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Improvements resulting from respiratory-swallow phase training visualized in patient-specific computational analysis of swallowing mechanics

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Abstract

The aim of this study was to visualize improved swallowing mechanics resulting from respiratory-swallow phase training using patient specific computational analysis of Modified Barium Swallow (MBS) videofluoroscopic images. Imaging from a single subject showing improved MBSImP™ scores in 17 of 18 pre- to post-treatment swallows was selected for analysis. Using a semi-automated MATLAB tracker tool, a frame-by-frame annotation of 10 coordinates mapping muscle functional groups was performed during oropharyngeal swallowing. Computational analysis of coordinate shape change was executed using MorphoJ software to determine differences in swallowing mechanics associated with multiple independent variables. Canonical variant analysis indicated significant differences in mechanics associated with respiratory-swallow phase training ($D=1.92, p<.0001$). Vectors allowed for visualization of changes in swallowing mechanics associated with respiratory-swallow phase training. A regression of shape associated with laryngeal vestibular closure on respiratory-swallow phase training was highly significant ($p<.0001$) and accounted for 94.1% of the variance.

Keywords

Deglutition; swallowing mechanics; computational analysis; patient specific; videofluoroscopy; respiratory-swallow training

1. Introduction

The pharyngeal phase of swallowing is a complex biomechanical process that converts a respiratory channel into a swallowing conduit in less than 500 milliseconds. Changes in

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neuromusculoskeletal mechanics can lead to swallowing impairment. The standard diagnostic imaging for dysphagia is a 30 frames per second Modified Barium Swallow (MBS) (Jaffer et al. 2015). This videofluoroscopic imaging captures a patient swallowing barium infused boluses, allowing for visualization of oropharyngeal structures in motion. Various methods have been developed to characterize swallowing impairment using MBS (Kendall et al. 2000; Leonard et al. 2000; Logemann et al. 1989; Pearson et al. 2013; Rosenbek et al. 1996). The Modified Barium Swallowing Impairment Profile (MBSImP™) measures an array of physiological components of swallowing providing a numeric characterization of swallowing difficulty (Martin-Harris et al. 2008; Martin-Harris and Jones 2008). Computational analysis of swallowing mechanics (CASM) is a recent development allowing for a visualization of covariant swallowing mechanics of oropharyngeal swallowing in reference to any known categorical variable including MBSImP™ component scores (Pearson and Zumwalt 2014). In the present study, a patient specific computational analysis of pre- and post-treatment swallowing is used to visualize swallowing mechanics of oropharyngeal swallowing resulting from respiratory-swallow phase training, a new swallowing treatment under current investigation, and to determine if these changes are predictive of improvements indicated by MBSImP™ component scores (Martin-Harris et al. 2015).

1.1 Anatomy and physiology of oropharyngeal swallowing

The hypopharynx lies at the intersection of the upper respiratory and digestive tract and connects the oral cavity, nasal cavity, larynx, and esophagus. Oropharyngeal swallowing involves the conversion of a respiratory conduit into a digestive channel by closing and opening the appropriate portals to the hypopharynx. The hypopharynx, in contrast to the epipharynx, is the portion of the pharynx below the soft palate relevant to both respiration and digestion.

During oral transport, the genioglossus and intrinsic tongue muscles move the bolus from the anterior oral cavity into the hypopharynx as the levator veli palatini seals off the nasopharynx. The styloglossus, hyoglossus and intrinsic tongue muscles retract the tongue base to propel the bolus into the hypopharynx and effectively seal off the oral cavity.

As the bolus enters the hypopharynx, the rapid elevation of the hyolaryngeal complex marks the onset of the pharyngeal phase of swallowing. The suprahyoid muscles (mylohyoid, geniohyoid, stylohyoid and digastric) displace the hyoid anterosuperiorly, translating force through the thyrohyoid membrane and muscle to assist in elevating the larynx. The stylopharyngeus, attached to the posterior thyroid cartilage, further facilitates laryngeal elevation. The palatopharyngeus and salpingopharyngeus work together to shorten the pharynx and to elevate the larynx (Figure 1). The suprahyoid muscles and the long pharyngeal muscles (stylopharyngeus, palatopharyngeus, and salpingopharyngeus) all displace the hyolaryngeal complex comprised of hyoid bone, larynx, and associated structures, including the trachea and cricopharyngeus muscle that forms the upper esophageal sphincter. The net movement of the hyolaryngeal complex displaces the laryngeal inlet of the upper airway from the trajectory of an oncoming bolus contemporaneous with laryngeal vestibular closure resulting from approximation of the

arytenoid cartilages to the petiole of the epiglottis and epiglottic inversion (Logemann et al. 1992). Vocal fold adduction is the final mechanism to protect the airway. Prior to laryngeal elevation and pharyngeal shortening and associated pharyngoesophageal segment (PES) opening, the cricopharyngeus muscle relaxes and further facilitates PES opening. After the bolus enters the PES, pharyngeal constrictors clear the remaining bolus through the PES thus completing the pharyngeal phase of swallowing.

1.2 Respiratory-Swallowing Training

A novel respiratory-swallow phase training protocol has been shown to reduce health risks such as aspiration in chronic dysphagic patients by optimizing respiration-swallowing patterns. This training is a non-traditional effort to treat chronic dysphagic patients, as these patients are nonresponsive to traditional therapies that focus on strengthening the muscle groups in the head and neck. Since respiration and swallowing share a common anatomical space, the coordinated sequence of swallowing and respiration is essential to swallowing and breathing safety. The typical respiratory pattern in 67–79% of normal, healthy adults during liquid swallows consist of an exhale-swallow-exhale pattern (Matsuo and Palmer 2009). However, in dysphagic patients, this pattern is disordered and swallowing is often initiated during inspiration – yielding in greater risk of swallowing impairment and aspiration (Martin-Harris et al. 2015). Respiratory training retrains patients to “initiate swallows during mid-expiratory phase of quiet breathing at mid to low lung volume and to [continue to] expire after swallowing” (Martin-Harris et al. 2015). Initiating swallowing using the optimal pattern appears to protect the airway and facilitate several physiologic advantages such as hyolaryngeal movement (Martin-Harris et al. 2015). In preliminary studies, this optimal respiration-swallowing pattern resulted in improved MBSImPTM component scores; particularly in laryngeal vestibular closure (LVC), tongue base retraction (TBR) and pharyngeal residue (PR). However, the covariant mechanics of swallowing associated with these improvements have not been documented and are challenging to visualize in an individual patient using these scores alone.

1.3 Patient Specific Computational Analysis of Swallowing Mechanics

CASM is a multivariate analysis of covariant shape change of 2D coordinates captured from dynamic lateral view MBS imaging. Shape change analysis of coordinates mapping functional muscle groups underlying oropharyngeal swallowing allows swallowing mechanics to be associated with any identified variables of interest (Thompson ZT et al. 2014). A newly developed semi-automated MATLAB tracker tool by Natarajan and colleagues efficiently collects coordinates from every frame of an MBS, providing sufficient data to determine shape changes associated with independent and outcome variables within a single subject (Natarajan et al. 2015). CASM couples these coordinates with independent categorical variables including pre- and post-treatment (time of imaging acquisition), bolus properties, or MBSImPTM component scores to produce statistical analysis of group comparisons and vectors of swallowing improvement associated with variables such as treatment. Furthermore, morphometric regression analysis allows for identification of the independent variables that are predictive of outcome variables of interest. In the present study, we hypothesized that respiratory-swallow phase training results in mechanical

changes that are predictive of improved LVC, TBR, and PR MBSImP™ component scores as determined by a patient specific CASM.

Material and Methods

2.1 Subject

For the present study, the subject who showed the most improved LVC, TBR, and PR MBSImP™ component scores from pre- to post- respiratory-swallow treatment was selected from the cohort of the previously mentioned study (Martin-Harris et al. 2015). The subject selected was a white male who was 78 years old at the time of imaging and three years post chemoradiation treatment for stage II squamous cell carcinoma of the tongue base. This preliminary study was completed under a research protocol approved by the Medical University of South Carolina Institutional Review Board for Human Research. Under this research protocol two trials of nine swallows each including three different bolus viscosities (thin, nectar, honey thick liquid) at three different volumes volume (1 teaspoon/ 5mL, 1 tablespoon/15mL, cup sip) were captured on MBS imaging for a total of 18 video swallows per subject at each time point. Subjects were not given instructions regarding when to swallow during pre-treatment MBS, but were encouraged to use their learned respiratory swallowing pattern during the post-treatment MBS. All personal health information was removed from the MBS imaging at Medical University of South Carolina and imaging analysis was conducted at Georgia Regents University with ethics approval from both institutions.

For the selected subject, 17 of the 18 paired pre-post training videos showed improvement. Of these videos four of the pairs were excluded due to poor collimation from obscured visualization of key anatomical swallowing structures. The remaining 13 pairs of pre-post treatment MBS video clips were trimmed to include the oral transport and pharyngeal phase. Boluses that required several swallows were trimmed to include only the first complete cycle of the oral transport and pharyngeal phase. Oral transport was marked from the frame where the bolus moved from the anterior oral cavity toward the hypopharynx and ended at the initiation of the pharyngeal phase. The onset pharyngeal phase was marked by the rapid elevation of the hyoid and concluded with the closing of the PES.

2.2 MBS impairment profile component scores

MBSImP™ component scores for LVC, TBR, and PR were determined in the previous study as reported in Martin-Harris et al 2015. The MBSImP™ categorizes swallowing into 3 domains that are subdivided into a total of 17 components, each defining a key element of swallowing. Each component is associated with 3–5 scores beginning with 0, defined as normal. In this study, three sets of component scores were analyzed due to the greatest improvement recorded.

2.3 Coordinate mapping

A medical student (TT) who met reliability criterion for coordinate mapping with an inter-rater $r > .95$ (compared to a head and neck anatomist [WP]) for all coordinates using training videos recorded coordinate data using a semi-automated MATLAB (www.mathworks.com)

tracker tool (Natarajan et al. 2015). Coordinates of ten anatomical landmarks were collected that map muscle groups displacing the hyoid, larynx, pharynx, and tongue base during oral transport and pharyngeal phase of swallowing (Figure 1,2) (Thompson ZT et al. 2014). The semi-automated MATLAB tracker tool allowed for both automatic and manual placement of coordinates when necessary (Figure 3). To ensure correct placement of coordinates, a head and neck anatomist (WP) reviewed videos produced by the tracker tool that allowed for visualization of landmark placement.

2.4 Multivariate morphometric analysis

Data were organized for use in MorphoJ, an integrated morphometric software program, as follows (Klingenberg 2011). Spreadsheets of results were concatenated to create one spreadsheet of coordinates ($n=1068$) from all frames of oropharyngeal swallowing for all 13 pre- and post- treatment swallows included in the analysis. Categorical variables were assigned to each set of 10 coordinates including time of imaging acquisition (pre- vs. post-treatment), swallowing phase (oral transport vs. pharyngeal), bolus volume (large [$>15\text{ml}$] vs. small [5ml]), bolus viscosity (high [nectar or honey] vs. low [thin liquid]), LVC MBSImPTM component score (0 vs. 1), TBR MBSImPTM component score (1 vs. 2), and PR MBSImPTM component score (1 vs. 2).

Using MorphoJ, a principal component analysis was executed to determine which categorical variables should be named for a canonical variate analysis. Swallowing phase and treatment (time of imaging acquisition) were found to be the first and second principal component. Other independent variables were not associated with the top five principal components. A canonical variate analysis by swallowing phase and treatment was conducted to determine mechanical differences associated with respiratory-swallow phase training. Post hoc discriminant function analysis was used to determine eigenvectors (vectors characterizing swallowing mechanics) associated with treatment. A morphometric regression analysis was performed to determine if changes associated with treatment were predictive of improved LVC, TBR, and PR MBSImPTM component scores.

Results

Canonical variate analysis by swallowing phase and treatment resulted in 63.9% of variance associated with swallowing phase ($D=3.46$, $p<.0001$) and 35.5% of variance associated with pre- and post- treatment ($D=1.92$, $p<.0001$) (Figure 4). Eigenvectors of a post hoc discriminant function test indicated increased retraction of the tongue base, anteriorly repositioned hyolaryngeal complex, greater head flexion, and increased pharyngeal shortening in post-treatment swallows (Figure 5). Regression analysis showed that mechanics associated with treatment were highly predictive of mechanics associated with LVC ($r^2=.94$, $p<.0001$), with mechanics associated with TBR ($r^2=.12$, $p<.0001$) and PR ($r^2=.06$, $p<.0001$) being less predictive.

Discussion

Utilizing a newly developed MATLAB tracker tool, coordinates mapping swallowing mechanisms were collected from 13 swallows showing improvement from pre- and post-

respiratory-swallow training as measured by MBSImP™ component scores. Patient specific CASM was used to support the hypothesis that mechanical differences are associated with respiratory-swallow training and that these mechanics were predictive of MBSImP™ component scores with LVC, a key component of airway protection, being strongly predictive in this single subject. These results indicate that physiological improvements resulting from treatment have structural correlates that will inform the investigators regarding the mechanical benefits associated with the training.

Two notable changes in covariant swallowing mechanics associated with respiratory-swallow phase training in this subject were visualized with CASM including anterior repositioning of the hyolaryngeal complex and increased tongue base retraction. Inspiration creates traction on the trachea and larynx in a downward direction (Figure 6a). Animal and human studies have shown that pharyngeal dilators, including the stylopharyngeus and genioglossus are active during inspiration to stabilize the position of the larynx and open the pharynx (Guilleminault et al 1978; Rothstein et al 1983). We propose that the vector showing posterior repositioning of the larynx in disordered respiratory-swallow phase (inspiration) is due to the stylopharyngeus opposing the descent of the larynx, holding it in place. The line of action of the stylopharyngeus combined with the downward traction of the trachea pulls the larynx posteriorly against the prevertebral compartment of the neck (Figure 6b). For the vector showing decreased retraction of the tongue base, we propose that the genioglossus, effecting tongue protrusion, works as an antagonist to tongue base retraction that is otherwise unopposed in swallowing at mid to low expiratory phase. Swallowing during expiration allows the swallowing musculature to function unopposed and facilitates favorable positioning of the airway anterior to the trajectory of the bolus through the hypopharynx, and also facilitates increased tongue base retraction, which has been associated with reduced pharyngeal residue (Figure 6c,d)(Pauloski and Logemann 2000). This study shows that the combination of repositioning the hyolaryngeal complex and increased retraction of the tongue base contributed to improved laryngeal vestibular closure in the subject studied, which presumably promotes swallowing safety.

This patient specific CASM was greatly facilitated by the semi-automated tracker tool. Prior to the use of a semi-automated MATLAB tracker tool, a frame-by-frame analysis of a single swallow could take up to two hours. With the use of the tracker tool, the same analysis could be completed in an average of 20 minutes. The tracker tool produces a video of coordinate placements allowing for additional reliability check by visual inspection.

The efficiency of the semi-automated tracker tool depends greatly on the quality of the imaging study. In this study, four swallows were excluded due to poor image collimation of key anatomical structures. Though not a factor here, compensatory strategies such as a head turn to reduce the risk of aspiration compromise the use of CASM as many structures are obscured from view. Higher resolution imaging could improve the tracker tool's ability to track moving and soft tissue structures, which are less radiopaque than bony structures, by providing clearly defined points. To date, the tracking of the pharyngeal constrictor muscles is an unrealized goal of CASM.

Patient specific studies using CASM allow for the visualization of covariant swallowing mechanics associated with swallowing impairment and improvement. This analysis also provides statistical insight into what outcomes are associated with treatment. In these ways CASM has a distinct advantages over conventional kinematic measurements, which produce univariate measurements that require population data for interpretation. While population data may indicate particular trends associated with swallowing impairment, a patient specific CASM provides multivariate analysis of covariant swallowing mechanics associated with any number of independent variables. As swallowing impairment result from an array of variables, patient specific CASM provides a means of personalized treatment for dysphagic patients. As CASM technology advances, it may be possible in the future to visualize impaired swallowing mechanics in the clinical setting and formulate and perhaps even practice rehabilitative strategies based on vectors of swallowing improvement.

Conclusion

CASM documented that for this subject, a respiratory-swallow phase training program effected more normalized swallowing function per a clinical rating tool as well as with improved swallowing biomechanics. Improved biomechanics associated with training are strongly predictive of improved airway protection as measured by LVC MBSImpTM component score. The patient specific computational analysis is useful in determining biomechanical correlates of swallowing in a single patient and is promising as an application for personalized medicine.

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Figure 1.

Muscles underlying pharyngeal swallowing: GH= geniohyoid, HG= hyoglossus, LVP=levator veli palatini, MH=mylohyoid, PP=palatopharyngeus, SG=styloglossus, SP=stylopharyngeus, TH=thyrohyoid (pharyngeal constrictors not pictured).

Figure 2. Ten skeletal and soft tissue structures underlying hyolaryngeal excursion, pharyngeal shortening, and tongue base retraction are illustrated, labeled and overlaid on a head and neck videofluoroscopic imaging.

Figure 3.
Semi-automated MATLAB tracker tool used to map coordinates frame-by-frame.

Figure 4.

Canonical Variate (CV) analysis of morphometric data and categorical variables indicated CV1 (Swallowing Phase) resulted in 63.9% of shape change and CV2 (Treatment) resulted in 35.5% of shape change.

Figure 5.

Eigenvectors from a discriminant function analysis of pre and post respiratory-swallow phase training shows increased tongue base retraction (10) and anterior repositioning of the hyolaryngeal complex (7–9), slight flexion of the head (1-3-4-5), and increased pharyngeal shortening (6).

Figure 6.

Figure 6a–d. Traction on the trachea and larynx associated with respiratory inspiration shown in (a). Forces acting on the larynx during inspiration (b) are shown in light blue with the resulting negative impact on swallowing mechanics during inspiration shown in dark blue. The absence of traction on the trachea and larynx associated with respiratory expiration shown in (c). Facilitating of swallowing mechanics resulting from swallowing at mid to low volume expiration shown in dark blue (d).