role of submental musculature in the excursion of the hyolaryngeal complex, a rehabilitation program may then be initiated that targets that muscle group which would ideally be in line with principles that are applied to programs targeting other groups of striated muscles.

**Established Swallow Rehabilitation**

It has been demonstrated that the biomechanical aspects of swallow can be voluntarily altered in both healthy adults and populations suffering from pathological disease processes. Specifically, tongue pressures, hyoid displacements, and UES opening can be altered in terms of duration and/or amplitude (Bartolome & Neumann, 1993; Bulow, Olsson, & Ekberg, 1999; Ding et al., 2002; Hind, Nicosia, Roecker, Carnes, & Robbins, 2001; Langmore & Miller, 1994; Lazarus, Logemann, Song, Rademaker, & Kahrilas, 2002; Logemann, 1999; Logemann & Kahrilas, 1990). Examination of the swallow maneuvers has been the focus of multiple studies with the aim of documenting the treatment activity, efficacy, and effectiveness of particular rehabilitative strategies, although studies documenting the latter two are scarce. These maneuvers have been used as compensatory mechanisms to overcome dysphagia resulting from weak swallowing musculature, or decreased range of motion of various head or neck structures (Clark, 2003; Langmore & Miller, 1994; Lazarus et al., 2002; Logemann, 1998; Logemann, 1999; Saleem, Sapienza, & Okun, Submitted). When using swallow maneuvers, the patient is required to take voluntary control over the movements and timings associated
with the swallow, as well as to practice independently of the clinician (Clark, 2003; Langmore & Miller, 1994; Logemann, 1999; Saleem et al., Submitted).

To date, the five most widely documented swallowing-specific maneuvers are: the supraglottic swallow, the super-supraglottic swallow, the Masako technique, the effortful swallow, and the Mendelsohn Maneuver, each targeting specific aspects of oral or pharyngeal swallow physiology (Clark, 2003; Fujiu & Logemann, 1996; Langmore & Miller, 1994; Logemann, 1999). Physiological changes which may be the targets of these swallow exercises include duration and onset of airway closure, extent and duration of hyoid excursion, and duration and extent of upper esophageal sphincter opening (Fujiu & Logemann, 1996; Hiss & Huckabee, 2005; Logemann, 1998; Logemann, 1999).

Two of the swallowing maneuvers have been shown to affect displacements and durations associated with hyoid movement during swallow: the effortful swallow and the Mendelsohn Maneuver (Bulow et al., 1999; Ding et al., 2002; Hind et al., 2001; Langmore & Miller, 1994; Lazarus et al., 2002; Logemann, 1998). The effortful swallow was developed to increase posterior motion and duration of contact of the tongue base to the posterior pharyngeal wall during the swallow, and the Mendelsohn to increase the extent and duration of laryngeal elevation and subsequently increase the duration of UES opening (Ding et al., 2002; Langmore & Miller, 1994; Logemann, 1998; Logemann, 1999). Both the effortful swallow and the Mendelsohn Maneuver have been recommended for persons with “weak” swallows, characterized by inadequate laryngeal elevation, diminished extent/duration of UES opening, or tongue base-pharyngeal wall contact (Bulow et al., 1999; Hiss & Huckabee, 2005; Logemann, 1998; Logemann, 1999; Logemann & Kahrilas, 1990).
The Mendelsohn Maneuver has been investigated in healthy adults using both videofluoroscopy and surface electromyography (sEMG) independently. It has been shown to significantly increase maximal vertical hyoid displacement and prolong UES opening (Langmore & Miller, 1994). Additionally, it has been shown to result in higher peak amplitudes and longer duration of muscle activation of the submental muscle group (Ding et al., 2002). As well, the effortful swallow has been shown to result in elevation of the hyoid bone pre-swallow, increase hyoid vertical displacement, increase the duration of hyoid anterior excursion, and increase duration of UES opening in healthy adult subjects (Bulow et al., 1999; Hind et al., 2001).

The Mendelsohn and the effortful swallow have been studied in head and neck cancer patients. Both were found to result in durational changes in tongue base contact to posterior pharyngeal wall, laryngeal vestibule closure, and UES opening that most approximated those reported in healthy subjects (Lazarus et al., 2002; Logemann, 1998). As well, the Mendelsohn Maneuver and effortful swallow have been examined in patients with dysphagic symptoms resulting from neurologic disorders. Findings indicate that the swallowing maneuvers resulted in quantifiable changes in specific elements of swallowing (Logemann & Kahrilas, 1990). Specifically, increase in duration of the UES opening and increased speed of bolus head propulsion as well as decreased incidence of aspiration have been reported (Bartolome & Neumann, 1993; Logemann & Kahrilas, 1990; Neumann, 1993). Cognitive status associated with the ability to follow directions and take volitional control over head and neck structures was identified as a potential barrier to the success of these techniques in neurologically compromised populations (Neumann, 1993).
Differences in biomechanical measures between normal swallows and swallows utilizing a maneuver in both healthy individuals and in those with pathological disease have been demonstrated. However, these studies have focused on swallow maneuvers primarily as compensatory techniques (Lazarus, Logemann, & Gibbons, 1993; Lazarus et al., 2002; Logemann, 1998; Logemann, 1999). Swallowing maneuvers may also be considered as skilled, specific strength training exercises that target the swallow musculature. Increased and prolonged hyoid displacement and submental muscle activation (as evidenced by increased surface electromyographic activation) during the use of the Mendelsohn Maneuver and effortful swallow indicate muscles are being taxed beyond their capacity to respond during normal swallow (Ding et al., 2002; Hind et al., 2001; Huckabee, Butler, Barclay, & Jit, 2005). Additionally, because execution of the task includes the act of swallowing, they inherently encompass the principle of specificity. However, because they each require the volitional manipulation of the swallow they may differ with regard to muscle activation pattern and timing, and they may be considered novel skilled tasks, which is important because it imparts potential to alter the cortical representation and motor/sensory thresholds of that muscle group (Kleim et al., 2002; Monfils, Plautz, & Kleim, 2005).

Respiratory Based Swallow Therapy

An expiratory muscle strength training (EMST) device which has been shown to improve pulmonary, cough, and vocal loudness parameters in healthy adults as well as in high-risk vocal performers, those with spinal cord injury and patients with Parkinson’s Disease, has recently come under investigation as a potential treatment for dysphagia (Saleem, Sapienza, Rosenbek, Musson, & Okun, 2005; Saleem, Sapienza, Rosenbek, Musson, & Okun, 2005; Saleem et al., Submitted; Sapienza, 2004, 2004; Sapienza, 2004, 2004).
Davenport, & Martin, 2002; Sapienza, Hoffman-Ruddy, Davenport, Martin, & Lehman, 2001). To date, pilot videofluoroscopic studies of two healthy adults using the EMST device have been completed. These two participants were asked to blow against the pressure threshold valve in the trainer set at 75% of their maximum expiratory pressure. During the task, videofluoroscopic images showed hyoid vertical elevation and velopharyngeal closure occurred (Figure 1). As well, a study using surface electromyography demonstrated increased activation of the submental muscles during EMST tasks versus swallowing tasks. Electrodes were placed bilaterally on the submental muscles, and muscle activation was recorded as subjects used the EMST device (Wheeler, Chiara, & Sapienza, 2005). Use of the EMST device resulted in significantly increased activity in the submental muscle group when compared with activation of these muscles during swallowing tasks. Subsequently, it can be theorized that therapy utilizing the EMST device may be applicable to swallowing rehabilitation via increasing the force-generating ability of the submental muscles.

Figure 1. Pilot data: videofluoroscopic images of hyoid and palatal elevation during use of the EMST device.
While EMST may not be task-specific to swallowing (swallow non-specific; e.g., performance of EMST does not include an actual swallow), it is a task that requires the integration and coordination of multiple muscles systems, including inspiratory muscles, expiratory muscles, velopharyngeal port muscles, oral muscles, lingual muscles, and suprahypoid muscles, and thereby may potentially lead to neuroplastic changes in any of those groups. Specifically, during swallowing the submental muscles are activated for approximately 800ms, submaximally. However, their pattern of activation is different as seen on sEMG with EMST (Wheeler et al., submitted), and if the motor tasks associated with their activation are distinctively different than those associated with swallowing, it is reasonable to hypothesize that there may be changes in the sensory and motor representation and excitability of areas with which those muscles are associated with EMST, which would be a seemingly novel skilled task. Subsequently, this may lead to carryover of increased cortical drive and coordination of those muscles associated with EMST to tasks that require precise timing and strength targets, such as the act of swallowing.

Statement of the Problem

Currently, videofluoroscopic and submental sEMG activation measures have not been made simultaneously during the performance of an effortful swallow, Mendelsohn Maneuver, or during use of the EMST device, and as such have not been evaluated within the framework of an exercise-based rehabilitative model with regard to their applicability to rehabilitate the swallow of a dysphagic individual. Acquiring these measures simultaneously would allow for the examination of overload and specificity principles, as well as the uniqueness of each as a skilled task as it targets the submental musculature.
Videofluoroscopic and electromyographic measures will help to answer the question: are these tasks well suited to induce the neural and myogenic changes which may be necessary to rehabilitate the damaged swallowing mechanism?

**Purpose**

This study investigated the biomechanical properties distinct to two swallow-specific (effortful swallow and Mendelsohn Maneuver) and one swallow-nonspecific (EMST) swallow therapy task. This allowed for assessment regarding their appropriateness as skilled exercises in the rehabilitation of dysphagia and contribution to the development of better rehabilitation therapies for dysphagia.

**Aims and Hypotheses**

**Aim 1**: Determine the effects of effortful swallow, Mendelsohn Maneuver (MM) and expiratory muscle strength training (EMST) on the trajectory of hyoid motion.

**Hypothesis 1**: It is hypothesized that displacement and angle associated with the hyoid movement trajectory will be discretely different between each task

**Aim 2**: Determine the effects of effortful swallow, MM, and EMST task on submental sEMG activity as it relates directly to hyoid movement.

**Hypothesis 2**: It is hypothesized that the amplitude and duration of submental muscle activity, and its relationship to hyoid motion will be discretely different between each task.
CHAPTER 2
METHODS

Participants

Twenty-five healthy adults served as participants for this prospective experimental study with one participant group. There were 15 females (ages 18 – 35 years, mean = 24 years) and 10 males (ages 19 – 33 years, mean = 26 years). Participant information is in Table 1. All participants completed a questionnaire regarding their general health and medical history. None had a history of dysphagia, neurologic disease, chronic respiratory disease, smoked cigarettes within the past 5 years, had untreated hypertension, or vascular disease. As well, normal head and neck anatomy was confirmed by the principal investigator (PI) for all participants on oral and videofluoroscopic examination. Study protocol approval was obtained from the University of Florida Institutional Review Board as well as the Malcom Randall VA Medical Center Radiation Safety Committee and Research and Development Committee.

Description of the Expiratory Training Device

The EMST device is an expiratory pressure threshold trainer, which is a calibrated device consisting of a mouthpiece with a one-way spring loaded valve. The valve blocks airflow produced by the user until a sufficient “threshold” pressure is produced to overcome the force. The target threshold is defined as a percentage of the maximum expiratory pressure generation capabilities of the individual user. In order to reach the threshold pressure the user is required to breathe out with sufficient expiratory effort to open the valve against an adjustable spring (Figure 2). As long as the threshold pressure
in maintained, air will flow through the device. The expiratory strength trainer and its load are not dependent on airflow or breathing rate, a factor that is much different than the “traditional” respiratory training programs. The maximum threshold of the experimental device is 150cmH2O, and the range is from 0cmH2O to 150cmH2O.

Figure 2. EMST device used in the study.

Procedures

After participants gave their informed consent, they were given a brief health history questionnaire to confirm inclusionary/exclusionary criteria (Appendix A). Maximum expiratory pressures were then measured (see description below) and the participant was instructed as to correct execution of each task: EMST, Mendelsohn Maneuver, and effortful swallow. Participants were then escorted to the videofluorography suite where simultaneous fluoroscopic and sEMG recordings were made of three trials of each exercise task, as well as three trials of a normal swallow, for a total of twelve trials, all completed in random order.
**Task Learning**

Measurement of maximal expiratory pressures (MEP) was completed on each participant in order to properly set the EMST device to 75% of each participant’s MEP (Sapienza et al., 1997). MEP was measured with the participant standing upright with a nose clip in place. Participants were instructed to inhale completely, or to total lung capacity. A disposable mouthpiece coupled to a manometer (Smart Manometer 350, Meriam Instruments, Cleveland, OH) was then placed in the participant’s mouth and he/she exhaled as fast and hard as possible. Each participant repeated the maneuver until three trials were achieved within +/- 5% of each other. Participants waited a minimum of 30 seconds between each trial in order to avoid dizziness or lightheadedness.

Each participant was trained by the principal investigator to properly execute the Mendelsohn Maneuver and effortful swallow. Directions for the Mendelsohn Maneuver were as follows: “Put your hand on your throat and feel when you swallow, your Adam’s Apple moves up. Now, when you swallow I want you to hold your Adam’s Apple up for a few seconds, squeezing your throat and neck muscles and not letting go” (Logemann, 1998). Participants utilized sEMG signals as biofeedback (Figure 3) and practiced until they successfully completed 5/5 trials defined as elevation of the submental sEMG signal for a minimum of two seconds (Ding et al., 2002). Directions for the effortful swallow were as follows: “As you swallow, squeeze hard with all of your throat and neck muscles” (Logemann, 1998). Surface EMG biofeedback (Figure 3) was again utilized to aid in task learning, and practice continued until 5/5 successful trials defined as a doubling in sEMG amplitude as compared with normal swallow maximum sEMG amplitude was attained (Huckabee et al., 2005). Task learning for both the Mendelsohn Maneuver and effortful swallow averaged 5-7 minutes per subject.
Figure 3. Waveforms obtained for sEMG biofeedback for Mendelsohn maneuver and effortful swallow (right top and bottom, respectively) compared with normal swallow (left) for task learning.

**Surface EMG Procedure**

Surface EMG was used for biofeedback purposes during task learning as well as simultaneously with videofluoroscopy during the experiment. Surface EMG signals were obtained from a single three-point, circular disposable electrode with a 2.25 inch diameter (Figure 4). Each patch contained a triad of three electrodes; two were recording electrodes and one a ground. Inter-electrode distance was 0.25 inches edge-to-edge and 0.75 inches center-to-center. The skin under the chin was cleansed with alcohol swabs prior to electrode placement. Electrode patch placement was determined by having participants press their tongues to the top of their mouth with force, thereby allowing the principal investigator to identify the submental muscle group. The patch was then placed such that the center of the patch was located at midline and the two recording electrodes
were to the left and right of midline, with the ground electrode oriented posteriorly. The sEMG signals were recorded and processed by the Kay Swallow Signals Lab (Kay-Pentax, Lincoln Park, NJ) which was coupled to the Kay Elemetrics Swallowing Workstation, with a sampling rate of 1000Hz. The raw signal was band-pass filtered (50 – 250 Hz), integrated (time constant = 50ms) and rectified.

Videofluoroscopic Procedure

The videofluoroscopic studies of each task were recorded with a resolution of 30 frames per second using the Kay Digital Swallowing Workstation, model 7100 (Lincoln Park, NJ). Participants were positioned in the lateral viewing plane sitting upright and self-administered 3 trials for each swallow task (normal, Mendelsohn, and effortful) of 10mL thin liquid swallows of barium contrast solution per graded medicine cup. The liquid contrast material was the manufacturer preparation EZ-EM (Varibar contrast agents, EZ-EM, Inc, Lake Success, NY). Participants were instructed to take the material into the mouth, and stabilize the head (in case of neck flexion during bolus introduction into the oral cavity) in order to minimize movement artifact when measuring hyoid trajectory. Once the head stabilized, they were told to swallow when ready. The fluoroscope was activated prior to the self-administration of the contrast material into the oral cavity and remained activated for two seconds after the bolus tail exited the upper esophageal sphincter (UES) to allow reliable and valid measurement of hyoid movement. For three trials of the task using the EMST device, the fluoroscope was activated prior to the introduction of the trainer’s mouthpiece into the participant’s mouth and remained activated for two seconds after the device has been removed from the oral cavity. The resulting videofluoroscopic images and sEMG data were integrated within the Kay...
Swallowing Workstation, which allowed for postacquisition concurrent analyzation of the data (Figure 5).

Figure 4. Electrode triad used for submental sEMG recording. The electrode on top is the ground electrode; the other two are recording electrodes.

Figure 5. Concurrent videofluorographic and sEMG data recorded to the Kay Swallow Station. Note: tag arrows at the bottom of the sEMG signal denoting task onset and offset points based on corresponding fluoroscopic image.
Data Analysis

sEMG Measures

Submental myoelectrical activity was recorded to the Swallow Signals Lab and quantified in microvolts (µV) and milliseconds (ms). A baseline sEMG measure was taken from the middle 500ms of an initial 30-second period of quiet breathing with EMG electrodes in place. In order to obtain sEMG onset and offset points associated with hyoid motion during each task, the videofluorographic images were tagged for task onset defined for swallow tasks as the point where the bolus was seen to begin posterior movement in the oral cavity, and for the EMST task as the point where the device was situated within the oral cavity (see Figure 5). This point was subsequently referred to as T0, or the starting point for the task to which subsequent temporal characteristics were referenced. The images were also tagged for the point of maximum hyoid excursion, and for hyoid return to rest after task completion. These onset and offset points were then identified on the sEMG trace, where measures of peak amplitude and average amplitude were obtained. Tags were dropped at the peak amplitude in order to allow for subsequent analysis of peak sEMG amplitude relative to measures of hyoid displacement and angle of elevation. As well, the duration of submental muscle activation relative to hyoid movement was determined by measuring the interval between the onset and the offset (offset time minus onset time) of submental muscle activity during each task (Ding et al., 2002; Ertekin et al., 1995).

Each EMG measure was recorded and then calculated as a departure from the baseline measure and subsequently normalized to the maximum EMG signal recorded for the effortful swallow task (which represented the task characterized by the theoretical
greatest effort generated by a participant. Measures obtained from the sEMG signal included:

1. HStart EMG – EMG activity at the onset of hyoid movement (T0)
2. HMax EMG – EMG activity at the point of maximum hyoid movement
3. Max EMG – Peak EMG amplitude between onset and offset points
4. Avg EMG – Mean amplitude of the EMG signal between onset and offset points.
5. T EMG max – time (in milliseconds) between T0 and peak EMG amplitude.

**Hyoid Trajectory Measures**

Our laboratory has recently developed a MATLAB routine for the quantification and tracking of hyoid trajectory during a swallow (Wheeler, Martin-Harris, & Sapienza, submitted). Individual JPEG images of the swallow were extracted from the Kay recording device using the ImagePro Plus program (Media Cybernetics, Silver Spring, MD). The image sequences consisted of all frames from T0 to task completion as tagged on the Kay Swallow Station in order to maintain the integrity of temporal relationships between the sEMG signal and hyoid movement measures. Once extracted, the files were transferred to a computer (Dell OptiPlex GX 280, Dell, Inc.) set up with MATLAB, version 7.0.1 (The MathWorks Inc.). The Matlab swallow routine was designed to track the motion of the hyoid using the third cervical vertebrae (C3) as a reference. The program uses first frame in the sequence as a reference line, and hyoid movement subsequent to that frame is referenced to the line and to C3 (Figure 6). All frames subsequent to the first frame are randomized by the program and presented to the user for subsequent data analysis. The most anterior and inferior points on the hyoid bone and on C3 were identified for all frames of measurement. After measurement of the randomized frames of the swallow were completed, the routine calculates the displacement and angle...
of the hyoid bone relative to the initial resting position for each frame of the swallow and generates these calculations in Excel (Microsoft, Inc.).

![Image of measurements](image1)

Figure 6. Example of measurements the MATLAB routine makes during task analysis.

Note: C3 = third cervical vertebrae, H1 = hyoid starting point, first frame, H2 = hyoid location in subsequent frame of the task.

From the data in the Excel files for each subject across the three trials of each task, the point of maximum displacement (D1), maximum angle (A2), and the associated angle (A1) and displacement (D2), respectively, were identified. The displacement (D3) and angle (A3) associated with the last frame of each task, or hyoid return, were also identified. Displacement measures were normalized for each participant across to the first frame of each task. As well, the associated time in milliseconds was calculated for each measure (T1, T2, and T3, respectively). These were the points which were chosen
to quantify the most salient characteristics of hyoid bone movement: how much excursion (displacement), how much vertical elevation (angle), and when these occurred within each task.

**Participant Task Performance and Follow-up**

Because it is often questioned by both clinicians and researchers as to whether swallow exercise tasks are actually performed correctly, participants were scored by two independent raters as well as the PI as to whether they correctly performed each of the two swallow exercise tasks (the Mendelsohn Maneuver and the effortful swallow) correctly. A score of “1.00” indicated correct performance of a task, “0.50” indicated the task was partially correct, and “0.00” indicated the participant was not able to correctly perform the task according to specified criteria (Ding et al., 2002; Huckabee et al., 2005). Also of interest was the perceived difficulty and effort required for task completion experienced by the participants. Therefore, approximately 2 weeks following their participation in the experiment participants were emailed a short questionnaire asking questions related to how well they remembered each of the tasks and how difficult the tasks were to perform relative to a normal swallow (Appendix B).

**Statistical Analysis**

Statistical analysis of the data was completed using SPSS software version 11.5. Repeated measures analysis of variance (ANOVA) was used to determine if discrete differences existed for each trajectory measures between the four different tasks. Post hoc analyses were then completed using pairwise comparisons in order to identify for which tasks they were significantly different. An additional repeated measures ANOVA was completed on sEMG tasks in order to determine if submental activation was significantly different between tasks. Further analyses using Pearson $r$ correlations and
paired samples $t$-tests were completed on hyoid displacement and angle measures and sEMG measures in order to determine relationships between the magnitude and timing of hyoid movement and submental muscle activity. Lastly, a stepwise multiple linear regression analysis was completed in order to identify which variables, including trajectory and sEMG variables, found to be significantly different between tasks, were the most relevant with regard to their relationship to the task being performed.
Table 1. Participant information and task performance scores. Note: MM = Mendelsohn Maneuver, ES = effortful swallow, NR = no response, 1.00 = correct task performance, 0.50 = partially correct performance, 0.00 = incorrect task performance. Memory and effort scores are based on a Likert scale, with 1 being the best memory, or easiest level of difficulty/effort, and 5 being the worst or most difficult/effortful, respectively.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age</th>
<th>Sex</th>
<th>MM</th>
<th>ES</th>
<th>Task Performance</th>
<th>Memory for task</th>
<th>Difficulty of task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>MM</td>
<td>ES</td>
<td>MM</td>
<td>ES</td>
<td>EMST</td>
</tr>
<tr>
<td>1</td>
<td>21</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>f</td>
<td>0.50</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>28</td>
<td>f</td>
<td>0.50</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>22</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>23</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>24</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>f</td>
<td>0.00</td>
<td>1.00</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>24</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>26</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>20</td>
<td>f</td>
<td>0.50</td>
<td>1.00</td>
<td>3</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>12</td>
<td>32</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>13</td>
<td>31</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>31</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>33</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>18</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td>21</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>18</td>
<td>19</td>
<td>m</td>
<td>0.50</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>21</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
<td>m</td>
<td>1.00</td>
<td>1.00</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td>32</td>
<td>m</td>
<td>0.50</td>
<td>1.00</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>22</td>
<td>21</td>
<td>f</td>
<td>0.50</td>
<td>1.00</td>
<td>NR</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>23</td>
<td>21</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>24</td>
<td>35</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>25</td>
<td>21</td>
<td>f</td>
<td>1.00</td>
<td>1.00</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mean</td>
<td>24</td>
<td></td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>
CHAPTER 3  
RESULTS  

Mean and standard deviation of each of the sEMG and trajectory measures are in Table 2. Intrarater as well as interrater reliability was completed on 15% of the data using Pearson-\(r\) correlations. Intrarater reliability was found to be excellent (\(r = .823 - .945\)). Interrater reliability was also excellent for all measures (\(r = .872 - .949\)) with the exception of T2, which was good (\(r = .642\)).

Table 2. Means (M) and standard deviations for each task. Note: A1 = angle associated with maximum displacement; D1 = maximum displacement; A2 = maximum angle; D2 = displacement associated with maximum angle; A3 = angle at end of task, D3 = displacement at end of task. Displacements and sEMG data have been normalized for each participant.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Task M(SD)</th>
<th>Normal</th>
<th>MM</th>
<th>ES</th>
<th>EMST</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Trajectory</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A1</td>
<td></td>
<td>7.49(5.91)</td>
<td>10.30(7.06)</td>
<td>10.35(8.06)</td>
<td>6.84(4.95)</td>
</tr>
<tr>
<td>D1</td>
<td></td>
<td>1.42(0.09)</td>
<td>1.43(0.12)</td>
<td>1.39(0.11)</td>
<td>1.09(0.07)</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>10.39(5.76)</td>
<td>16.71(7.05)</td>
<td>15.77(10.12)</td>
<td>15.36(6.44)</td>
</tr>
<tr>
<td>D2</td>
<td></td>
<td>1.22(0.15)</td>
<td>1.23(0.14)</td>
<td>1.23(0.15)</td>
<td>1.00(0.09)</td>
</tr>
<tr>
<td>A3</td>
<td></td>
<td>-2.24(6.72)</td>
<td>-3.51(8.66)</td>
<td>-3.49(9.05)</td>
<td>0.62(8.82)</td>
</tr>
<tr>
<td>D3</td>
<td></td>
<td>1.05(0.17)</td>
<td>1.06(0.06)</td>
<td>1.06(0.06)</td>
<td>0.98(0.09)</td>
</tr>
<tr>
<td><strong>sEMG</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg EMG</td>
<td></td>
<td>0.15(0.06)</td>
<td>0.35(0.12)</td>
<td>0.34(0.07)</td>
<td>0.30(0.20)</td>
</tr>
<tr>
<td>Max EMG</td>
<td></td>
<td>0.43(0.14)</td>
<td>0.88(0.29)</td>
<td>0.96(0.04)</td>
<td>0.64(0.39)</td>
</tr>
<tr>
<td>Hstart EMG</td>
<td></td>
<td>0.32(0.12)</td>
<td>0.49(0.25)</td>
<td>0.64(0.21)</td>
<td>0.27(0.20)</td>
</tr>
<tr>
<td>Hmax EMG</td>
<td></td>
<td>0.27(0.14)</td>
<td>0.59(0.21)</td>
<td>0.74(0.16)</td>
<td>0.38(0.25)</td>
</tr>
</tbody>
</table>
Participant Task Performance and Follow-up

Results of the task effort and performance questionnaire are in Table 1. In general, participants indicated they remembered each task very well, and could perform it at that time if asked. The Mendelsohn maneuver was the task which participants reported as the most difficult to perform, indicating a moderate level of effort was required to perform the task relative to a normal swallow. Both the effortful swallow and EMST task were generally reported to be easy tasks, with minimal effort indicated by the participants.

All participants were able to successfully perform the effortful swallow. However, 24% (4 females, 2 males) of participants were only able to partially perform the Mendelsohn maneuver (Table 1). “Partially correct” Mendelsohn was defined as prolonged elevation of the hyoid bone and sEMG signal (as per criteria for successful completion put forth in the methods section), but opening of the laryngeal vestibule during prolonged hyoid elevation. One of the 25 participants, a 23 year-old female was unable to perform the Mendelsohn maneuver correctly, with no prolongation of hyoid elevation seen on videofluorography and no prolonged submental muscle activation evident from the sEMG signal.

Trajectory Differences between Experimental Tasks

To test the hypothesis set forth in Aim 1, a repeated measures analysis of variance (ANOVA) was completed for within subject factor task and between subject factor sex. For trajectory measures A1, D1, A2, D2, A3, and D3, significance was set at $p = .008$ (Bonferroni correction for multiple comparisons: $.05/6 = .008$). There was no significant effect found for sex ($F = 2.484, df = 6, p = .063$), nor was there a significant interaction between task and sex ($F = 0.949, df = 18, p = .575$). Data was then collapsed across sex. A significant effect was found for task ($F = 17.595, df = 18, p = .001$). Trajectory
variables which were found to be significantly different across tasks included maximum
displacement (D1; $F = 120.140, df = 3, p < .000$), maximum angle (A2; $F = 4.959, df = 3,$
$p = .004$), and displacement associated with the maximum angle (D2; $F = 27.761, df = 3,$
$p < .000$).

Post-hoc analysis with independent variable task and dependent variables D1, A2,
and D2 was then completed in order to examine which tasks differed significantly from
each other on these measures (Table 3, Figure 7). The three tasks which included an
actual swallow (e.g., normal swallow task, Mendelsohn Maneuver, and effortful swallow)
did not differ significantly from each other in the maximum displacement of hyoid
movement (D1) or in displacement associated with maximum angle (D2), while EMST
was significantly different with overall shorter D1 and D2 than the other tasks. For the
measure of maximum angle (A2) the normal swallow task was significantly lower than
the Mendelsohn maneuver, indicating the hyoid bone did not possess as much of a
vertical component to the motion pattern during the normal swallow as it did during the
Mendelsohn maneuver.

sEMG and Hyoid Movement

To test the hypothesis set forth in Aim 2, a repeated measures ANOVA with
within subject factor task, and between subject factor sex was completed on sEMG
measures to determine if different levels of submental muscle activation occurred for the
different tasks. A significance level of $p < .012$ was set (Bonferroni correction for
multiple comparisons: $.05/4 = .012$). No significant effect for sex ($F = 3.719, df = 4, p =$
$.021$) and no significant interaction between sex and task ($F = 1.214, df = 12, p = .378$)
was found. However, a significant effect was found for task ($F = 74.432, df = 12, p <$
$.000$) for each of the sEMG measures, including maximum sEMG (Max EMG; $F =$
18.773, \( df = 3, p < .000 \), average sEMG (Avg EMG; \( F = 12.121, df = 3, p < .000 \)), sEMG level at onset of hyoid movement (Hstart EMG; \( F = 25.265, df = 3, p < .000 \)), and sEMG level at maximum hyoid movement (Hmax EMG; \( F = 24.373, df = 3, p < .000 \)).

Table 3. Results of post hoc analysis for trajectory and sEMG measures found to be significantly different between tasks. Note: NML = normal swallow, MM = Mendelsohn maneuver, ES = effortful swallow, EMST = expiratory muscle strength trainer.

<table>
<thead>
<tr>
<th>Task Pairing</th>
<th>D1</th>
<th>D2</th>
<th>A2</th>
<th>Max EMG</th>
<th>Avg EMG</th>
<th>Hstart EMG</th>
<th>Hmax EMG</th>
</tr>
</thead>
<tbody>
<tr>
<td>NML-MM</td>
<td>-.015</td>
<td>-.001</td>
<td>-6.320*</td>
<td>-.448**</td>
<td>-.202**</td>
<td>-.176**</td>
<td>-.316**</td>
</tr>
<tr>
<td>NML-ES</td>
<td>.023</td>
<td>-.003</td>
<td>-5.373</td>
<td>-.528**</td>
<td>-.200**</td>
<td>-.324**</td>
<td>-.470**</td>
</tr>
<tr>
<td>NML-EMST</td>
<td>.322*</td>
<td>.224*</td>
<td>-4.966</td>
<td>-.210**</td>
<td>-.152**</td>
<td>.052</td>
<td>-.111</td>
</tr>
<tr>
<td>MM-ES</td>
<td>.038</td>
<td>-.002</td>
<td>.948</td>
<td>-.080</td>
<td>.013</td>
<td>-.149</td>
<td>-.154**</td>
</tr>
<tr>
<td>MM-EMST</td>
<td>.337*</td>
<td>.225*</td>
<td>1.354</td>
<td>.238**</td>
<td>.051</td>
<td>.227**</td>
<td>.205**</td>
</tr>
<tr>
<td>ES-EMST</td>
<td>.300*</td>
<td>.227*</td>
<td>.407</td>
<td>.317**</td>
<td>.038</td>
<td>.376**</td>
<td>.259**</td>
</tr>
</tbody>
</table>

* \( p < .008 \)

** \( p < .012 \)

Post hoc analysis (see Table 3) revealed significant differences for the measure of maximum EMG for all tasks except between the Mendelsohn maneuver and effortful swallow, which were both significantly higher than either EMST or normal swallow. The normal swallow task had the lowest maximum sEMG measures, which was significantly lower than all other tasks. Average sEMG was also significantly lower for the normal swallow, versus that of other tasks (which were not significantly different from each other). The sEMG signal at the start of hyoid movement (Hstart EMG) was not significantly different between the normal swallow task and the EMST task, or between the Mendelsohn maneuver and effortful swallow task. More specifically, both the Mendelsohn maneuver and effortful swallow had higher Hstart EMG measures than either the normal swallow or EMST task. Lastly, the sEMG at maximum hyoid
movement (Hmax EMG) was not significantly different between the normal swallow task and the EMST task, but were different for all other task pairings such that the Mendelsohn maneuver and the effortful swallow had significantly higher Hmax EMG values than normal swallow and the EMST task. Further, the effortful swallow had a Hmax EMG value that was also significantly higher than the Mendelsohn maneuver. (see Table 3 and Figure 8).

Figure 7. Post-hoc analysis for trajectory measures including D1, D2 (bottom), and A2 (top) between tasks.

* $p < .05$
Figure 8. Post-hoc analysis of surface electromyographic measures for each experimental task.

A Pearson $r$ correlation analysis was completed on maximum sEMG (Max EMG), maximum hyoid displacement (D1), and maximum angle of elevation (A2). No significant correlations were found between any of these variables. A partial correlation analysis was then completed to determine if there was a correlation between these variables controlling for task. Significant positive partial correlations were found between A2 and D1, and between D1 and maximum EMG measures (Table 4).
Table 4. Bivariate and partial correlations for maximum sEMG measures (Max EMG), maximum displacement (D1), and maximum angle (A2). Partial correlations are controlling for task.

<table>
<thead>
<tr>
<th></th>
<th>Max EMG</th>
<th>D1</th>
<th>A2</th>
<th>Max EMG</th>
<th>D1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bivariate correlations</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max EMG</td>
<td>--</td>
<td></td>
<td></td>
<td>--</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D1</td>
<td>.131</td>
<td>--</td>
<td></td>
<td>.402*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A2</td>
<td>.197</td>
<td>.151</td>
<td>--</td>
<td>.153</td>
<td>.400*</td>
<td>--</td>
</tr>
</tbody>
</table>

* $p < .01$.

Paired sample t-tests and Pearson $r$ correlations were completed to determine if there were significant differences between the timing of the maximum sEMG signal (Tmax EMG) and times of hyoid maximum displacement (T1), and hyoid maximum angle (T2) for each of the tasks, and if significant correlations existed between these measures. Results, which are summarized in Table 5, indicated that strong positive correlations and significant differences exist between the timing of maximum displacement, maximum angle, and maximum sEMG for the normal swallow task. However, for each subsequent task, the nature of these relationships changed such that the strength of correlations between timings generally decreases, with the exception of T1 and Tmax EMG on the effortful swallow ($r = .762, p < .000$), and T2 and Tmax EMG on the EMST task ($r = .804, p < .000$). Additionally, significant differences disappear with tasks other than the normal swallow with the exceptions of T2 and Tmax EMG for the Mendelsohn Maneuver ($t = 3.089, df = 23, p = .005$) and T1 and Tmax EMG for the effortful swallow ($t = 3.655, df = 23, p = .001$).
Table 5. Pearson correlations and paired samples t-tests for timing measures of maximum sEMG and sEMG associated with hyoid maximum displacement and angle measures. Note: Pair 1 = TMax EMG and T1; Pair 2 = TMax EMG and T2; Pair 3 = T1 and T2.

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>MM</th>
<th>ES</th>
<th>EMST</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r$</td>
<td>$t$</td>
<td>$r$</td>
<td>$t$</td>
</tr>
<tr>
<td>Pair 1</td>
<td>.770**</td>
<td>5.59**</td>
<td>.329</td>
<td>-1.18</td>
</tr>
<tr>
<td></td>
<td>.762**</td>
<td>3.66**</td>
<td>.401</td>
<td>-1.97</td>
</tr>
<tr>
<td>Pair 2</td>
<td>.752**</td>
<td>2.23*</td>
<td>.111</td>
<td>3.10**</td>
</tr>
<tr>
<td></td>
<td>.613**</td>
<td>0.432</td>
<td>.804**</td>
<td>-0.407</td>
</tr>
<tr>
<td>Pair 3</td>
<td>.797**</td>
<td>3.15**</td>
<td>-.173</td>
<td>-3.80**</td>
</tr>
<tr>
<td></td>
<td>.423</td>
<td>2.05</td>
<td>.550**</td>
<td>-1.63</td>
</tr>
</tbody>
</table>

* $p < .05$
** $p < .01$

**Regression Analysis**

Because of the preponderance of measures which were significantly different between tasks, a stepwise multiple linear regression analysis was completed in order to determine which variables were the most important with regard to their correlation to dependent variable *task*. As such, each task was assigned a numeric value, with “1” corresponding to normal swallow, “2” to Mendelsohn Maneuver, “3” to effortful swallow, and “4” to EMST. Predictor variables then included D1, A2, D2, Max EMG, Avg EMG, Hstart EMG, and Hmax EMG. Stepwise regression results (Table 6) indicate that a model including only D1 as a predictor variable was able to explain 42.9% of the variance in task ($F = 72.338, df = 1, p < .001$). By adding HMax EMG to the model, 55.6% of variability was explained ($F = 60.523, df = 2, p < .000$), and by adding both Hmax EMG and A2 to the model, 61.3% of the variance was explained ($F = 52.552, df = 3, p < .000$). Therefore, the three measures D1, A2, and HMax EMG were identified as the best suited to differentiate between tasks. As can be appreciated by examination of $\beta$ values.
and on Figure 9, as task “increases” (e.g., from normal swallow to Mendelsohn, to effortful, to EMST), the D1 value decreases, Hmax EMG increases, and A2 increases.

Table 6.  Stepwise regression analysis with dependent variable task.

<table>
<thead>
<tr>
<th>Model</th>
<th>Beta</th>
<th>t</th>
<th>R²</th>
<th>∆R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>-.771</td>
<td>-11.802*</td>
<td>.429</td>
<td>.429</td>
</tr>
<tr>
<td>Hmax EMG</td>
<td>.321</td>
<td>4.861*</td>
<td>.556</td>
<td>.127</td>
</tr>
<tr>
<td>A2</td>
<td>.264</td>
<td>4.059*</td>
<td>.613</td>
<td>.057</td>
</tr>
</tbody>
</table>

* p < .01

Figure 9.  Illustration of the relationships between task and individual predictor variables D1, A2, and Hmax EMG.
Compensatory rehabilitation techniques and maneuvers aimed at actively changing the physiology of the swallow and thus improving swallow safety are some common strategies used clinically for treating dysphagia following neurologic or anatomical injury (Clark, 2003; Logemann, 1998). Specifically, the Mendelsohn maneuver and effortful swallow have been shown to increase the activation of the submental muscle group when compared to a normal swallow task (Ding et al., 2002; Hind et al., 2001; Huckabee et al., 2005). Hence, the active manipulation of swallow physiology, characterized previous to the present study by increased EMG activity levels, implicates these techniques as swallow rehabilitative exercises. However, to date studies have not examined these maneuvers under the constructs of exercise-based rehabilitation nor with regard to their potential as neuroplastic-inducing mechanisms. As well, swallow-related effects of the EMST device, which thus far has been promoted for its effects on respiratory and voice parameters, has also not been studied under those constructs. Therefore, the aims of this study were to determine the effects of the Mendelsohn Maneuver, effortful swallow, and EMST program on the trajectory of hyoid bone movement, and to further determine the effects of those same tasks on submental sEMG activity as it related to movement of the hyoid bone. Accomplishment of these aims allowed for the assessment of specificity, overload, and “skill” components of each task, which are vitally important for exercise-induced neural and myogenic adaptations to occur.
Findings of this study supported the hypotheses that discrete differences do exist with regards to both quantitative measures of hyoid trajectory of motion, and to submental sEMG activity and its relationship to hyoid movement. Further, three variables were identified using a stepwise multiple linear regression analysis that explained up to 61.3 % of the variability in which task was being performed, including maximum hyoid displacement, maximum hyoid angle, and sEMG activity at the point of maximum hyoid displacement. Therefore, these measures may be clinically useful in determining which task is chosen for rehabilitation. For example, if overall displacement is decreased, the Mendelson maneuver or effortful swallow are the best options; if hyoid vertical elevation or contraction of the submental muscles is decreased, any of the three experimental tasks may be appropriate.

Components of Motion

The trajectory of motion of an object is, by definition, the path of a moving body through space. Trajectories have horizontal and vertical components, which can each be thought of in terms of overall displacement and angle. A projectile object is one that once projected, continues to move by its own inertia and is influenced only by gravity (Henderson, 2004). Therefore, the projectile may experience horizontal and vertical motion such that the resultant trajectory of motion is parabolic in nature thus enabling quantitative description by mathematic equations given known parameters of initial velocity and angle (Henderson, 2004). The physics of biomechanical motion can also be described quantitatively, although the application of mathematical equations to describe biomechanical motion is not quite as simple (Adamovich et al., 2001; St-Onge, Adamovich, & Feldman, 1997).
Biomechanical motion takes into account many more factors besides inertia and gravity, including anatomical constraints, muscle force production, co-activation of synergistic or antagonistic muscle groups, motor neuron firing, motor planning, proprioceptive feedback, mechanoreceptor feedback, and additional sensory feedback from muscle and tendon length/tension receptors (Adamovich, Levin, & Feldman, 1997; Feldman, Adamovich, & Levin, 1995; St-Onge et al., 1997). It has been hypothesized that the path of movement of an anatomical structure results from a motor plan based on some initial reference for the desired motion (Adamovich et al., 2001; Adamovich, Levin, & Feldman, 1994; Feldman et al., 1995; St-Onge et al., 1997). With regard to swallow function the initial referent would include bolus intake to the oral cavity, passage through the pharynx with an occluded airway (hyoid excursion, laryngeal closure), and flow into the esophagus.

**Movement Pattern**

The swallow movement pattern, which involves multiple muscle groups, is functionally organized at the level of the central nervous system, as opposed to organization based on subparts (Hamdy et al., 1996; Miller, 1993). In fact, investigations into the sensorimotor control of the swallow and speech mechanisms have demonstrated that individual muscles within functional groups of synergistic muscles, such as the submental or lingual muscle groups, have varying activity patterns between individual people (Abbs, Gracco, & Blair, 1984; Abbs, Gracco, & Cole, 1984; Gay et al., 1994; Gracco & Abbs, 1989; Perlman et al., 1999; Schultz et al., 1994; Spiro, Rendell, & Gay, 1994). However, overall timings of speech and swallow acts (in the absence of pathology) remain relatively invariant (Abbs et al., 1984; Gracco & Abbs, 1986; Palmer, Luschei, Jaffe, & McCulloch, 1999; Perlman et al., 1999). This suggests functional
organization of muscle force such that when a task is initiated and completed, modifications can occur in response to external perturbations experienced along the path of motion. For example, when a swallow is initiated prematurely (e.g., the bolus spills unexpectedly into the pharynx following brief discoordination within the oral cavity), reflexive modulation may occur in the manner of instantaneous hyoid elevation and/or laryngeal closure. Within the motor plan itself this could include increased motor neuron firing or muscle fiber recruitment in response to unexpected perturbation during the movement, in order to minimize alterations to the initial plan. In general, a motor plan is designed and executed such that ideally the recruitment and firing of motor neurons and subsequently muscle fibers results in the most efficient movement pattern in terms of energy expenditure, both centrally and peripherally (Abbs & Gracco, 1984; Adamovich et al., 1997; Gracco, 1994; Gracco & Abbs, 1988).

The characteristic movement patterns associated with swallowing are thought to result from motor commands emerging at the level of the brainstem within nuclei comprising central pattern generators (CPGs) (Broussard & Altschuler, 2000, 2000; Jean, 1984). CPGs have been shown to exist and play vital roles in the execution of movements that are hard-wired or oscillatory in nature (for example, breathing or walking). The movements generated are efficient, functionally effective and do not impose a large cognitive load in order to be executed. Reflexes routed through either single or multi-synapse feedback loops are typically able to modulate the pattern in an effective manner as well, further minimizing cognitive loading for task completion (Jean, 1984; Mitchell, 1980; Selley, Flack, Ellis, & Brooks, 1989; Smith et al., 1989). This has been demonstrated with regard to swallowing by examining differences between discrete
and rapid sequential swallows: sequential swallows are characterized by shorter
displacements of hyoid excursion, but similar velocities of hyoid movement when
compared to discrete swallows, changes which were hypothesized to represent a motor
plan modification for large bolus amounts that allowed for safe and efficient swallowing
in the presence of changes within the system (Chi-Fishman & Sonies, 2000, 2002;
Daniels et al., 2004; Daniels & Foundas, 2001).

Theoretically, then, taking a movement pattern which would under normal
conditions be executed by a CPG and actively modifying it at the cortical level (i.e., the
experimental tasks) may have differential effects with regards to the resulting trajectory
of motion in the targeted anatomical structure and to the activation of muscles or groups
of muscles which are involved with the target movement (Abbs et al., 1984; Adamovich
et al., 1997). More specifically, that motor plan may undergo changes affecting the
overall physiologic coordination of the movement if the plan is volitionally modified
such that the desired motor output is physiologically distinct from the original referent
generated by the CPG. The production of target movement patterns which are
physiologically distinct from existing referents may be thought of as distinct motor skills,
and therefore subject to neuroplastic mechanisms including motor map enhancement for
that task and changes in cortical motor and sensory thresholds, as has been demonstrated
in both animal models and in humans (Kleim et al., 2002; Monfils et al., 2005; Powers &
Howley, 2004).

Motor Skill

In order for the experimental tasks used in this study to be considered skilled
movements, they need to possess a sequence of motions, whereby multiple muscles or
groups of muscles may be involved, and require time for cognitive processing and
learning to occur (Adamovich et al., 1994; Kleim et al., 2002). The motor tasks involved in the present study included swallow-specific exercises (Mendelsohn Maneuver and effortful swallow) as well as the EMST task, a respiratory based exercise. Each of these tasks can be considered a motor skill when each of their component parts is considered.

For example, the Mendelsohn maneuver in the simplest terms is a volitional prolongation of the airway protective component of a swallow. However, parsing the task into the components that make up the technique reveals a complex sequence of events involving multiple muscle groups brought under voluntary control which are required to successfully integrate contractile timings in order to complete the task. First, cognitive processes are involved to interpret the auditory directions given for the task (e.g., “Put your hand on your throat and feel when you swallow, your Adams Apple moves up. Now, when you swallow I want you to hold your Adam’s apple up for a few seconds, squeezing your throat muscles and not letting go”) (Logemann, 1998). In fact, participants in the current study reported that the Mendelsohn maneuver required a moderate amount of volitional effort to perform, indicating increased cognitive loading imposed by the task (see Table 1). The instructions are then processed and developed into a distinct sequence of motor movements. These include taking the bolus material into the mouth (involvement of lingual musculature), swallow initiation with bolus propulsion into the pharynx (genioglossus, pharyngeal constrictor muscles), glottal closure (intrinsic laryngeal adductor muscles), hyoid and laryngeal excursion (contraction of submental muscles and thyrohyoid muscle), relaxation of the UES, and finally continued contraction of the submental muscles in order to maintain hyoid elevation.
beyond passage of the bolus through the UES, when these muscles would typically cease to contract and allow the hyoid to return to a rest position.

Similarly for the effortful swallow, specific verbal instructions are given regarding task execution (“As you swallow, squeeze hard with all of your throat and neck muscles”) (Logemann, 1998). This results in cognitive processing, and subsequently a motor plan intended specifically for that task which includes bolus intake, propulsion into the pharynx with concurrent squeezing of the “throat and neck” muscles, and then bolus passage into the esophagus. While the cognitive effort associated with performing the effortful swallow was less than was reported by participants for the Mendelsohn maneuver, it was still rated as slightly more effortful than a normal discrete swallow, which is indicative of a small increase in cognitive demand for task execution.

With regard to the EMST task, participants were instructed to inspire, put the device in the mouth, close the lips, and blow out forcefully until they heard air rush through the device, indicating they had successfully completed the task. Subsequent components of task execution include coordinating a deep inspiration and manipulation of lung volume, placing the device in the mouth, sealing the lips around the device’s mouthpiece, and then developing the required expiratory pressure with the expiratory muscles in order to successfully break the spring loaded valve and allow air to flow through the device. This task was also rated as requiring increased volitional effort versus a normal discrete swallow by participants, however not as much effort as the Mendelsohn maneuver. Here the cognitive effort and motor plan includes components from multiple muscle groups and across functional systems, including the respiratory, laryngeal, and articulatory subsystems.
The mechanism used in the current study to quantify the components of the motor movements associated with each experimental task was to identify a structure involved in a salient part of the skill, such as the hyoid bone, and make measurements on its movement and muscle activity. The measures which were of interest in the present study suggested that discrete differences do exist between each task both in terms of the trajectory of hyoid bone motion and the activation of submental muscles important for actual movement of the hyoid bone. These findings lend support to the hypothesis that each of the swallow-specific tasks and the EMST task examined in the present study may be well suited to induce neuroplastic changes within the cortex, as the motor plans generated with each is unique with regard to at least one element of trajectory or sEMG activity. While many components of the motor plans for Mendelsohn maneuver and effortful swallow are not different from that of a normal swallow, the added volitional component and modification of the overall motor skill duration, along with modification of trajectory and muscle activity pattern (e.g., increased angle of hyoid elevation for the Mendelsohn maneuver and increased submental sEMG activity evident in both tasks versus the normal swallow task), indicate that mechanisms coordinating and driving the motor plan at the central level are somehow modified from the initial swallow referent plan.

**Motor Skill Acquisition**

Motor skill acquisition occurs and has enduring effects on the motor cortex due to neuroplastic mechanisms that, within the past 30 years, have become better understood. Various theories on motor skill development have been put forth, both with regard to human infant development as well as adult motor learning (Bernstein, 1967; Dale, 2003; Feldman et al., 1995; Gottlieb, 1998; Levin, Lamarre, & Feldman, 1995; Spencer &
Thelen, 1999; Thelen, 1995). As well, animal studies and advances in neuroimaging techniques have made it possible to study the neurobiologic mechanisms (e.g., synapse formation, dendritic arborization, etc.) by which learning occurs and is consolidated into new motor skills (Doyon & Benali, 2005; Kleim et al., 2002; Kleim et al., 2004; Monfils et al., 2005). According to the dynamic systems theory new forms of movement emerge from cooperative interactions of multiple components within a functional context (Bernstein, 1967). As perturbations occur which necessitate changes in the motor pattern, the new versions of the pattern may replace the previous preferred version (Bernstein, 1967; Thelen & Ulrich, 1991). “Perturbations” in this context may be positive or negative in nature. For example, a motor pattern change may stem from consolidation of learning a particular skill, whereby the overall pattern becomes less variable and more efficient over time and repetitions (Feldman et al., 1995; Kleim et al., 2004; Thelen, 1995). Conversely, a peripheral muscle weakness may interfere with the desired motor output and thus require changes in the motor pattern which replace previous more effective and efficient motor patterns in order to compensate (Hamdy et al., 1998).

While abstract in nature, the dynamic systems theory is supported by recent advances in neuroscience which have identified empirical neural mechanisms by which task learning occurs. New motor skills have been shown to expand the areas of motor cortex associated with anatomical areas associated with the task, which is thought to be related to enhanced dendritic arborization of pyramidal cells and synaptic formation (Kleim et al., 2002; Kleim et al., 2002; Kleim et al., 2004). These changes correlate with
increased accuracy of the skill, which would represent the idea of more refined versions of the skill replacing the old referent as part of the dynamic systems theory.

The representational area of a structure/function in the motor cortex is continuously changing in response to behavior and skill acquisition (Chen, Zhang, Schwarzschild, Hernan, & Ascherio, 2005; Chen, Cohen, & Hallett, 2002; Remple, Bruneau, VandenBerg, Goertzen, & Kleim, 2001). Research studies which have focused on the cortical representation of the limbs contain evidence regarding the plasticity of cortical representation following nerve block, deafferentation, or amputation (Chen et al., 2002; Hamdy et al., 1998; Jones et al., 1996; Kleim, Jones, & Schallert, 2003; Mano, Chuma, & Watanabe, 2003). Specifically, it has been demonstrated that when there is a change in anatomy, decreased sensation to an area, or neurologic damage, cortical representation of that area changes in as little as a few minutes (after nerve block) through up to six months (after amputation) (Mano et al., 2003). With regard to swallowing, studies involving patients with unilateral hemispheric strokes with dysphagia show the total area of cortical representation of the pharyngeal musculature initially decreased in both the affected and unaffected hemisphere (Hamdy et al., 1998). With recovery, the cortical representation in the unaffected hemisphere was reorganized, resulting in the observed recovery of function according to the authors’ hypotheses (Hamdy et al., 1998). As well, it has been demonstrated in healthy adult subjects that after only 30 minutes of pharyngeal sensory stimulation, pharyngeal representation in the motor cortex increased, indicating cross-system changes between the sensory and motor cortices (Hamdy et al., 1998). These findings of cortical reorganization represent cortical plasticity in the adult central nervous system, both in health and disease. In healthy individuals specifically, representational
change appears to depend on task skill and novelty. However, in patients who had
experienced unilateral hemispheric stroke, Hamdy et al. (1998) noted cortical
reorganization associated with functional recovery in response to a previously familiar
task (e.g., swallowing). Under the constructs of the dynamic systems model, the
neurologic injury may be thought of as a systemic perturbation, and recovery as an
adaptational process, with continued refinement of the motor plan via reorganization of
the non-affected hemisphere in order to account for the perturbation.

The implications with regard to the present study are that each of the tasks is suited
at the definitional level to induce neuroplastic mechanisms which may lead to an
expansion in the representation or decrease the threshold properties of cortex governing
descending motor drive to the submental musculature. Specifically, the Mendelsohn
maneuver includes a desirable combination of increased cognitive loading, differential
effect on angle of hyoid movement, and distinct pattern of submental sEMG activation
associated with hyoid movement which indicate this is a novel skilled task that still
includes an actual swallow which may be best suited among the experimental task to
induce cortico-modulatory and eventual plastic changes associated with skill learning
(Kleim et al., 2002; Monfils et al., 2005; Powers & Howley, 2004). Based on known
neuroplastic mechanisms which exist in the adult motor cortex (Chen et al., 2002; Doyon
& Benali, 2005; Hamdy et al., 1998), it may reasonable to conclude that the ability of this
task to treat dysphagia resulting from perturbations in peripheral structures (e.g., radiation
and surgery for head and neck cancer) stem from its ability to enhance the cortical motor
plan with increased representational area and subsequent drive to peripheral nerves
projecting to the submental muscles in a manner that may result in better timing and
coordination of the physiologic mechanisms necessary for a safe swallow to occur (Figure 10). Additionally, both the Mendelsohn maneuver and effortful swallow, because they include an actual swallow, may serve to refine motor plans and patterns associated with swallowing disorders resulting from neurologic pathology according to the dynamic systems model.

![Figure 10. Schematic representing the paradigm for motor skill development for the Mendelsohn maneuver leading to a motor output pattern affecting the primary mover muscle.](image)

**Task Specificity**

Because the nature of the experimental tasks is different (e.g., “swallow-specific” versus EMST as “swallow non-specific”) it is necessary to discuss the peripheral aspects of each task with regard to the task specificity each possesses related to swallowing. Task specificity is known to be an important component of exercise related to the functional result of an exercise program (see Chapter 1, ‘Review of the Literature.’) As well, rehabilitation of a previously familiar task which has become disordered secondary to neurologic injury may be best induced via task-specific exercises (Hamdy et al., 1998).
Task specificity in the current project was defined according to hyoid movement measures and sEMG relationships.

Measures of maximum hyoid displacement did not differ significantly between the Mendelsohn maneuver, effortful swallow, and normal discrete swallow, however the displacement was less for the EMST task versus the other tasks. It has been previously demonstrated that varying the size of the bolus results in different measures of hyoid displacement (Ertekin et al., 1997; Leonard et al., 2000). In the present study, bolus volume was consistent between tasks (10mL). As such, the lack of displacement differences between the normal swallow, Mendelsohn maneuver, and effortful swallow are not surprising. This suggests that while the contractile and temporal relationships between biomechanical events may be altered by executing the volitional swallow exercise tasks, the resulting displacement of the hyoid bone is preserved. This may be due to anatomic or physiologic constraints such that the hyoid bone is only able to move a given amount, and increasing the force generated by the primary mover muscles is not going to increase movement, at least not in an already healthy swallow.

However, the angle of hyoid displacement was significantly higher for the Mendelsohn maneuver versus and normal swallow. While it did not achieve statistical significance, the angle of hyoid displacement was also generally higher for effortful swallow and the EMST task versus normal swallow as well (see Figure 7 in ‘Results’). This indicates that the hyoid bone was achieving a larger vertical component to its movement with the experimental tasks relative to normal discrete swallows. It has been reported that the angle of elevation during a normal discrete swallowing task remains constant within and between individuals, indicating that a specific amount of elevation
relative to the hyoid starting point at onset of pharyngeal swallow is associated with a healthy swallow (Wheeler, Martin-Harris, Brodsky, Thekkevalappil, & Sapienza, 2006). As was discussed previously, vertical motion of the hyoid bone is primarily related to oral bolus manipulation, while anterior movement has been associated with the pharyngeal swallow (Ishida et al., 2002). In the present study, the measures of hyoid motion for the swallow tasks were made at the onset of bolus posterior movement in the oral cavity such that there was not extraneous movement of the hyoid bone associated with oral bolus manipulation at that point in the swallow (this movement had already occurred). As such, the specific increase in vertical hyoid motion in these cases is associated with pharyngeal swallow. Therefore, each of the Mendelsohn maneuver, effortful swallow, and EMST task may play a role in improving the overall range of motion of the hyoid bone (e.g., enhancing the vertical component of hyoid motion) and contribute to improvement in airway protective mechanisms associated with the ability to first raise the hyolaryngeal complex and then tuck it forward.

Additionally, it was found that the submental sEMG activity associated with the onset of hyoid movement (HstartEMG) and the point of maximum hyoid displacement (HmaxEMG) was greatest for the effortful swallow, followed by the Mendelsohn maneuver and lastly the normal swallow and EMST task (which were not significantly different from each other, see Table 3). This indicates that the timing relationship between hyoid movement and submental muscle activity changes between tasks such that with the Mendelsohn maneuver and effortful swallow, activity levels are greater at task onset and maintained to the point of maximum hyoid displacement versus the levels exhibited by the normal swallow and EMST task (Figure 11). This finding is further
substantiated by previous reports of pre-task initiation hyoid elevation, which would logically be associated with increased submental sEMG activation at task initiation, for both the Mendelsohn maneuver and effortful swallow (Bulow et al., 1999; Hind et al., 2001; Huckabee et al., 2005). The absolute maximum sEMG (max EMG) with the EMST task was not significantly different from the effortful swallow or Mendelsohn maneuver, with all three being significantly greater than the normal discrete swallow.

More in-depth study of the relationships between hyoid movement and submental activation was achieved by examining the temporal relationships between the times of maximum sEMG amplitude (Tmax EMG), maximum hyoid displacement (T1), and maximum hyoid angle of elevation (T2). It was found that these measures were also different between the swallow tasks (for a summary of these relationships, refer to Figure 11). With the normal swallow task, the sequence generally occurred with Tmax EMG first, followed by T2 and then T1. Each had high positive correlations, suggesting that they maintained the integrity of that relationship in time such that if Tmax EMG occurred later in the task, so did T2 and T1, respectively. With the Mendelsohn maneuver, T1 occurred closely in time with the time of maximum Tmax EMG, while T2 occurred later in the task than T1 or Tmax EMG. With the effortful swallow, T1 occurred later than T2 or Tmax EMG, which were not significantly different in their time of occurrence according to paired samples t tests. Similar to the normal swallow, however, these relationships were maintained with significant positive correlations between the measures, indicating that as the time of each within the task increased so did the times of the other two (see Figure 11).
Findings related to the EMST task indicated a difference in hyoid trajectory such that the maximum displacement achieved by the hyoid bone was significantly less than each of the swallow tasks. In fact, both the maximum displacement (D1) and the displacement associated with maximum angle (D2) were significantly less in the EMST task. Reviewing the patterns of motion exhibited under fluoroscopy of participants performing the EMST task subjectively confirms these statistical findings: the hyoid bone moved superiorly as the participant initiated expiratory airflow while using the device, and returned to a rest position at task completion, a movement pattern that was not observed to contain an anterior component (Figure 12). The superior movement accounts for the increased angle of elevation compared to the normal swallow task, and the lack of anterior movement explains the significantly smaller displacements. As well, the temporal relationships between hyoid movement and submental EMG were different than those associated with a normal swallow task. They were not significantly different between Tmax EMG, T1 or T2 according to paired samples t tests; significant positive correlations existed between all three measures. This indicates that as one measure occurs later during the task, the other two do as well. These findings suggest that while these events occur in a given time interval within the EMST task they do not necessarily occur in a particular order. This is in contrast to the normal swallow, effortful swallow, and Mendelsohn maneuver, where the timings of each occurred in a specific order whose temporal relationship was maintained within the task, suggesting physiologic interdependence of those events.
Figure 11. Schematic representing the temporal relationships between sEMG and hyoid movement for each of the experimental tasks. Dashes (-) represent non-significant differences between the measures, arrows represent significant differences between the measures, boxes around the measures indicate significant positive correlations. Note: TmaxEMG = time of maximum sEMG amplitude, T1 = time of maximum displacement, T2 = time of maximum hyoid angle, A2 = maximum hyoid angle.

The findings of physiologic interdependence within swallow tasks are in agreement with findings reported in the literature whereby multiple events, including laryngeal vestibule closing, bolus propulsion into the pharynx, vocal fold closure, UES opening, bolus flow through the UES, and others, occur in clusters that are sequentially occurring such that the successful completion of one set of events enables the next set to occur safely (e.g., preventing aspiration) (Dodds et al., 1990; Donner, 1985; Ekberg, 1986 A; Gay et al., 1994; Logemann et al., 2000; Martin-Harris et al., 2005; Martin-Harris, Michel, & Castell, 2005). Because the EMST task is not associated with an actual swallow, that specific physiologic interdependence is not present and therefore the temporal relationships between hyoid motion and sEMG activity is different. This is not
to suggest a lack of relationship between the variables, in fact there are moderate to strong positive correlations between Tmax EMG, T1, and T2 for the EMST task. It simply means the nature of the relationship is different, and that EMST lacks the task specificity that both the Mendelsohn Maneuver and the effortful swallow inherently possess.

More specifically, preservation of the sEMG-hyoid relationship and maximum hyoid displacement and angle measures indicates that with regard to task specificity the effortful swallow is the most task-specific. This is due predominately to the ability of the effortful swallow to maintain the temporal relationships between maximum submental sEMG activation and hyoid movement such that Tmax EMG and T2 occurred earlier within the task than did T1. The underlying physiology which can be interpreted suggests that upon swallow initiation, the submental muscles contract in a manner that is greater than a normal swallow (HstartEMG) which pulls the hyoid with more force to a higher A2 (at T2), and then anteriorly, leading to the maximum displacement. This is in line with previous investigations identifying the submental muscles as part of the “leading complex” resulting in the important airway protective mechanism associated with hyoid excursion necessary for a safe swallow (Cook et al., 1989; Dodds et al., 1990; Doty & Bosma, 1956; Ekberg, 1986A).

If not for attaining the swallow-skill components the Mendelsohn maneuver possesses, nor the task specificity that the effortful swallow possesses, then why and how is EMST having an effect on the swallow mechanism, as is being actively demonstrated by an ongoing project examining the effects of EMST on, among other outcome variables, the swallow? Three distinct mechanisms present themselves hypothetically:
First, EMST affects the overall central and peripheral drive to submental and other suprahyoid muscles; second, EMST increases sensory stimulation to stretch and mechano receptors in the larynx, hypo- and oropharynx; and third, EMST effects on the systems via increased physiologic loading (discussed in next section). Support for the first mechanism was initially established by Wheeler and colleagues (submitted) in a study that demonstrated significantly higher peak and average submental muscle activation achieved during the EMST task versus a normal swallow task (Wheeler, Chiara, & Sapienza, submitted). Results from the present study are congruent with those results, indicating higher maximum and average submental sEMG activity during the EMST task versus normal swallowing. This hypothesis is further substantiated based on the simultaneous fluorographic and sEMG data collected in the present study. Specifically, while the overall displacements were decreased during EMST than swallowing, the vertical component of hyoid motion increased as evidenced by increased maximum angle of elevation. Thus, the physiologic correlate for increased submental EMG activation in the case of EMST is vertical hyoid movement. Vertical movement of the hyoid bone occurs secondary to suprahyoid muscle contraction, which may include genioglossus and posterior suprahyoids which consist of the posterior belly of the digastric and stylohyoid muscles, in addition to the submentals (Zemlin, 1998). In particular, the genioglossus is the primary muscle involved with oral bolus propulsion into the pharynx (Dodds et al., 1990). As such, the EMST device may stimulate increased neural drive and recruitment of peripheral nerves to the genioglossus that enhance the speed of muscle contraction and subsequently the swallow at the point of initiation of the pharyngeal stage (i.e., bolus propulsion into the pharynx). From a coordination standpoint, this may pose a problem
specifically for populations where the initiation of hyoid movement is compromised. However, based on evidence from the current study and previous study (Wheeler et al., submitted), suprahyoids responsible for anterior movements (submental muscles) experience enhancement in neural drive and muscle activation which may affect onset and overall hyoid excursion, and thus the airway protection mechanism, leading to a quicker and safer swallow.

The second mechanism by which EMST may have an effect upon the swallow mechanism is related to observations of airway expansion during the blowing portion of the task whereby expiratory effort is increased, thus creating a positive pressure gradient in the upper airways. This may lead to enhanced stimulation to length/tension receptors within the constrictor muscles, as well as sensory mechanoreceptors sensitive to pressure changes within the larynx and upper airway (Kuna & Vanoye, 1999; Mathew, Sant'Ambrogio, Fisher, & Sant'Ambrogio, 1984; Sant'Ambrogio, 1995; Sant'Ambrogio, Mathew, Fisher, & Sant'Ambrogio, 1983). In 100% of participants, airway expansion was observed during the EMST task whereby the lateral diameter of upper airway visually increased (Figure 12). Use of positive upper airway pressure is documented in the sleep apnea literature, whereby continuous positive airway pressure (CPAP) is commonly utilized chronically by that patient population (Beninati & Sanders, 2001; Qureshi & Ballard, 2003; Qureshi & Lee-Chiong, 2005; White, Cates, & Wright, 2002). Sleep apnea is characterized by a collapse of the upper airway during sleep, owing to the inadequate tonic activity of the genioglossus, and secondarily the pharyngeal constrictor muscles, which are each known to be important for maintaining airway patency (Berry & Randall, 2005; Carrera et al., 2004; Collop, 2005; White, 2006). CPAP has not been
found to have an enduring effect on the genioglossus muscle, and in fact removal of CPAP even after six or more weeks of usage has not been shown to result in improved upper airway patency (Guilleminault, Huang, Kirisoglu, & Chan, 2005). Subsequently, it cannot be concluded that the mere presence of positive pressures in the upper airway affect the contractile properties of the genioglossus, or any other muscle group involved in upper airway patency.

Figure 12. Airway expansion and hyoid vertical excursion that occurs during the EMST task. The illustration on the top depicts the system at rest with the EMST device in the oral cavity, the bottom image depicts active blowing through the device.

One difference between CPAP and the EMST device is the volitional components associated with EMST. CPAP is presented during sleep only; the user ideally is not
attending to it. As well, CPAP is a passive treatment (e.g., a CPAP mask is put in place and the user is not breathing against a resistance). EMST requires attention and physiologic resources from the user, which explain task differences that may lead to adaptations in the upper airways not seen with CPAP. Perhaps the expansion of the upper airways enhances sensory feedback to cortical areas controlling genioglossus as well as submentals and pharyngeal constrictor muscles by way of enhanced sensitivity of certain mechanoreceptors to the increased pressure, or stretch and tension receptors within muscles sensitive to the change in the length-tension relationship between sarcomeres. It is plausible that this sensory integration combined with increased motor activation demonstrated within the submental muscle group is capable of decreasing the sensorimotor threshold for contraction of the genioglossus and constrictor muscles (Figure 13). Support for this hypothesis comes from the Hamdy group, where reports of expansion of the cortical motor map of the pharyngeal constrictor muscles occurring after sensory stimulation of the pharynx (Hamdy, Aziz, Rothwell, Hobson, & Thompson, 1998). Thus, the effects of the stimulation crossed sensory-motor cortical areas, and ultimately facilitated functional swallow improvement.
The Principle of Overload

With regard to the principle of overload, findings indicate that the normal swallow exhibited significantly smaller average and maximum sEMG measures than the Mendelsohn Maneuver, effortful swallow, or EMST task. These findings are congruent with prior studies, which have demonstrated each of the latter three tasks are associated with sEMG recordings from the submental muscles that are at least 1.5 times greater than activation acquired during a normal swallow (Ding et al., 2002; Hind et al., 2001; Huckabee et al., 2005; Wheeler et al., submitted). These findings confirm the principle of overload for each of these tasks; these muscles are being taxed beyond the capacity with which they would normally respond in order to successfully perform the exercise tasks. However, the nature of the load (e.g., cognitive versus physiologic, or both) for the tasks differs and discussion here is warranted. With the Mendelsohn Maneuver and effortful swallow, the load imposed is volitional. That is, the submental muscle activity found to increase on sEMG results from the intention of the participant to “squeeze”
those muscles, or to “swallow hard.” A respiratory equivalent to that may be to instruct participants to blow out forcefully, which has been shown to be ineffective as a therapeutic mechanism with regard to voice and cough parameters (Ramig, Countryman, Thompson, & Horii, 1995). This is not to suggest the Mendelsohn maneuver or effortful swallow is ineffective, just that the nature of their effectiveness may not have as much to do with the load they impose as with the neuroplastic and task-specific properties they possess.

Conversely, the load imposed by EMST results from an externally imposed threshold which must be overcome in order to break the spring loaded valve and allow air to flow through the device. This is the third manner in which EMST may affect the swallow mechanism. While the original targets of the EMST load were the expiratory musculature (Fitsimones, Davenport, & Sapienza, 2004; Kim, 2006; Sapienza et al., 2002; Sapienza et al., 2001), results of this study confirm cross-systems effects of that loading to the upper airways. Literature describing myogenic changes to exercise, including hypertrophy and distribution of muscle fiber types, is dependent upon introduction of a physiologic load that is based on a percentage of that muscle or muscle group’s existing maximum force generation capabilities (Kamen, 2004; Powers & Howley, 2004). This percentage is typically between 60 – 80% of the measured maximum capacity and it is here that strength gains associated with muscle hypertrophy or change in muscle fiber type have been shown to readily occur (Powers & Howley, 2004). While the load imposed by EMST is based on measures of maximum expiratory pressures, and not measures of maximum output of upper airway muscles, there is a coupling of the lower and upper respiratory tract that occurs with the abducted vocal
folds. It is likely that because anatomically the lower airways and supralaryngeal pathways are a continuous system during this exercise, there is an external load imposed on the supralaryngeal muscles, including the submental group and possibly other suprahyoid muscles, although their involvement is inferred and cannot be confirmed as a result of the present study. Therefore EMST would be the task which has the best potential to induce strength gains secondary to the externally imposed load that is based on a percentage of an individual's maximum output.

**Application to Swallowing Disorders**

Salient symptoms of oropharyngeal dysphagia may include aspiration or penetration of bolus material in the airway, or bolus residue in the hypopharynx after a swallow. Multiple pathophysiologic mechanisms can lead to the observed symptoms, including stroke, degenerative neurologic or neuromuscular disease, respiratory disease, or cancer in the head and neck (Bartolome & Neumann, 1993; Good-Fratturelli, Curlee, & Holle, 2000; Hadjikoutis, Pickersgill, Dawson, & Wiles, 2000; Horner, Buoyer, Alberts, & Helms, 1991; Logemann & Bytell, 1979; Logemann & Kahrilas, 1990; Sellars et al., 1999). When dysphagic symptoms result from decreases in the amplitude or timing of hyoid movement underlying causes can include muscle weakness, problems with generation, initiation, and execution of a motor plan at the central or peripheral level, or anatomical pathology. Coordination of swallow-respiratory timings and maintaining swallow-related apnea is also very important for swallow safety (Lazarus et al., 2000; Leslie, Drinnan, Ford, & Wilson, 2002; Logemann & Bytell, 1979; Martin-Harris et al., 2005; Martin-Harris et al., 2003; Pauloski et al., 2002).

Each experimental task was shown to possess differential components with regard to skill, specificity, and overload. Therefore, over time and with appropriate repetition
and intensity, each would be theoretically capable of inducing changes at the level of the motor cortex, peripheral nerves, or muscle. Cortically, plasticity is important with regard to reorganization of functional motor areas following stroke within certain vascular distribution, following decreased sensation or anatomical changes to the oropharynx (i.e., following radiation therapy or surgery for cancer), or as a neuroprotective purpose, slowing the progression of degenerative diseases (Chen et al., 2005; Chen et al., 2002; Hamdy et al., 1998; Kleim et al., 2003; Mano et al., 2003). It is known that the principles of overload and specificity are important with regard to strength and functional adaptations occurring with exercise in both healthy and diseased populations (Chen et al., 2005; Lieber, 2002; Powers & Howley, 2004). As such, the study results provide insight into therapeutic exercise tasks which are theoretically able to induce neural, myogenic, and ultimately functional adaptations required to treat some kinds of dysphagia. With this knowledge in hand, it is now of interest to discuss each as they may be appropriate as a rehabilitative mechanism for different dysphagic symptoms.

**Mendelsohn Maneuver**

Cognitively, the Mendelsohn maneuver appears to require the most resources and also results in a movement pattern which is different from the normal discrete swallow, while still including an actual swallow within the task. Therefore, while the Mendelsohn is not the most task-specific, nor is it the best with regard to the principle of overload, it may be the best suited as a novel swallow-skill task to lead to changes in cortical motor representation and sensorimotor threshold adaptations. These adaptations may be desirable following surgical and/or radiation treatment for head and neck cancer, or possibly with certain peripheral degenerative diseases, where functional decreases in swallow function stem from peripheral rather than central changes. This distinction is
important because with peripheral pathology the health of the cortex is presumably maintained. In order to induce neuroplastic changes related to functional outcome in the healthy cortex, a novel skilled task would be required (Kleim et al., 2002; Monfils et al., 2005).

When the dysphagic symptoms accompanying the pathology include delay or slowness in swallow initiation, inability to maintain swallow-related apnea and airway protection, or decreased time of UES opening with subsequent pharyngeal residue post-swallow, the Mendelsohn maneuver may be of particular applicability. The Mendelsohn maneuver has been shown in a small number of studies to increase UES opening time, thus allowing more bolus material to flow into the esophagus and reducing pharyngeal residue (Lazarus et al., 1993; Lazarus et al., 2002; Lazarus et al., 1996; Logemann, 1999). Because a goal of the maneuver is to maintain hyoid elevation and laryngeal vestibule closure, enhancement of airway protection occurs due to prolonged airway closure, if done correctly. As well, increased submental sEMG activity indicates increased descending neural drive to those muscles, which would also increase sensory feedback pathways sending information regarding the length-tension status of the muscles. Subsequently, functional improvement in the coordination of swallow initiation, swallow-related apnea and UES opening during the swallow may result directly from decreases in the motor response thresholds, resulting in a faster triggering of a swallow; or changes in the functional cortical motor representational area, resulting in increased central drive descending on the brainstem, and finally increased drive to the cranial nerves and ultimately the peripheral swallow mechanism (see Figure 10). Additionally, enhancement of sensory feedback from the primary mover muscles involved may also
occur as a result of changing contractile parameters resulting from the increased central neural drive mechanism.

To reiterate, the Mendelsohn maneuver did impose the largest cognitive load on participants, and in fact 25% of the healthy subjects involved in this study could not accurately perform the maneuver after a brief period of practice, even with sEMG biofeedback to assist with task learning. Conversely, some participants who appeared to successfully execute the task by sEMG criteria (see methods section) were actually not performing it correctly upon visual inspection on videofluoroscopy (Figure 14). Many of those participants indicated that seeing themselves performing the maneuver on the computer screen during fluoroscopy then helped them correctly perform the task. This may be of use clinically both for teaching patients to do the task successfully, and for ensuring the clinician is confident the task is being done correctly. Over time with additional practice, it is possible that the participants unsuccessful in the task would have been able to learn to correctly perform the maneuver; however this should be a consideration in treatment. Those patients who are not cognitively intact are not good candidates for this particular therapeutic exercise.
Figure 14. Example of the correct execution of the Mendelsohn maneuver (top image), with the laryngeal vestibule closed completely for the duration of the task, and incorrect performance (bottom image) with hyoid elevated, but with the laryngeal vestibule opened before task termination. Both were considered “correct” per sEMG criteria.

**Effortful Swallow**

This study has shown the effortful swallow to be a task-specific mechanism associated with increased activity level in the submental muscles. While the healthy adult cortex requires a degree of novelty in a skilled task in order to induce neuroplastic mechanisms, neuroplasticity underlying functional recovery of the swallow in an unhealthy adult cortex appears to depend more on the task-specific experience (Hamdy et al., 2001). Subsequently, the effortful swallow would be well suited to rehabilitate the swallow in a patient with stroke, or possibly with neurodegenerative disease via neuroprotective mechanisms. The observed increase in sEMG activity seen with the effortful swallow is dependent upon volitional loading which would target both
Peripheral and central drive mechanisms to the submental muscles. Peripherally by way of increased or better coordinated motor unit recruitment or rate of cranial nerve discharge, and centrally the areas of cortex functionally organized to drive the swallow motor plan may experience increased stimulation due to the volitional component of the task. Additionally, increased sensory feedback following motor output to the muscle would be integrated both within the brainstem medulla and primary cortical sensory area, perhaps leading to decreased threshold level necessary to trigger the initiation of a swallow (Figure 15). Consequently, better central and peripheral motor drive and coordination of the motor plan may result, possibly leading to enduring functional improvement in the swallow, or neuroprotective mechanisms which may slow the progression of swallow-related problems of neurodegenerative disease.

Problems that may result from stroke or with some neurodegenerative diseases include achievement of adequate amplitude of hyoid movement needed both for airway protection and UES opening, discoordination between muscle activation and bolus location within the pharynx, or discoordination between breathing and swallowing (Groher, 1997; Logemann, 1998). Given the above mentioned mechanisms, functional improvements that may be targeted with the effortful swallow include a more timely initiation of movement and better coordination of that movement with other swallow events. Therefore, the task may lead to enduring functional swallow improvement via neuroplastic reorganization of cortical areas functionally related to swallow, while assisting with swallow safety in the interim. Additionally, the effortful swallow task appears to be cognitively less demanding than the Mendelsohn, and thereby may be a good option for patients who are less cognitively intact.
EMST

From an “overload” perspective the EMST task is best suited to lead to peripheral neural or myogenic adaptations which may be of interest for certain dysphagic symptoms. In symptoms resulting from pure muscle weakness, as may be present after disuse (e.g., prolonged NPO status), or as part of a degenerative neuromuscular or neurogenic disease process, rehabilitation with EMST should provide mechanisms by which the strength of the muscle group is improved or maintained (slowing the progression of that disease symptom). Symptoms resulting from submental muscle weakness specifically include delayed or decreased hyoid excursion (Clark, 2003; Ishida et al., 2002; Kendall & Leonard, 2001; Lazarus et al., 1996; Neumann, 1993; Zuydam et al., 2000). According to the results of the present study, the EMST device would be a good option to treat this particular symptom, as it imposes a high physiological load, thus
increasing muscle activation necessary to make strength improvements required for a functionally safer swallowing (see Figure 13).

In patients where dysphagic symptoms lead to swallowing unsafe to the point of heavily restricted per oral intake, and where therapy including a swallow (e.g., swallow-specific therapies) is not safe, it is desirable to have an alternative treatment which is safe while still maintaining the potential to improve the ability to swallow. In addition to the increased load on the submental muscles, and possibly additional suprahypoid muscles, other mechanistic pathways by which EMST targets swallowing include decreases in central sensorimotor thresholds required to elicit motor output from those muscles stemming from stimulation of motor cortex during the task (Hamdy et al., 1998), and sensory feedback resulting from positive upper airway pressure experience during the task (see Figure 13) (Sant'Ambrogio et al., 1983). As such, in the patient where swallow-specific therapies are not appropriate, there are multiple mechanisms by which the EMST task may improve the swallow. By utilizing the EMST task as a primer for a swallow-specific therapy the patient may be able achieve functional gains, first by improving strength and coordination of the swallow mechanism with loading and sensorimotor stimulation, and then initiating task-specific exercises to begin to refine that swallow motor plan.

With regard to the cognitive requirements for the EMST task, study participants indicated only a small amount of volitional effort needed to perform the task. However, clinicians providing ESMT treatment to patients with neurodegenerative diseases have noted that some patients do have trouble with motor coordination for the task (e.g., putting device into the mouth, lip seal, coordinating inspiratory/expiratory patterns).
Accordingly, caution should be used when using the EMST treatment with regard to the patient’s cognitive status.

**Summary and Conclusions**

In conclusion, each of the experimental tasks examined in this study, including the Mendelson maneuver, effortful swallow, and EMST task, was found to be discretely different from each other as well from the normal swallow in terms of at least one of the trajectory or sEMG measures made. As well, each experimental task was demonstrated to possess unique properties with regard to task skill, specificity, and overload. Specifically, the Mendelsohn maneuver included timing relationships between hyoid movement and sEMG measures that were distinctive for that task only, and was reported by study participants to the most effortful with regard to cognitive requirements. Thus, the Mendelsohn maneuver is thought to possess the highest degree of novel skill. The effortful swallow was found to be the most task-specific to a normal swallow, and was characterized by significantly higher peak sEMG amplitudes, indicating an increase in the neural drive to the submental muscles. Lastly, the EMST task was shown to expose the upper airway, specifically the submental muscle group, to an external physiologic load. The differing strengths of each task with regard to skill, specificity, and overload is indicative of the potential to treat certain dysphagic symptoms, taking into account cognitive status as well as the current status of swallow safety. Therefore, clinicians must carefully profile the individual patient’s physiologic status as well as the dysphagic symptom, and it may be that combinations of the experimental tasks may ultimately prove to be best option, instead of focusing purely on one or another.

The outcomes from this study help to direct future research towards several paths because the data suggests that the observed peripheral changes in pattern and muscle
activity that occurred may be mechanistically distinct. Studying the underlying
neuroplastic mechanisms that are likely to occur following task learning of the
Mendelsohn maneuver (a novel skill task) and EMST (a non-swallow specific task) in
healthy individuals would be of interest. This would lend good insight to the ability of
the healthy adult cortex to adapt to these tasks, and may provide new insight into the
treatment of non-neurologically impaired dysphagic patients (e.g., patients with cancer or
other peripheral injury). Second, study directed specifically at patient populations with
dysphagia in order to further examine functional, neural, and myogenic changes which
may occur with each (or a combination) of the study tasks in order to establish
effectiveness and efficacy data.
APPENDIX A
HEALTH HISTORY QUESTIONNAIRE

Age: ___ ___ ___  Gender (M/F): ___

Have you ever had significant difficulty swallowing? (Y/N): ___

Have you ever been told you had dysphagia (a swallowing disorder)? (Y/N): ___

Have you ever been diagnosed with cancer of the head or neck? (Y/N): ___

Have you ever been diagnosed with any neurologic disease (e.g., Parkinson’s, Huntington’s, or ALS)? (Y/N): ___

Have you ever been diagnosed with a respiratory disease (e.g., asthma, chronic obstructive pulmonary disease or COPD, emphysema)? (Y/N): ___

Have you ever been diagnosed with a heart condition or heart disease? (Y/N): ___

Have you ever been diagnosed with hypertension? (Y/N): ___.
If yes, are you currently taking medication to control this? (Y/N): ___

Have you ever had a stroke? (Y/N): ___

Are you currently taking Coumadin (warfarin)? (Y/N): ___
APPENDIX B
MEMORY AND EFFORT RATING FORM

1. **Please rate your memory for each task:**

Please rate how well you recall the tasks you performed during participation in this study according to the following scale:

1 = remember the task perfectly (you could do it now)
2 = remember the task very well (you could do it now, but may need practice first)
3 = remember the task (you could do it now with a little coaching)
4 = don’t remember it very well (you would need significant coaching to do it)
5 = don’t remember it at all (you would need to be re-taught in order to do it again.)

Mendelsohn Maneuver:  
1  2  3  4  5

Effortful swallow:  
1  2  3  4  5

Expiratory training task:  
1  2  3  4  5

2. **Please rate how difficult you felt each task was to perform according to the following scale:**

1 = very easy to perform, no effort needed
2 = easy to perform, small amount of effort needed
3 = moderate, some effort needed
4 = difficult
5 = very difficult, most effort needed

Normal swallow:  
1  2  3  4  5

Mendelsohn Maneuver:  
1  2  3  4  5

Effortful swallow:  
1  2  3  4  5
Expiratory training task:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
LIST OF REFERENCES


BIOGRAPHICAL SKETCH

Karen M. Wheeler received both her bachelor’s and master’s degrees from the University of Florida, in 2001 and 2003, respectively. Following completion of her Ph.D., she will begin a position as Assistant Professor at Arizona State University, Department of Speech and Hearing Sciences, in Tempe, Arizona. Her research plans for the future include the study of functional and neural adaptations that occur in patient populations with rehabilitation for dysphagia. Her interests outside of academics include running, hiking, Gator football, and live music.