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Research Article

Taste Manipulation and Swallowing Mechanics in Trauma-Related Sensory-Based Dysphagia

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Purpose: This study explored the effects of high-concentration taste manipulation trials on swallow function in persons with sensory-based dysphagia.
Method: Dysphagia researchers partnered with clinical providers to prospectively identify traumatically injured U.S. military service members (N = 18) with sensory-based dysphagia as evidenced by delayed initiation and/or decreased awareness of residue/penetration/aspiration. Under videofluoroscopy, participants swallowed trials of 3 custom-mixed taste stimuli: unflavored (40% weight/volume [wt/vol] barium sulfate in distilled water), sour (2.7% wt/vol citric acid in 40% wt/vol barium suspension), and sweet–sour (1.11% wt/vol citric acid plus 8% wt/vol sucrose in 40% wt/vol barium suspension). Trials were analyzed and compared via clinical rating tools (the Modified Barium Swallow Impairment Profile [Martin-Harris et al., 2008] and the Penetration-Aspiration Scale [Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996]). Additionally, a computational analysis of swallowing mechanics (CASM) was applied to a subset of 9 swallows representing all 3 tastants from 3 participants.
Results: Friedman's tests for the 3 stimuli revealed significantly (p < .05) improved functional ratings for Penetration-Aspiration Scale and pharyngoesophageal opening. CASM indicated differences in pharyngeal swallowing mechanics across all tastant comparisons ($p \leq$ .0001). Eigenvectors revealed increased tongue base retraction, hyoid elevation, and pharyngeal shortening for sweet–sour and, to a lesser extent, sour than for unflavored boluses.
Conclusion: Advantageous changes in certain parameters of oropharyngeal swallowing physiology were noted with high-intensity tastants per both clinical ratings and subsequent CASM, suggesting potential therapeutic application for taste manipulation.

In an intact swallowing system, motor patterns are known to vary based on sensory response to bolus properties (Lazarus, 2017). A range of bolus properties—including temperature, volume, texture, carbonation, and taste—has been explored relative to certain temporal and kinematic swallowing features in neurotypical adults. Taste stimulation, particularly strong sour, elicited increases in tongue-to-palate pressures (Nagy, Steele, & Pelletier, 2014; Pelletier & Dhanaraj, 2006) and submental muscle activity (Leow, Huckabee, Sharma, & Tooley, 2007; Miura, Morita, Koizumi, & Shingai, 2009; Palmer, McCulloch, Jaffe, & Neel, 2005) in healthy persons. In contrast, Miyaoka et al. (2006) reported no differences in suprahyoid muscle activity for a low-concentration sour stimulus compared to four other taste profiles in healthy young adults. These responses to taste stimulation may be explained by the sensorimotor networks underlying oral sensation and swallowing. Pure taste information is relayed via branches of the facial and glossopharyngeal nerves from the taste buds in the oral cavity to the nucleus tractus solitarius in the brainstem and other subcortical and cortical regions involved in taste perception (Simon, de Araujo, Gutierrez, & Nicolelis, 2006; Steele & Miller, 2010). Neuroimaging studies indicate similarly increased neural blood flow to these areas regardless of the specific type of taste stimulus (Prinster et al., 2017; Yeung, Goto, & Leung, 2018). In addition to this taste network, somatosensory information about temperature, texture, and touch is conducted to the brainstem through the trigeminal nerve. Inputs from the trigeminal pathway are theorized to have stronger, more preferentially

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attenuated input to the nucleus tractus solitarius as compared to those from the facial and glossopharyngeal nerves (Pelletier & Lawless, 2003). Intense sour is different from most other tastes in that it stimulates additional chemoreceptors associated with pain, touch, and thermal perception in a process called *chemesthesis*. Thus, strong sour tastants may amplify the trigeminal nerve signal and further influence swallowing physiology through feedforward and feedback mechanisms that function to "prime" the associated swallowing network (Simon et al., 2006; Steele & Miller, 2010). Studies reporting that extremely sour tastants elicited increased cerebral blood flow in swallowing-specific regions compared to baseline levels or other taste properties (Humbert & Joel, 2012; Mulheren, Kamarunas, & Ludlow, 2016) support this notion and may help explain the behavioral effects of intense sour on swallowing.

Although studies of sensory manipulation in healthy persons give some indication of how such strategies might be used to improve swallow function in dysphagia, it is important to confirm these findings in persons with swallowing disorders. Persons with dysphagia may have less capacity to adapt their swallowing mechanics in response to sensory manipulations because of their altered neuromuscular systems. Preliminary evidence regarding the effects of taste on swallowing suggests that certain tastes may induce advantageous swallowing changes in persons with neurogenic dysphagia, including stroke, traumatic brain injury, and degenerative processes (Lee et al., 2012; Logemann et al., 1995; Pelletier & Lawless, 2003), as well as head/neck cancer (Pauloski et al., 2013). For example, a very sour liquid elicits more rapid oral and pharyngeal onset times (Logemann et al., 1995), reduced pharyngeal transit time (Pauloski et al., 2013), and lower Penetration-Aspiration Scale (PAS; Rosenbek, Robbins, Roecker, Coyle, & Wood, 1996) scores (Lee et al., 2012) than other stimuli. Since extremely sour tastants are typically perceived as unpalatable, Pelletier and Lawless (2003) assessed the effects of a sour as well as a mixed sweet–sour taste stimulus (McBride & Johnson, 1987; Pelletier, Lawless, & Horne, 2004) on swallowing in persons with neurogenic dysphagia using fiberoptic endoscopic imaging. Applying a three-tiered rating of clear, penetration, or aspiration to airway invasion of the bolus, a statistically significant decrease in occurrences of penetration/aspiration was observed for sour versus water, but not sweet–sour versus water (Pelletier & Lawless, 2003). Further investigations of the effects of sweet–sour mixtures using more precise physiological measures have not been published to date.

Polytraumatic injuries involve significant damage to multiple body parts and organ systems, often as a result of motor vehicle accidents, gunshot wounds, blast events, or other trauma (Pape et al., 2014). By their nature, such injuries often include both neurological and structural components. Thus, swallowing function can be affected in multiple ways and may not respond to sensory stimulation or other interventions in the same ways as dysphagia resulting from other etiologies. Previously, we reported complex relationships between bolus size, viscosity, artificial airway status, and swallowing safety in persons with dysphagia due to polytraumatic injuries (Dietsch, Rowley, Solomon, & Pearson, 2017). Briefly, the results suggested that differences in swallowing mechanics accounted for at least part of the relationship between lower PAS scores, higher viscosities, and smaller bolus volumes, supporting a sensorimotor link between bolus properties and swallow physiology. Notably, the effects of taste manipulation have not been reported in persons with polytrauma-related dysphagia, nor has the nature of the swallowing impairments in this population been consistently described in the extant literature (Solomon, Dietsch, Dietrich-Burns, Styrmisdottir, & Armao, 2016).

Existing studies suggest some potential for sensory manipulation as a management strategy, but clinical implementation has been limited at best. This may be partially due to the range of stimuli, patient selection criteria, and outcomes reported, which make it difficult to ascertain which manipulations to attempt and with whom. Clinical tools, such as the PAS (Rosenbek et al., 1996) and the Modified Barium Swallow Impairment Profile (MBSImP; Martin-Harris et al., 2008), can provide information about responses to a particular swallowing stimulus by characterizing swallowing movements and effects according to ordinal scales. Additionally, subclinical differences in swallowing biomechanics may be important for identifying whether and how stimuli influence the relevant physiology. Computational analysis of swallowing mechanics (CASM; Tadavarthi et al., 2018) considers the interaction of various component movements within oropharyngeal swallows by relationally tracking the displacement of anatomical landmarks. Whereas MBSImP categorizes ratings of specific movement trajectories and tissue approximations using ordinal scales, CASM tracks landmarks' movements in any direction using interval measures. This may enable detection of subtle changes in oropharyngeal swallowing physiology that could be unappreciated using clinical ratings or more traditional distance measurements of isolated swallowing movement trajectories. A more precise understanding of the physiological effects of specific taste stimuli on swallowing morphology may help target selection of such therapeutic interventions in the future.

In the present study, dysphagia researchers and clinicians partnered to identify patients with polytraumatic injuries and sensory-based dysphagia during their clinical videofluoroscopic swallowing studies (VFSSs). Custom-mixed taste trials were administered to determine whether high-intensity tastants had immediate effects on swallowing function compared to unflavored barium trials. We anticipated that a sour stimulus would elicit improved swallowing physiology as measured by lower MBSImP scores (H1), and improved swallowing safety as measured by lower PAS ratings (H2), than unflavored trials. A third exploratory hypothesis (H3) speculated that CASM on a subset of trials would confirm the sour-versus-unflavored differences in swallowing mechanics. For all three hypotheses, we predicted that differences in swallowing physiology and safety associated with more palatable sweet–sour trials (McBride & Johnson, 1987; Pelletier et al., 2004) would be similar to, but less extreme than, the sour-versus-unflavored contrast (Pelletier & Lawless, 2003).

Method

Participants

Individuals included in this data set were participants in a larger study of dysphagia in U.S. military service members who were referred to the speech pathology clinic at Walter Reed National Military Medical Center (WRNMMC) from June 2013 to January 2015 for evaluation of swallowing function during acute hospitalization for management of service-related traumatic injuries. The overarching study entailed inclusion of the participant's de-identified medical records in a database (Dietsch, Rowley, Solomon, & Pearson, 2017; Solomon et al., 2016) as well as prospective trials of taste stimulation if a clinically appropriate VFSS was completed during the hospitalization. As detailed elsewhere (Dietsch et al., 2017), these patients passed rigorous predeployment physicals, consumed regular diets without difficulty prior to injury, sustained injuries during overseas deployment, were stabilized in local hospitals, and were intubated (or tracheotomized if clinically indicated) for the long journey to WRNMMC. Injured service members were excluded from study participation if they were admitted for reasons other than traumatic injuries or if they were discharged from WRNMMC prior to evaluation of swallowing function by a speech-language pathologist (SLP). Eligible potential participants (or their legally authorized representatives) provided written informed consent (WRNMMC IRB# 357205) either for database inclusion only or for database plus prospective trials if they were agreeable and were expected to receive additional SLP services that might include instrumental swallowing assessment.

When a clinical SLP (cSLP) determined that a prospectively enrolled participant was appropriate for the VFSS, both the cSLP and a research SLP attended the VFSS. The cSLP conducted the VFSS according to WRNMMC's clinically standard protocol (based on the MBSImP bolus administration protocol; Martin-Harris et al., 2008) and their own clinical judgment, using a range of commercial premixed flavored barium products (Varibar product line, Bracco Imaging) designed for VFSSs. Immediately following the last clinical VFSS trial administered, the cSLP made a determination as to whether the participant exhibited oropharyngeal dysphagia and, if so, the nature of the impairments. Indications of sensory impairment used by cSLPs to inform their clinical judgments included (a) delayed onset of the pharyngeal swallow response and/or (b) reduced awareness of pharyngeal residue, laryngeal penetration, and/or aspiration. The onset of the pharyngeal response was considered delayed if the leading edge of the (liquid) bolus had advanced beyond the valleculae at the initiation of hyoid movement. Factors marking reduced awareness included the absence of a cough or throat clear when the bolus pooled on or passed below the vocal folds, lack of spontaneous repeated swallow to clear marked pharyngeal residue, and/or verbal acknowledgment that the bolus had cleared despite visual presence of residue on fluoroscopy.

Procedure

If oropharyngeal dysphagia and sensory-based symptoms were identified by the cSLP, the research SLP administered additional taste-stimulus trials to the study participants while all parties were still in the fluoroscopy suite. Three custom-mixed stimuli included an unflavored barium mixture (40% weight/volume [wt/vol barium sulfate in distilled water), a sour lemon-juice–like mixture (2.7% wt/vol citric acid in 40% wt/vol barium suspension), and a sweet–sour lemonade-like mixture (1.11% wt/vol citric acid plus 8% wt/vol sucrose in 40% wt/vol barium suspension), presented at 55°F–65°F. Presentation sequences were counterbalanced across participants to avoid order effects. Between two and six taste stimulus trials were administered per participant, depending on accumulated radiation exposure during the clinical and experimental trials and on participant disposition. All but two participants took at least one trial of plain, sour, and sweet–sour boluses. The remaining two each had one plain and one sour bolus before their studies were aborted due to vomiting or frank aspiration. For each trial, the participant first completed multiple oral rinses with tap water until no residual taste sensation was reported (typically two to three rinses). Next, a syringe was used to place a 5-ml bolus into the anterior-most part of the participant's oral cavity, and the participant was instructed to swallow normally whenever they were ready (the same instruction used during the clinical portion of the exam). The fluoroscopic swallowing images included in this study were captured in the lateral view at pulse rates consistent with clinical standards at that time (typically 7.5 or 15 pulses/s) and digitally recorded at 30 frames/s for further analysis.

Analysis

The recorded VFSS was segmented into individual trials and coded such that researchers were blinded to the participant and stimulus type during subsequent analysis. Research SLPs, each a registered MBSImP clinician with at least 10 years of clinical dysphagia management experience, assigned clinical ratings to all research swallows. Taste trials were analyzed using the MBSImP component rating system (Martin-Harris et al., 2008) to characterize swallowing physiology and the PAS (Rosenbek et al., 1996) to describe airway compromise. In accordance with PAS and MBSImP guidelines for reporting the most impaired scores observed, ratings from the trial with the worst overall impairment score for a given trial type were included in the analysis whenever available. If a particular component could not be rated in the trial with the worse overall impairment and another trial of that type had been administered, the component score from the alternate trial was included to achieve a maximum of one score per component per tastant per participant in the analysis. Inter- and intrarater reliability was assessed on 10% of a larger sample (N = 230) of VFSS clips, including both clinical and research trials from the overarching study (Dietsch et al., 2017). Intraclass correlation coefficients for PAS were .999 and .916, indicating excellent intra- and interrater reliability levels, respectively. Friedman's tests compared PAS and MBSImP component ratings (for all components except bolus preparation/mastication [not applicable for liquid trials] and pharyngeal contraction [not rated in lateral view]) across all three tastants.

To further examine the oropharyngeal swallowing physiology associated with taste trials, a subset of swallow events was analyzed using CASM (May et al., 2017). Trial selection for this analysis was based on (a) availability of an unflavored (baseline), sour, and sweet–sour trial from the same date and participant in order to control for subject morphology in a small data set and (b) VFSS collimation that included all anatomical structures required for the analysis in all three trials from that participant. Ten key anatomical landmarks representing muscle groups underlying pharyngeal swallowing mechanics were tracked frame by frame from the beginning of oral transport through the pharyngeal phase of swallowing using a MATLAB-based semiautomated software tool (Natarajan, Stavness, & Pearson, 2015). These landmarks were points on the (a) genial tubercle of the mandible, (b) posterior edge of the hard palate, (c) anterior tubercle of the atlas, (d) anterior–inferior edge of C2, (e) anterior–inferior edge of C4, (f) superior border of the upper esophageal sphincter, (g) posterior vocal fold, (h) anterior vocal fold, (i) anterior–inferior edge of hyoid body, and (j) pit of valleculae. The biomechanical data from the video clips were extracted by researchers who, after training, demonstrated interrater reliability of $r > .95$ for all coordinates when compared to an expert rater (W. G. P.). The raters were blinded to patient information and PAS/MBSImP scores (Dietsch et al., 2017).

A morphometric canonical variate analysis of coordinate sets (Klingenberg, 2011) was performed to evaluate relative differences in pharyngeal swallowing mechanics associated with tastants in the pharyngeal phase of swallowing. Post hoc pairwise comparisons using discriminant function analysis were performed to visualize differences in pharyngeal phase mechanics by tastant using eigenvectors. Eigenvectors were scaled by Mahalanobis distances and mathematically aligned to the vertebrae to provide an intuitive interpretation of results using a customized MATLAB anatomical alignment function (Tadavarthi et al., 2018).

Results

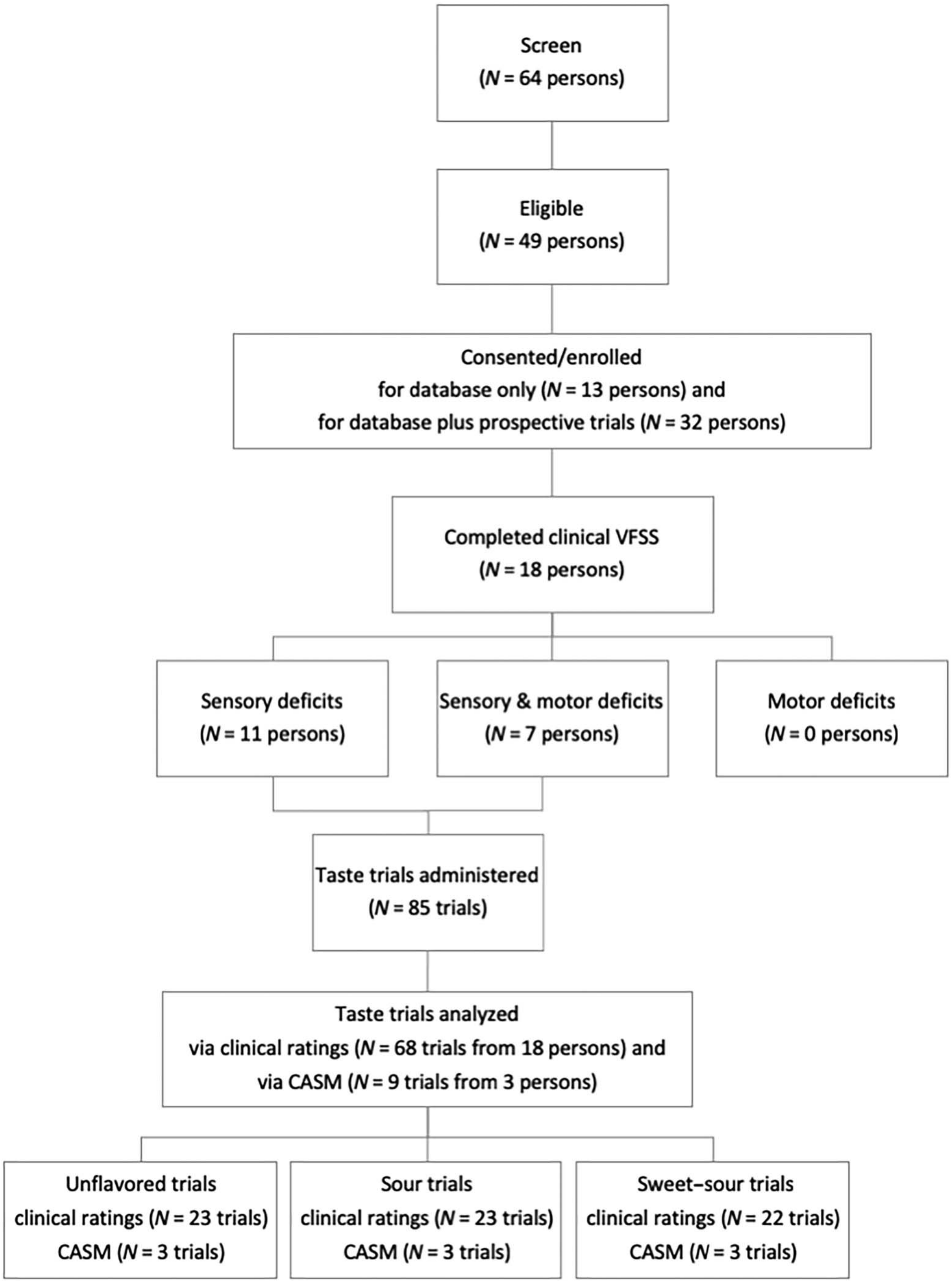
Of the 45 inpatients enrolled in the study, 32 were eligible for and agreed to participate in prospective taste stimulation trials, and 18 eventually underwent a standard VFSS as part of their clinical dysphagia management plan. Demographic data, etiologies of injuries, and swallowing status are shown in Table 1. Of note, more than half of the participants were not receiving an oral diet prior to the VFSS due to swallowing safety concerns, and PAS scores during the clinical VFSS trials generally reflected airway compromise to or below the level of the vocal folds, confirming the cSLPs' impressions regarding the existence of dysphagia. The cSLP determined that each of the 18 participants had oropharyngeal dysphagia with sensory impairments; seven also demonstrated concomitant motor deficits (see Figure 1). A total of 85 taste trials were administered. Of these, 68 trials representing the 18 participants were of adequate collimation and fluoroscopy on/off timing capture for clinical rating analysis. There were three participants for whom trials of all three tastants met the criteria for CASM in that they included all of the necessary anatomical landmarks and timing parameters. All three were

Table 1. Participant demographics.

Variable	
Age at videofluoroscopic swallowing study (VFSS)	M = 28.8 (range: 22.0–41.7 years)
Sex	16 men, 2 women
Primary mechanism of injury	8 dismounted blast, 8 vehicular accident with or without concurrent blast, 1 gunshot wound, 1 fall
Relevant structural injuries	9 orofacial fractures plus lacerations, 1 deep neck laceration, 8 no significant orofacial or neck injuries
Artificial airway history	14 intubation only (duration median = 6 days, elapsed time between extubation and VFSS median = 13 days), 1 trach in situ, 2 decannulated, 1 no artificial airway history
Elapsed time between injury and VFSS	*Mdn* = 18 days (range: 6–297 days)
Nutrition/hydration status at VFSS	10 nothing by mouth, 4 oral intake of some consistencies with supplemental tube feeding, 4 oral intake with restricted textures and/or external cueing
Worst PAS per participant during clinical VFSS trials	*Mdn* = 5 (range: 3–8)
Worst PAS per participant during research taste trials	*Mdn* = 2 (range: 1–8)

Note. PAS = Penetration-Aspiration Scale (Rosenbek et al., 1996); scores range from 1 (no airway compromise) to 8 (aspiration with no effort to clear). Summary statistics for ordinal scores show relative differences in performance between trials but have limited meaning in relation to the original scale.

Figure 1. Flowchart of study recruitment and analysis inclusion. VFSS = videofluoroscopic swallowing study; CASM = computational analysis of swallowing mechanics.



receiving nothing by mouth prior to the VFSS; their demographics were representative of the overall sample.

Friedman's pairwise tests on MBSImP and PAS ratings for the three stimuli (see Table 2) revealed two sets of statistically significant (uncorrected asymptote of significance [AoS] < .05) results: PAS (AoS = .014) and pharyngoesophageal opening (AoS = .039). Post hoc Wilcoxon signed-ranks tests assessed pairwise differences, as indicated in Figure 2. Penetration-aspiration scores were significantly lower for sour trials compared to unflavored trials (AoS = .007). The significant difference in pharyngoesophageal opening scores was primarily influenced by lower scores for sweet–sour trials compared to unflavored and sour trials (AoS = .046).

Table 2. Descriptive statistics and Friedman's test results for clinical ratings.

Variable	Plain	Sour	Sweet–sour	*N*	$X^2(df = 2)$	Friedman's AoS
PAS						
M	2.06	1.44	1.88	16	8.54	0.014*
SD	1.12	0.63	1.15			
Tongue control during bolus hold						
M	0.64	0.79	0.93	14	2.00	0.368
SD	0.93	0.98	1.00			
Bolus transport/lingual motion						
M	1.36	0.79	0.86	14	5.48	0.065
SD	1.15	0.89	0.77			
Oral residue						
M	1.64	1.57	1.79	14	4.67	0.097
SD	0.50	0.65	0.43			
Initiation of pharyngeal swallow						
M	2.00	2.08	1.62	13	1.81	0.405
SD	0.91	0.76	1.12			
Laryngeal elevation						
M	0.81	0.44	0.56	16	4.53	0.104
SD	0.91	0.63	0.73			
Anterior hyoid movement						
M	0.44	0.19	0.31	16	4.80	0.091
SD	0.51	0.40	0.48			
Epiglottic movement						
M	0.50	0.25	0.37	16	3.13	0.210
SD	0.73	0.45	0.50			
Laryngeal vestibular closure						
M	0.44	0.19	0.25	16	4.33	0.115
SD	0.51	0.40	0.45			
Pharyngeal stripping wave						
M	0.29	0.29	0.21	14	0.67	0.717
SD	0.47	0.47	0.43			
Pharyngoesophageal segment opening						
M	0.69	0.63	0.44	16	6.50	0.039*
SD	0.70	0.72	0.63			
Tongue base retraction						
M	1.33	1.20	1.20	15	1.60	0.449
SD	0.72	0.56	0.41			
Pharyngeal residue						
M	1.38	1.13	1.19	16	4.33	0.115
SD	0.50	0.62	0.40			

Note. PAS = Penetration-Aspiration Scale (Rosenbek et al., 1996); scores range from 1 (no airway compromise) to 8 (aspiration with no effort to clear). Modified Barium Swallow Impairment Profile component rating (Martin-Harris et al., 2008) scores for lip closure, soft palate elevation, and esophageal closure data were omitted due to insufficient data or lack of variability needed to conduct statistical tests. Summary statistics for ordinal scores show relative differences in performance between trials but have limited meaning in relation to the original scale.

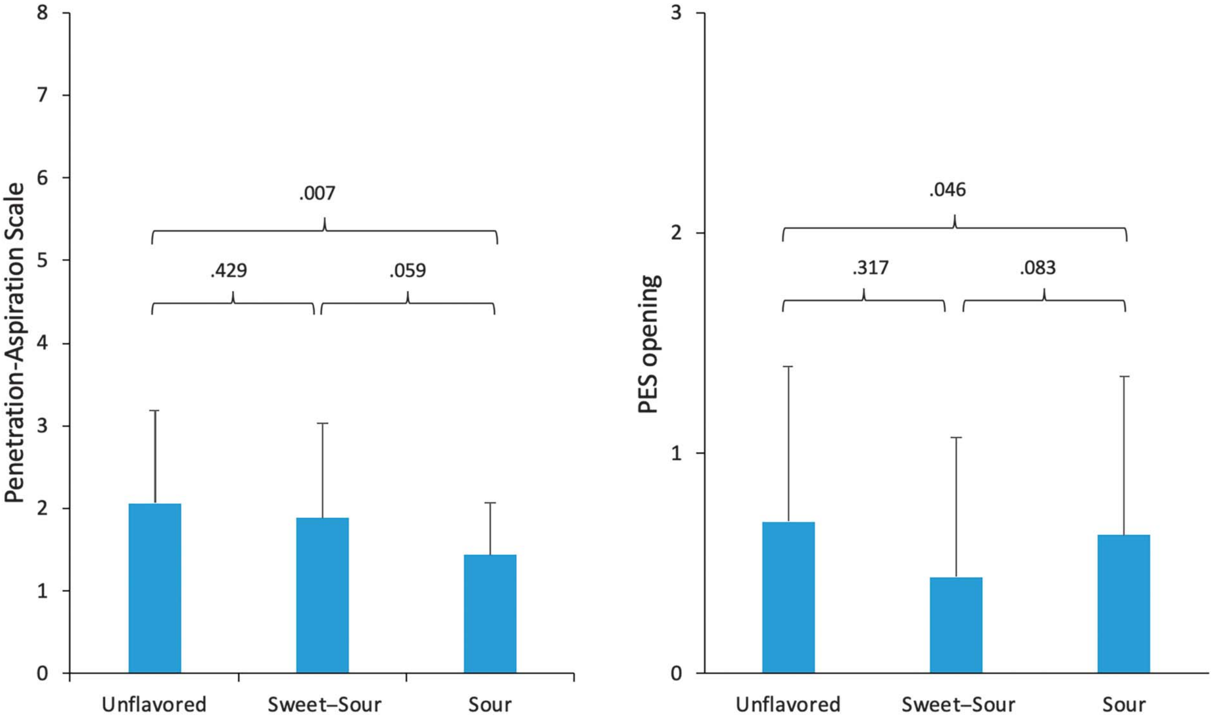
*Friedman's asymptote of significance (AoS) < .05.

Morphometric canonical variate analysis of pharyngeal swallowing mechanics for the CASM subset of swallows revealed that tastant type was a primary predictor of swallowing physiology. As illustrated in Figure 3, there were three distinct clusters of pharyngeal swallow movement patterns (Canonical Variates 1 and 2 represent these shape changes). Color coding by taste stimulus type reflects complete separation in the pharyngeal swallow shape features across the three taste stimuli. Pairwise comparison of tastants further underscored these profound differences (sweet–sour vs. unflavored: $D = 7.36$, $p = .0001$; sour vs. unflavored: $D = 10.26$, $p < .0001$; sweet–sour vs. sour: $D = 10.87$, $p < .0001$). Eigenvectors characterizing pharyngeal swallowing mechanics associated with each stimulus contrast are illustrated in Figure 4. Sweet–sour and sour stimuli elicited increases in hyolaryngeal displacement, pharyngeal shortening, and tongue base retraction during the pharyngeal phase compared to the unflavored trials (see Figures 4a and 4b). The magnitude of increase in hyolaryngeal displacement and tongue base retraction was greater for the sweet–sour stimulus compared to sour tastants (see Figure 4c).

Discussion

The present study aimed to characterize the effects of sour and sweet–sour taste stimuli on swallowing physiology in persons with sensory-based dysphagia related to

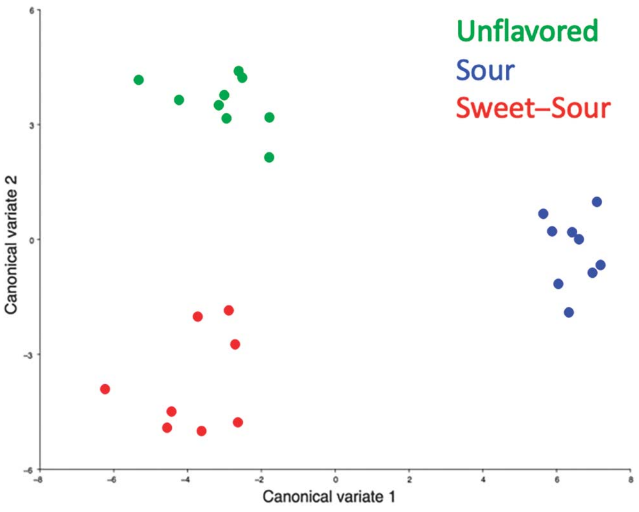
Figure 2. Comparisons of clinical ratings for taste stimuli. Friedman's asymptote of significance = .014 and .039 for the Penetration-Aspiration Scale scores and the Modified Barium Swallow Impairment Profile pharyngoesophageal opening component rating, respectively. Post hoc pairwise Wilcoxon signed-ranks results are shown in the graphs. Error bars represent one standard deviation. PES = pharyngoesophageal segment.



polytraumatic injuries. The results largely confirmed study hypotheses, supporting that both the sour and sweet–sour stimuli were associated with advantageous changes in swallowing physiology compared to the unflavored bolus.

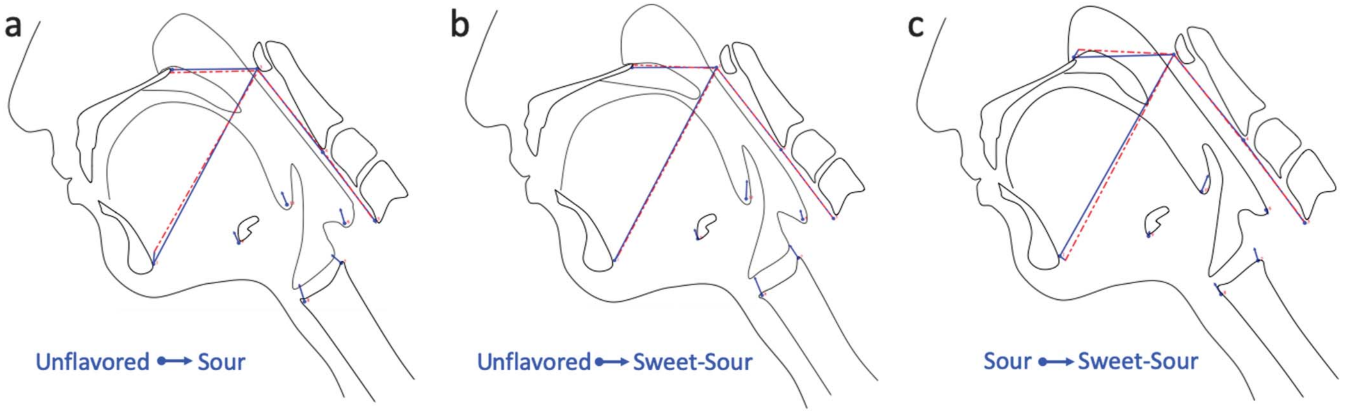
Per the MBSImP and PAS clinical ratings (H1 and H2, respectively), sour trials were associated with advantageous changes in airway protection during swallowing compared to the unflavored trials. Relative improvements in mean ratings for MBSImP components anterior hyoid movement and laryngeal vestibular closure could have contributed to the lower PAS scores noted with sour trials. Although these differences did not achieve statistical significance in the three-way Friedman tests, scores were twice as high for unflavored trials as compared to sour trials. Exploratory CASM results (H3) confirmed that sour elicited increased hyolaryngeal excursion and also identified increased pharyngeal shortening and tongue base retraction for sour versus unflavored trials in this small sample. These biomechanical changes have been shown to contribute to laryngeal vestibular closure and may also help explain the lower PAS scores. Although the CASM findings were drawn from a small subset of the study sample and must be interpreted with caution, it is encouraging that they are consistent with both the clinical rating results and those of previous studies using extremely sour taste stimulation (Lee et al., 2012; Pauloski et al., 2013; Pelletier & Lawless, 2003).

Figure 3. Morphometric canonical variate analysis of taste stimulus by swallow phase.



As compared to unflavored boluses, sweet–sour trials were linked to lower impairment ratings for pharyngoesophageal opening (H1) but, like the results reported by Pelletier and Lawless (2003), did not elicit significantly lower PAS scores (H2). The exploratory CASM detected differences in swallowing physiology that were not captured by the ordinal clinical ratings and associated analysis (H3). Per CASM, sweet–sour was associated with improved hyoid

Figure 4. Differences in pharyngeal-phase swallowing biomechanics by taste stimulus. The eigenvectors reflect the difference in direction and magnitude for each anatomical landmark when comparing movements associated with the first (circle) and second (arrowhead) stimulus types listed at the bottom of each panel.



excursion, laryngeal elevation, and tongue base retraction compared to unflavored trials. These advantageous shape changes were equivalent to or greater than those observed in the sour/unflavored comparison. Since pharyngoesophageal opening is mediated in part by hyolaryngeal excursion, these preliminary CASM findings offer a possible explanation for the statistically significant sweet–sour result from the MBSImP comparisons. Although the more palatable sweet–sour stimulus has reduced airway invasion as effectively as the strongly sour tastants in the only two reports comparing the two (Pelletier & Lawless, 2003), the physiological changes highlighted by CASM suggest that further investigation is warranted. It is possible that both stimuli may have clinical utility, perhaps each being most effective for persons with distinct patterns of altered swallowing physiology.

For both taste contrasts, CASM provided additional movement-related data beyond what was captured in the clinical ratings. Since CASM uses interval measures whereas MBSImP uses ordinal variables, statistically speaking, CASM is a more sensitive tool by its nature. Additionally, MBSImP focuses on specific movement trajectories and tissue approximations, whereas CASM tracks landmarks' movements in any direction. For example, MBSImP's tongue base retraction rating is defined by the amount of space between the vertical portion of the tongue base and the posterior pharyngeal wall, whereas CASM identified a superior–posterior movement difference for the tongue base landmark independent of its relativity to the posterior pharyngeal wall. In other words, CASM has greater flexibility to account for the many subtle variations in swallowing movement patterns that are available within the oropharyngeal anatomy. These results illuminate potentially important differences in swallowing physiology but are considered exploratory since only a small portion of the data met the stringent requirements for CASM. Thus, the CASM serves as a complement to, rather than a replacement for, clinical ratings of swallowing physiology.

It is of particular clinical relevance that taste stimulation was associated with changes in swallowing physiology even in a patient population likely to have both peripheral and central nervous system damage. Damage to peripheral nerves or to any part of the central neural networks may disrupt the complex interactions between the facial/glossopharyngeal (taste-specific) and trigeminal (somatosensory and chemesthetic) inputs to the brainstem and higher structures, resulting in swallowing dysfunction. Certain stimuli, such as intense sour, stimulate multiple cranial nerve pathways to a greater extent than do tastants without chemesthetic properties. Thus, stimuli that take advantage of the multisensory integration within the gustatory/swallowing network, including strong sour and possibly intense sweet–sour, may be more able to overcome or bypass any "breaks" in the circuitry of the polytrauma population studied here, as well as in other clinical populations with peripheral and/or central nervous system damage (Pauloski et al., 2013; Pelletier & Lawless, 2003).

Although these data are encouraging, several factors must be considered in their interpretation. First, they are drawn from a small sample that is not necessarily representative of the general population. Military service members are generally younger and more physically fit than the typical person with dysphagia. Whereas most civilian dysphagia is due to either neurological (stroke, traumatic brain injury, degenerative process) or structural (head/neck cancer, intubation) insult, the polytraumatic injuries sustained in the study population may have included both neurological and structural components. In addition, the cSLPs' diagnosis of sensory-based dysphagia may have been complicated by other issues such as incoordination and alterations to sensorimotor processing and integration. Second, VFSS image quality was problematic for many trials. Aggressive collimation often excluded key anatomical features from view, severely limiting the comparisons available for the CASM. Furthermore, the limitations of pulsed fluoroscopy and suboptimal pulse rates (Bonilha et al., 2013) may have failed to capture the entire range of motion for some swallows. Therefore, it is possible that the MBSImP scores contain errors and the coordinate data represent underestimated shape changes associated with the analysis. The fluoroscopy timing and collimation problems also led to the elimination of potentially useful trials, thus limiting our data set. Despite these constraints, the robust differences in PAS for research trials support that there are true differences in swallowing function across taste stimuli, and the clinical ratings (taken from all administered research trials) and the CASM (taken from a subset of trials) offer preliminary data, albeit potentially underestimated, regarding the nature of physiological differences associated with taste stimulation.

To summarize, this study revealed that both sour and sweet–sour high-concentration taste trials were associated with immediate advantageous changes in swallowing according to clinical/functional ratings as well as the morphological analysis of swallowing physiology. These results suggest potential therapeutic application for taste manipulation as a means of stimulating more functional motor patterns of swallowing physiology, even in patients with complex or multifactorial dysphagia etiologies. Principles of motor learning and neuroplasticity underscore that behavioral experience directly influences behavioral outcomes (Kleim & Jones, 2008), so stimulating an optimized swallow response, rather than a less functional one, may facilitate the acquisition of more functional swallowing physiology over time. The analysis also illustrates the benefit of CASM as a means to extend our clinical perceptions about swallowing physiology. Finally, the limitations of this work highlight the need for radiology and speech-language pathology staff to reconsider previous operational standards for VFSSs in order to obtain images of adequate pulse rate and field of view for CASM in clinical and research studies.

The present study considered the effects of taste on otherwise similar barium suspensions. Future examinations of taste stimulation should focus on additional outcome measures, populations, effect durations, and interactions with other bolus properties, such as viscosity, volume, density, and temperature. CASM is well suited to address these kinds of questions at a group or participant level with a more robust data set. Since delays in swallowing movements are often considered a marker of sensory or sensorimotor impairment, consideration of timing parameters in conjunction with CASM is an important next step. Additionally, it is possible that some individuals or patterns of swallow dysfunction are more amenable to advantageous effects of taste stimulation than others or that certain taste profiles are more beneficial than others. In order to translate these results to functional outcomes, the long-term effects of taste stimuli on swallowing behaviors must be examined in terms of neurorecovery and carryover of improved swallow function for normally flavored foods and liquids. The present results help establish a foundation for specific, and potentially more palatable, taste profiles as a stimulus for improved swallow function.

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