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ORIGINAL ARTICLE

Variations in Healthy Swallowing Mechanics During Various Bolus Conditions Using Computational Analysis of Swallowing Mechanics (CASM)

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Abstract

Bolus properties such as volume, consistency, and density have been shown to influence swallowing through the analysis of kinematics and timing in both normal and disordered swallowing. However, inherent intra- and inter-person variability of swallowing cloud interpretation of group data. Computational analysis of swallow mechanics (CASM) is an established methodology that uses coordinate tracking to map structural movements during swallowing and yields statistically powerful analyses at both the group and individual levels. In this study, the CASM method was used to determine how different bolus properties (volume, consistency, and density) altered swallow mechanics in healthy young adults at the group and individual levels. Videofluoroscopic swallow studies of 10 (4 females) healthy young adults were analyzed using CASM. Five bolus types were administered in each study (3 × 5 ml 40% w/v nectar, 3 × 5 ml 22% w/v thin, 3 × 5 ml 40% w/v thin, 3 × 10 ml 22% w/v thin, and 3 × 20 ml 22% w/v thin). Canonical variate analyses demonstrated that bolus condition did not affect swallowing mechanics at the group level, but bolus condition did affect pharyngeal swallow mechanics at the individual level. Functional swallow adaptations (e.g., hyoid movement) to bolus conditions were not uniform across participants, consistent with the nonsignificant group finding. These results suggest that individual swallowing systems of healthy young individuals vary in how they respond to bolus different conditions, highlighting the intrinsic variability of the swallow mechanism and the importance of individually tailored evaluation and treatment of swallowing. Findings warrant further investigation with different bolus conditions and aging and disordered populations.

Keywords Swallowing · Dysphagia · Bolus properties · Volume · Density · Consistency

Introduction

Oropharyngeal swallowing is a cortically informed brainstem-driven response, resulting in a complex, coordinated motor pattern. The swallowing motor sequence is intrinsically connected to and modified by sensory input, which informs temporal and kinematic characteristics of the motor pattern [1–3]. Various bolus properties have been shown to affect timing and kinematic measures in both normal and disordered swallowing. Larger bolus volumes have been associated with earlier onset and longer duration of the temporal events [4–6] and greater magnitude of structural movement during swallowing [7–9]. Bolus consistency has also been shown to affect swallowing biomechanics. Increased consistency results in increased delay and duration of swallowing events [5, 6] and greater submental and infrahyoid muscle activity [10]. Further, the density of the bolus solution (i.e., concentration of a barium solution) has been shown to effect swallow timing measures, with one study by Stokely et al. [11] demonstrating that higher density results in increased stage transition duration, pharyngeal transit time, and duration of opening of the upper esophageal sphincter (UES). The density of barium stimuli has been shown to affect swallowing safety; Fink and Ross [12] found higher incidence

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of aspiration on lower density boluses (i.e., "ultra-thin" barium) compared to standard thin liquid barium.

Temporal, kinematic, and/or electrical muscle activity measures are typically grouped and analyzed collectively across multiple individuals. Measurement also generally focuses on discrete characteristics of swallowing, rather than relationships between components during the swallow. As discussed above, these methods have yielded evidence of systematic, predictable changes in swallowing characteristics across individuals. Yet, high variability exists in all quantifiable characteristics of swallowing between people [13, 14]. There is also evidence of variability within individual swallowing systems from one swallow to the next, even with all external sources of variation held constant [15]. Given this intra- and inter-person variability, there is reason for concern that collapsing data across individuals could be masking clinically relevant differences between systems.

In skeletal muscle research, the challenges associated with using group-level analyses to investigate movement patterns have been recognized for decades. In 1995, Kelso [16] remarked that averaging movement performance across individuals is similar to comparing "apples and oranges," given the high degree of inter-person variability in the execution of movements. Thus, individual analysis of kinematic properties has been recommended as best practice in skeletal muscle research [17].

As a complex and dynamic movement system, swallowing may be best analyzed using methods recommended and adopted in research on other movement systems. When swallowing kinematic and temporal data are collapsed across individuals (even when drawn from the same population), differences between individuals may be masked. Exploring these sources of variability will improve understanding of how individual systems adapt, compensate, or fail to adapt to different conditions. Moreover, the high between-person variability that is present under normal conditions suggests that swallowing will be affected differently by disorder and degeneration. The ability to identify different between-person patterns in normal swallowing is an initial step towards predicting how individuals may be differentially affected by aging or disease.

Reliable methods for analyzing swallowing characteristics on individual and group levels have been established. One such method is computational analysis of swallowing mechanics (CASM) [18, 19]. This methodology uses multivariate morphometric analysis of coordinate mapping data to analyze relationships between structural movements during swallowing on videofluoroscopic swallow studies (VFSSs). Anatomical landmarks (i.e., coordinates) defining multiple muscle groups are annotated on each VFSS frame. The resulting coordinates represent the interactions of multiple muscle groups over the course of the swallow. As shown in Fig. 1, coordinates 1–5 represent proximal muscle attachment sites and the posture of the head and neck. The remaining five distal muscle attachments (coordinates 6–10) are dynamic during swallowing. Shape change analysis applied to these coordinates, or CASM, allows for analysis and visualization of how the various components of swallowing mechanics interact under various conditions, including varying bolus properties. CASM is a statistically powerful analysis of swallow mechanics that can be assessed at the group level (across swallows by different individuals) and at the participant level (across swallows in a single VFSS).

The purpose of this study was to use CASM to evaluate how subtle differences in bolus properties (volume, consistency, and density) influence swallow mechanics in healthy young adults at the group and individual levels.

Methods

Videofluoroscopy

VFSS recordings of 20 (10 females) healthy young adults (mean = 31.5 years, SD = 5.7) were collected and deidentified for a previous study [20] with IRB approval. Each original VFSS included 3 barium swallows of 5 boluses types: 3 × 5 ml 40% w/v nectar (IDDSI level 2, mildly thick), 3 × 5 ml 22% w/v thin, 3 × 5 ml 40% w/v thin, 3 × 10 ml 22% w/v thin, and 3 × 20 ml 22% w/v thin. For the current analysis, each swallow ($N = 300$) was individually inspected to confirm adequate visualization of the 10 anatomical landmarks required for CASM analysis, which resulted in excluding 84 swallows. Any individual participants that did not at least one bolus representing all five bolus conditions were then excluded from the sample. After excluding all swallows that were inadequate for CASM analysis and all participants with missing bolus conditions, the final dataset included 10 (4 females) healthy young adults in a total of 142 individual swallows.

CASM Analysis

Randomized swallows were analyzed by four research assistants trained in frame-by-frame coordinate mapping using a custom-built tracker tool in MATLAB [21]. Coordinate 1 is traditionally placed on the inferior genial tubercle of the mandible for studies using CASM [22]; however, in this study, the mandibular placement was at the intersection of the last molar with the ramus of the mandible because the anterior mandible was out of frame for the majority of the VFSS videos. This mandibular placement was chosen due to its functional equivalence for tracking head and neck posture and its reliable identification and visualization in VFSS videos. All other coordinates were marked according to previously described methods [22]. Excellent inter-rater

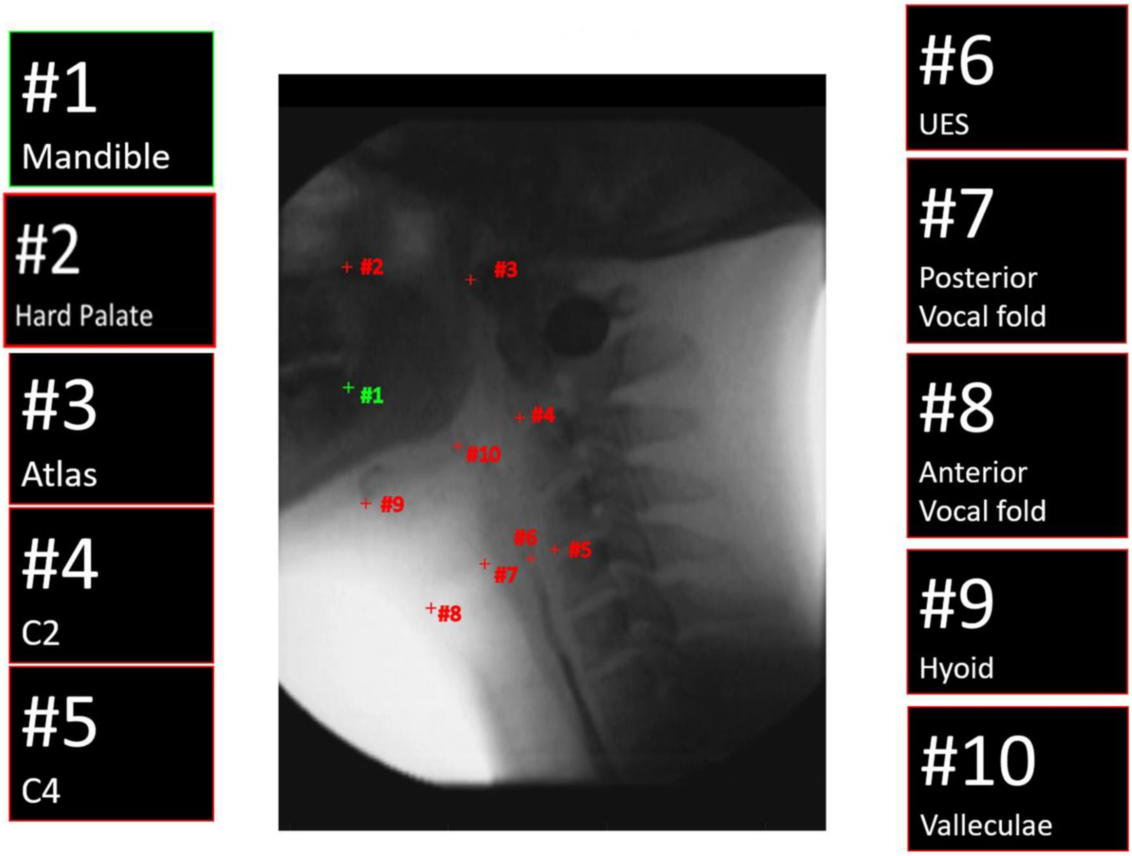


Fig. 1 Lateral VFSS image demonstrating the 10 coordinate marking points used in CASM. The mandibular placement (Coordinate #1) was adjusted to the intersection of the last molar with the ramus of the mandible

reliability scores (ICC > 0.95) were achieved for all raters prior to CASM analysis.

Coordinate tracking on each swallow began 30 frames prior to the onset of brisk anterior and superior movement of the hyoid ('hyoid burst') and continued until the frame depicting closure of the UES behind the bolus tail ('UES close'). Frames were then categorized as oral (30 frames before the onset of hyoid burst) or pharyngeal (hyoid burst to UES close). Coordinate mapping for oral and pharyngeal phases were automatically calculated by CASM software and then compiled and imported into MorphoJ integrated software [23].

Statistical Analysis

Statistical analyses were performed at the group and participant levels. Because the primary aim of this study was to investigate how bolus condition influenced pharyngeal swallow mechanics, oral phase observations were excluded from the dataset in MorphoJ by subdividing the dataset by swallow phase. At both the group and participant levels, canonical variate analyses (CVAs) were used to determined how much variance in swallow mechanics of the pharyngeal swallow phase could be explained by bolus properties (volume, consistency, density). CVA eigenvalues are used by MorphoJ to calculate what percentage of the variance in the dataset is characterized by the named canonical variables (i.e., bolus types). For example, a CVA may show that the first three canonical variables (CV1 = volume, CV2 = consistency, CV3 = density) account for 90% of the variance in the dataset. Each canonical variable may contribute equally (30% each) or unequally (CV1 = 75%, CV2 = 10%, and CV3 = 5%) to explain this overall 90% variance.

If CVA results stratified by bolus properties, pairwise CVAs were then used to produce scaled eigenvectors to visualize shape changes for the 10 coordinates based on volume (20 ml thin 22% w/v vs. 5 ml thin 22% w/v), density (5 ml thin 40% w/v vs. 5 ml thin 22% w/v), and consistency (5 ml mildly thick 40% w/v vs. 5 ml thin 40% w/v). These three binary comparisons allowed evaluation of a single bolus property (e.g., density) while holding two bolus properties constant (e.g., consistency and volume). Table 1 outlines pairwise comparisons of bolus conditions.

The CVA eigenvectors characterizing shape change were scaled by the Mahalanobis distances between pairwise comparisons and exported to .svg files. To better interpret the

Table 1 The pairwise comparisons of the five bolus types

Five Bolus Conditions			Pairwise Comparisons		
			Density	Consistency	Volume
5ml	22% w/v	thin	22% w/v	thin	5ml
5ml	40% w/v	thin	40% w/v		
5ml	40% w/v	mildly-thick		mildly thick	
10ml	22% w/v	thin			
20ml	22% w/v	thin			20ml

Shaded cells represent pairwise comparisons between bolus conditions

w/v weight/volume, *ml* milliliters

results anatomically, these .svg eigenvector graphs were subjected to a matrix transformation to align the vertebrae in all pairwise comparisons. The resulting eigenvectors depicted the reference bolus as a dot and the comparison bolus as an arrow.

To describe patterns of swallow mechanic changes for each bolus condition comparison for each participant, two trained CASM raters independently determined the presence and direction of change of the following parameters based on the resulting eigenvectors: head/neck extension, hyoid excursion, laryngeal excursion, base of tongue retraction, and pharyngeal shortening. A directional change was recorded if scaled eigenvectors displayed a defined starting and end point. For example, participant 05 (Fig. 5c) reduced pharyngeal shortening (6) and laryngeal excursion (7–8), but increased base of tongue retraction (10) for higher volume because these eigenvectors had a starting point (at the referent) and defined arrow (for the comparison); however, participant 05 did not change hyoid movement (9) because of the small vector. If any ratings differed, a third trained CASM rater resolved the discrepancy.

Head/neck extension was judged to be different between bolus conditions if both the lines from C1 (coordinate 3) to mandible (coordinate 1) and hard palate (coordinate 2) changed superior or inferior positions in unison in reference to the vertebrae. Hyoid coordinates (9) were judged to be different between conditions if vectors changed in anterior, superior, posterior, or inferior positions. Laryngeal coordinates were marked different between bolus conditions if both vectors (7 and 8) changed in anterior, superior, posterior, or inferior positions in unison. Base of tongue coordinates (10) were judged to be different between bolus conditions if vectors changed in anterior or posterior positions. UES coordinates (6) were judged to be different between bolus conditions if vectors changed in superior or inferior positions.

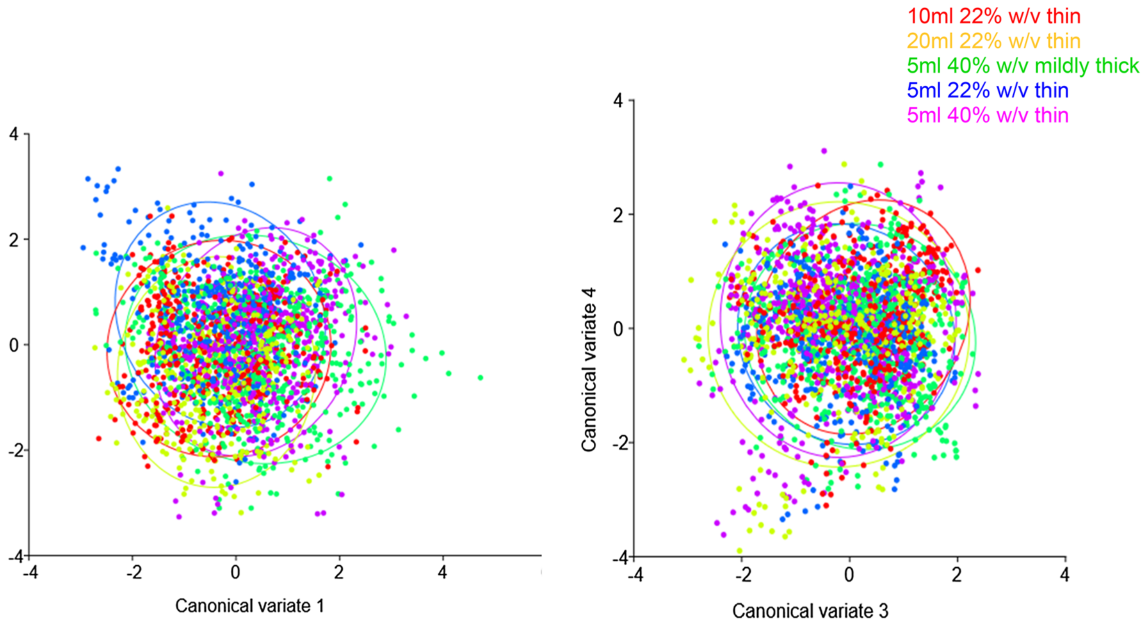
Results

For the group-level analysis, a CVA with bolus condition as the predictor variable revealed that bolus properties did not stratify the data for the first four canonical variables, which accounted for 100% of the variance in the group data (Fig. 2). Therefore, bolus condition was not significant at the group level for influencing swallow mechanics.

At the participant level, individual CVAs with bolus condition as the predictor variable demonstrated significant differences in swallowing mechanics between bolus types with eigenvalues ranging from 42.0 to 83.0%. Overall pharyngeal swallow mechanics (as represented by shape change) were not uniform across participants by bolus types. Table 2 provides a summary of changes in the elements of swallowing mechanics by bolus density, consistency, and volume as represented by pairwise CVA eigenvectors. Some participants modified their swallow mechanics for each bolus type, while other participants had few changes for differing boluses.

To illustrate the variation in the individual data, we have provided a representative sample of two contrasting participants (participants 05 and 10). For participant 05, bolus condition accounted for 61.3% of the variance in swallow mechanics and stratified the data (Fig. 3a). With increased density, participant 05 increased laryngeal excursion and base of tongue retraction (Fig. 4a). With increased consistency, participant 05 had head/neck flexion, decreased base of tongue retraction, and increased pharyngeal shortening (Fig. 4b). With increased volume, participant 05 reduced pharyngeal shortening and laryngeal excursion, but increased base of tongue retraction (Fig. 4c).

In contrast to participant 05, bolus condition accounted for 54.5% of the variance in swallow mechanics for participant 10, but data across bolus conditions overlapped to a greater degree than observed of participant 05 (Fig. 3b). Participant 10 decreased anterior hyoid movement and increased base of tongue retraction for density changes (Fig. 5a). For increased consistency (mildly thick compared to thin liquid barium), participant 10 had head/neck extension, increased anterior/superior hyoid and larynx, increased base of tongue retraction, and increased pharyngeal shortening (Fig. 5b). However, participant 10 has no changes in swallow mechanics for changes in bolus volume (Fig. 5c). All participant-level CVAs for bolus conditions can be found in Appendix.



(a)

(b)

Fig. 2 CVAs for canonical variates 1 and 2 (**a**) and 3 and 4 (**b**) were not stratified by bolus condition demonstrating that bolus condition had no effect on pharyngeal swallow mechanics at the group level (*CVA* canonical variate analysis)

Table 2 The distribution of altered swallow mechanics in response to various bolus properties

Bolus comparison	Direction	Head/neck extension	Hyoid excursion	Laryngeal excursion	BOT retraction	Pharyngeal shortening
Density 5 ml thin (22% w/v vs. 40% w/v)	Increased	1	2	4	2	3
	Decreased	2	6	2	1	4
	Unchanged	7	2	4	7	3
Consistency 5 ml 40% w/v (thin vs. mildly thick)	Increased	3	4	3	2	6
	Decreased	2	3	5	2	4
	Unchanged	5	3	2	6	0
Volume 22% 5 ml versus 20 ml (thin 22% w/v)	Increased	5	6	3	3	1
	Decreased	1	2	4	3	6
	Unchanged	4	2	3	4	3

BOT base of tongue, *w/v* weight/volume

Discussion

Using the CASM method, we found that, at the group level, bolus condition did not systematically affect pharyngeal swallowing mechanics in this sample of healthy young individuals. Only at participant-level analyses were significant differences in pharyngeal swallowing mechanics between bolus conditions revealed. These results indicated that within-person swallow mechanics changed based on varying bolus size, consistency, and density. The subtle differences in volumes, densities, and viscosities yielded no clear pattern of pharyngeal swallowing mechanics alterations across participants, which explains the lack of significant findings at the group level. Thus, using CASM with this small sample of healthy young adults, we found that the gestalt swallow mechanics were unchanged by bolus condition for the group but change differently for individuals depending on bolus condition.

To ground these findings in a theoretical framework, it is helpful to conceptualize swallowing in terms of a dynamical systems theory of motor control. The motor control underlying swallowing is highly complex and involves the coordinated function of many muscles to achieve safe and efficient swallowing. The dynamic systems theory describes motor systems as complex and self-organizing, and lacking

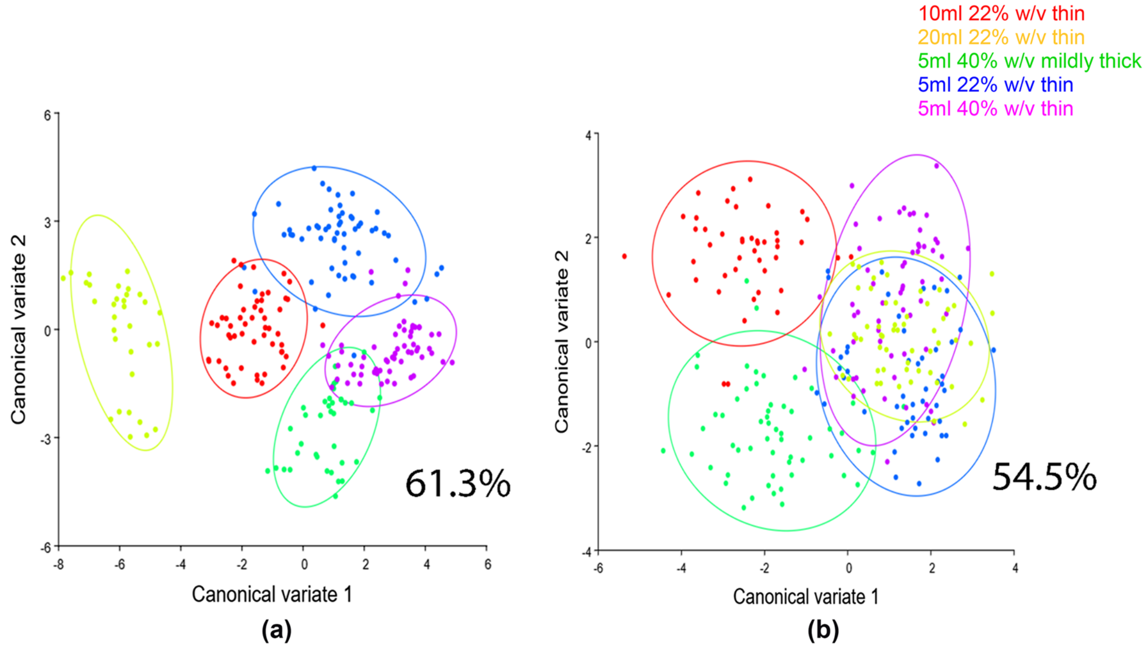


Fig. 3 The canonical variate analysis (CVA) of participant 05 (**a**) demonstrated little overlap of data among the five bolus conditions. The CVA of participant 10 (**b**) demonstrated much overlap between the 5 ml 22% w/v thin (blue), 5 ml 40% w/v thin (purple), and 20 ml 22% w/v thin (yellow) (*w/v* weight/volume)

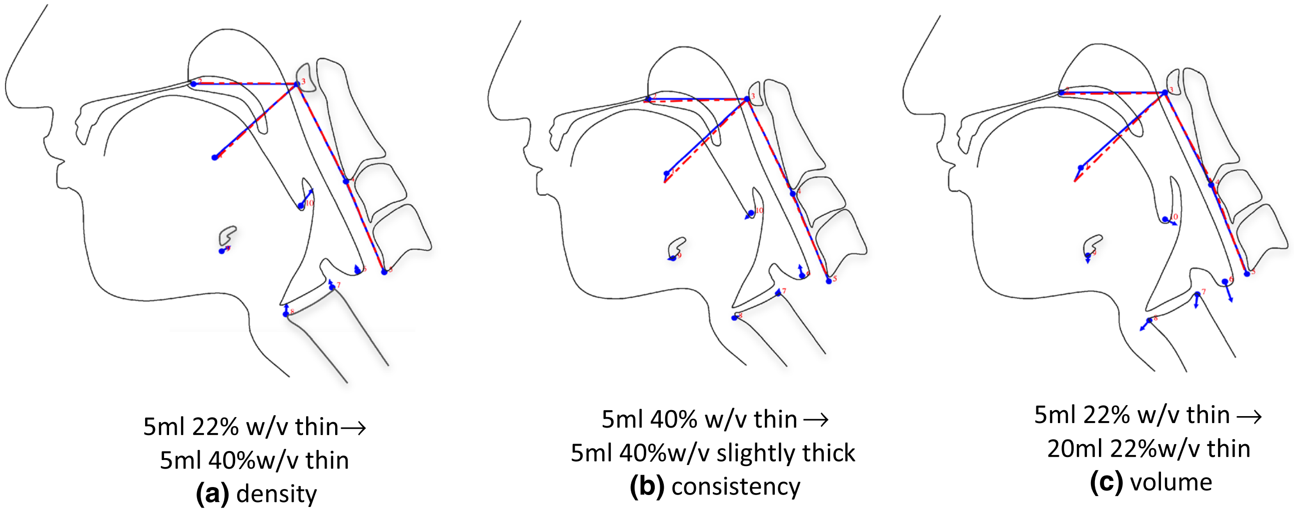
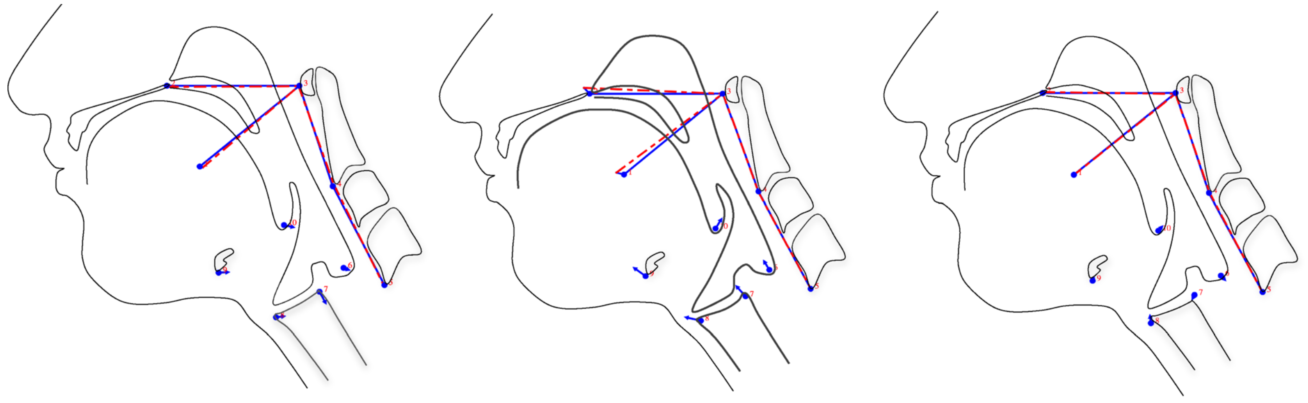


Fig. 4 Participant 05 changed swallow shape during the pharyngeal phase of swallowing based on bolus properties. The dot represents the 5 ml thin liquid reference bolus in each graph. The vectors represent scaled differences between the bolus conditions of density (**a**), consistency (**b**), and volume (**c**). This participant increased laryngeal excursion (7–8) and base of tongue retraction (10) for denser liquids (**a**). Participant 05 flexed their head/neck (dotted line), decreased base of tongue retraction, and increased pharyngeal shortening (6) for thicker liquids (**b**). Participant 05 reduced pharyngeal shortening (6) and laryngeal excursion (7–8), but increased base of tongue retraction (10) for higher volume (**c**) (*w/v* weight/volume)

conscious control [24, 25]. The ability to respond to constantly changing input requires a highly skilled system adapting to subtle constraints and changes in the environment to make fine-grained, coordinated adjustments, with each individual component continuously compensating and adapting in response to the others. The subsequent variability that is seen within and across individuals is reflective of this highly skilled system in action. From this perspective, it is expected that healthy, skilled swallowers will exhibit significant variability. Establishing this observed variability



5ml 22% w/v thin→ 5ml 40%w/v thin
(a) density

5ml 40% w/v thin→ 5ml 40%w/v slightly thick
(b) consistency

5ml 22% w/v thin → 20ml 22%w/v thin
(c) volume

Fig. 5 Participant 10 had few changes in swallow shape during the pharyngeal phase of swallowing based on bolus properties except for consistency. The dot represents the 5 ml thin liquid reference in each graph. The vectors represent scaled differences between the bolus conditions of density (**a**), consistency (**b**), and volume (**c**). This participant decreased hyoid (9) movement and increased base of tongue retraction (10) for increased density (**a**). This participant did not alter swallow shape based on volume (**c**). Participant 10 increased superior movement for hyoid (9), larynx (7 and 8) and pharyngeal shortening (6), and superior/posterior movement for base of tongue (10) for nectar-thick consistency (**b**) (*w/v* weight/volume)

as reflective of true physiologic adaptation would require the implementation of an environmental perturbation, which was outside the scope of the current study. Therefore, it cannot be stated definitively that individual changes to different bolus types were due to adaptations per se. However, based on principles of dynamical systems and given that these were healthy young subjects with no history of swallowing impairment, we hypothesize that our results do in fact reflect adaptation of the system to the stimuli tested.

As we have seen from this and previous research, healthy swallowing systems vary in how they respond to stimuli. This suggests that disease or impairment may manifest differently in disordered swallowing. Depending on the swallowing pattern pre-impairment, systems may respond or compensate in varying ways. Impairment may be thought of as the system's inability to coordinate the various elements of swallowing mechanics to achieve functional swallowing. It follows then that these dynamical swallowing systems may respond differently to treatment.

Ultimately, the evidence provided by this work highlights the critical importance of an individualized approach to the evaluation and treatment of swallowing; given the uniqueness of individual swallowing systems, a 'one-size-fits-all' approach to assessment and treatment may not be adequate. It is important to consider the individual's swallowing physiology, in conjunction with foundational knowledge about swallowing biomechanics based on neurophysiological underpinnings, to choose appropriate and effective interventions. Furthermore, these findings suggest that comparing discrete elements of swallowing mechanics in clinical research may limit or simplify the dynamical nature of swallowing. Swallowing ability is better determined by how individuals coordinate their various elements of swallowing mechanics to achieve safe and efficient swallowing.

Given the nuanced and subtle nature of intra- and inter-person swallowing variation, in addition to limitations of subjective swallowing evaluation [26–28], quantitative measurement of swallowing function can be useful for understanding the nature of specific characteristics of individual swallowing systems. However, the time intensive nature of these methods may limit ability to use quantitative analyses in most clinical settings. In time, machine learning and artificial intelligence may produce clinically accessible tools that can be applied to digital imaging studies. Nevertheless, systematic approaches to treatment, in which patients serve as their own baseline, and treatment protocols are modified over time and with careful monitoring, can help us assess changes over time and tailor the protocol as required.

Although this study demonstrated that swallow mechanics vary based on bolus condition, several limitations must be acknowledged. Although prior to coordinate mapping we achieved high inter-rater reliability, individual swallows were randomly rated by four trained lab personnel. Therefore, we were unable to control for rater or trial sequence in this analysis and do not know their influence on swallow mechanic analysis. Also, because these data were not collected for CASM, several participants and swallows had to be excluded from analysis for methodological reasons, resulting in an incomplete dataset. Finally, because the pharyngeal phase was defined as the time between hyoid burst and UES close, pharyngeal phase swallow mechanics did not include the final resting position of the pharynx/larynx which limits comparisons to traditional kinematic measures of swallowing.

Future research should incorporate a wider range of boluses to understand the effect of different and more challenging stimuli on within- and between-person variation in swallow patterns. Studies using CASM should also implement greater control over rater as well as trial sequence to increase control over the effect of rater on variability. Repeating this study with older and dysphagic populations is also a necessary next step to understand how degeneration and disease processes affect variability in the swallowing pattern. Further, the application of CASM in perturbation studies is also an exciting new direction for future study that will allow us to see holistic and interactive changes reflecting rapid, responsive motor adaptation.

Conclusion

CASM proved to be a powerful tool to detect changes in swallow mechanics at the individual level in response to subtle differences in bolus conditions. CASM would be a beneficial tool in single-subject design to guide personalized medicine, to choose therapeutic targets, and to monitor physiological adaptations at the individual level.

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Compliance with Ethical Standards

Ethical Approval All procedures performed in studies involving human participants were in accordance with the Ethical Standards of the Institutional and/or National Research Committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed Consent Informed consent was obtained from all individual participants included in the study.

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